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Smart Irrigation System for Precision Farming Using IoT, TinyML, Hybrid GSM & WiFi and Chatbot

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Abstract
Water scarcity and non-efficient irrigation practices reduces the productivity in agricultural field and the conservation of resources. This paper presents a smart irrigation framework which integrates IoT-based sensing, an ESP32 microcontroller with TinyML capabilities, hybrid GSM–WiFi communication, and a WhatsApp-enabled chatbot interface for intelligent and autonomous irrigation management. The smart irrigation framework enables collecting various environmental parameters such as temperature, moisture of soil and humidity through IoT sensors which are then processed using embedded TinyML models on the ESP32 platform which facilitates on-device irrigation facility and the distribution of water is automated via relay-controlled pumps. All the processed data are send to the cloud storage for undergoing data analytics in the future and to monitor the performance, the WhatsApp chatbot interface assists the farmers to receive the alerts, know the status of the system and to control the irrigation. This proposed design provides a scalable, energy-efficient and cost-effective solution for precision agriculture.
Keywords: *Internet of Things (IoT); Tiny Machine Learning (TinyML); ESP32; Precision Agriculture; Smart Irrigation; Chatbot.*

1. Introduction

1.1 Need of Water Resource Management in Agriculture

Developing countries like India focus on enrichment of agriculture activities to ensure global food security. Agriculture is marked as the largest consumer of freshwater resources worldwide. As per Food and Agriculture Organization (FAO, 2021), nearly 70% of the total freshwater is used for irrigation, where as in a country like India, the percentage of freshwater needed for irrigation facilities is nearly 85. This results in depletion of ground water levels which results in water scarcity for the domestic and industrial needs. The population in India is about to reach 1.64 billion by end of 2050 which shows the need and vast demand for food to be increased by about 70%. The agricultural productivity is varying due to unpredictable rainfall, floods, frequent droughts, and irregular monsoon cycles. Therefore, water resource management is needed for creating a sustainable, profitable agricultural ecosystem.

1.2 Limitations of Traditional Irrigation Techniques

Despite technological advancements, many farmers still rely on old irrigation methods such as flood irrigation, manual water pumps, canal irrigation as these traditional methods are simple and inexpensive to implement. These traditional irrigation methods suffer from various cons such as water wastage, unsuitable for sustainable agriculture, energy inefficiency, water distribution is uneven, water logging and so on.

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1.3 Advancements in Smart Irrigation Technologies

In recent years, there has been a rapid evolution in IoT-enabled smart irrigation systems. These systems collect the real-time data via various environmental sensors and microcontrollers to monitor the farm land and facilitate automatic irrigation. Research shows that such IoT-enabled smart irrigation systems can reduce the water usage by 40-50% and can show significant improvement in production.

1.4 Challenges with Commercial Irrigation Solutions

The commercial smart irrigation systems available in the market evolve with so many limitations and challenges for small and marginal scale famers. The limitations are mainly because of the high cost, unstable internet access in rural areas and complex user interfaces which requires amble practical skill and knowledge for the poor farmers to use the mobile apps or web dashboards.

1.5 Research Objectives

This research aims to bridge the gap between technological innovation and practical field deployment by developing a hybrid, cost-optimized smart irrigation system. The core objectives include:

- **TinyML integration:** Machine learning models are deployed on ESP32 microcontrollers for providing instant decision-making
- **Hybrid connectivity:** GSM and WiFi communication protocols are combined to ensure stable internet access
- **Simplified interface:** WhatsApp as a communication channel which requires no prior technical training.
- **Cost efficiency:** The targeted system is estimated to cost ₹25,000 which is reliable for small scale and marginal scale farmers to afford. This system seeks to provide technically robust, economically sustainable irrigation solution which enhances water management and yield in agriculture.

2. Related Work

S. Ramesh [5] formulated an IoT-based irrigation system model in which IoT sensors are used to collect various environmental parameters like humidity, temperature, soil moisture which transmits the collected data to web based dash boards or mobile apps which optimizes water usage and increased irrigation efficiency. The drawbacks of this system is lack of decision making because of poor internet connection and also it lacks offline performance.

J. Srikanthnaik [7] discussed a cloud-centric IoT based smart irrigation system model which facilitates storage of real time data from environmental sensors in central cloud server in which the machine learning algorithm process the data and supports the farmers with irrigation-based decisions. The limitations in this model are unreliability due to unstable internet access and dependency of cloud storage.

Hammouch [4] discussed about intelligent irrigation system with implementation of AI, TinyML that runs on microcontrollers like ESP32 or Arduino Nano 33BLE. TinyML bridges the gap between AI and IoT hardware. This low-cost system enabled smart irrigation accessible in rural areas.

Parashar [11] discussed about the various infrastructure and role of ICT (Information and Communication Technology) in farm fields.

Shafi [12]. Aggarwal and Singh [13] reviewed networks and wireless sensors in agriculture, and suggested a system with predictive technology using integration of IoT and AI. SIM900 GSM module is used as an effective solution to balance the failure due to lack of internet connection and also to ensure reliable data transfer to the cloud.

3. Methodology

3.1 System Architecture

The proposed framework consists of five layers.

- **Sensing layer:** The sensors used are capacitive soil moisture sensors, DHT11/22 sensors, optional light/photometric sensors.
- **Edge Processing layer:** TinyML deployed with ESP32 micro controller is used.
- **Actuation layer:** Relay modulated submersible pump is used.
- **Communication layer:** Here hybridized GSM(SIM800L) and Wi-Fi connection is deployed.
- **Application layer:** Cloud data repository

(Firebase/MySQL) and Whatsapp interface through flask backend.

3.2 Working of Proposed System

The proposed system starts with the sensing unit, where continuous monitoring of agricultural field through soil moisture sensor, DHT11/22, and optional light/photometric sensors. These sensors produce real-time data about the water level in the soil, temperature levels, humidity levels which are essential for irrigations. All the collected data are transferred to the ESP32 microcontroller. Here ESP32 microcontroller act as the central processing unit. An alert message is sent to the farmer through Wi-Fi to the farmers whatsapp. If the internet is down, alert message is sent through GSM module. TinyML model is implemented directly on ESP32, which provides offline decisions independent of internet dependency.

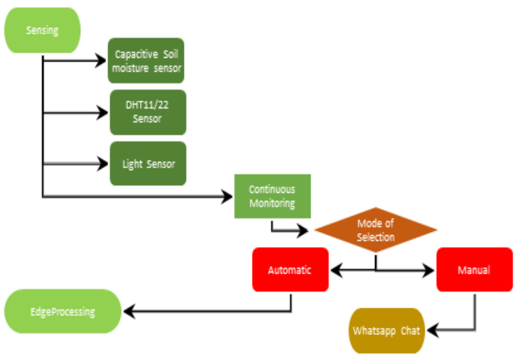

Figure 1 System Architecture

The system operates in two modes: (1) Automatic mode, where TinyML controls irrigation without human interference and without internet. (2) Manual mode, where farmer can remotely monitor and control irrigation, is depicted in Figure 1. The ESP32 analyze the soil moisture level and decides whether irrigation is needed. For example, if the soil moisture is less than 30%, the system will automatically turn the pump ON, whereas if it exceeds 60%, the pump is turned OFF. Every time the TinyML makes decision based on the collected data, the signal is sent to the relay module. The submersible water pump connected to the irrigation pipeline, is controlled by relay module. Based on the ESP32 commands, the relay perform as a switch for enabling and disabling the pump for efficient watering. In parallel, the ESP32 manages the communication, through a hybrid connectivity model, with the cloud backend. The ESP32 transfers collected data like sensor readings and pump status logs to the cloud server through a Flask backend and Firebase/MySQL database when the Wi-Fi is available. The system uses a GSM module (SIM800L) to transfer data through mobile network when Wi-Fi is unavailable. This method helps to ensure a reliable connection in rural areas even with poor internet. Here the cloud backend stores the historical data, analyze them and generate reports for future usage. Thus, reducing the wastage of water and ensuring efficient and effective usage of water. The proposed system architecture is depicted in Figure 2 and Figure 3.

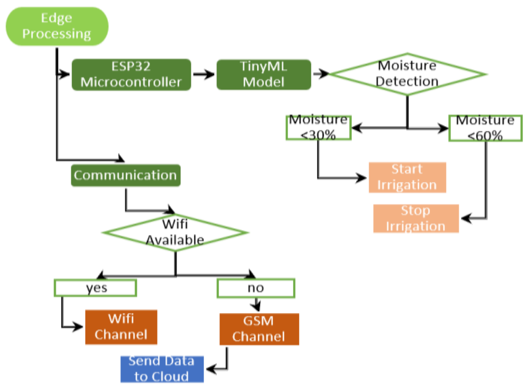

Figure 2 System Architecture

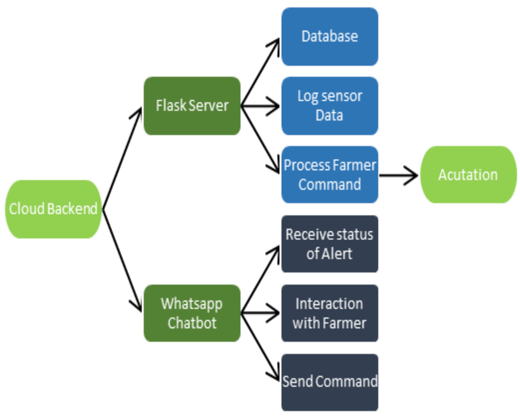

Figure 3 System Architecture

The system introduces a whatsapp chatbot interface to provide a seamless two-way communication, using

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the Meta Whatsapp Cloud API, for the farmer. Here the farmer can send text queries and will receive immediate responses, even can give commands like "turn ON pump" directly through whatsapp. The backend receives a query; it takes real-time data from ESP32 and responds to the farmer instantly. Also, when the farmer requests for manual pump control, the backend give commands through Wi-Fi or GSM to the ESP32. The ESP32 executes the action commanded by the farmer by controlling the relay and pump. For farmers accessibility, the chatbot is designed to send automated alerts and notifications of low soil moistures and irrigation completions in local languages. This system is farmer-friendly, cost effective, reliable, and sustainable, highly scalable for implementing in real world.

3.3 Hardware Components

- Field sensing: Capacitive soil moisture sensor, DHT11/22 sensor, optional light/photometric sensors.
- Central Processing Unit: ESP32 DevKit with integrated SIM800L GSM module.
- Actuation subsystem: Relay module and submersible pump.
- Power Management: Solar panel with battery backup.

3.4 Software Implementation

- Microcontroller Programming: Arduino IDE-based firmware for ESP32.
- Machine Learning: TensorFlow Lite models trained on regional crop datasets.
- Cloud: Python Flask backend with Firebase/MySQL persistence
- Conversational Interface: Whatsapp Cloud API Integration.

4. Results and Discussion

Compared to the traditional irrigation systems, the proposed system achieves 40-60% in conservation of water resources reducing the water wastage. Monitoring of soil moisture with ESP32 and controlling the irrigation with TinyML are the reason behind the success rate of water conservation. The decision-making process by TinyML on ESP32 was efficient with the response time less than 1 second and the delay for pump activation was around 2 seconds while activated either automatically or by commands from the farmers. TinyML enabled the irrigation to work in offline mode automatically. Also, the system is found to be reliable even in rural areas with poor internet connection, GSM module provided connectivity. The whatsapp chatbot interface is marked to be user friendly as it does not require any training for the farmers to use it as it is the most familiar interface used worldwide. All small scale and marginal scale agricultural field can adopt the system as it paves the way for the farmers to easily control by giving simple commands like start or stop irrigation, check soil moisture, temperature and can get alert notifications and daily reports. The traditional systems which exist in the market is ruling with a price range of ₹75,000 to ₹1 lakh. The proposed system is built for approximately ₹25,000 which is three times more affordable than the existing ones. The components cost is tabulated as follows:

Table 1: Cost of components

Components	Cost
ESP32 + GSM/Wi-Fi module	₹1,200
soil moisture and DHT11 sensor	₹400
relay and pump	₹1,500
power supply and optional solar integration	₹5,000
cloud + chatbot integration	₹2,000

Conclusion

This paper proposes an IoT sensing system with TinyML, hybrid connectivity (GSM/WiFi) and a chatbot for providing an innovative solution for irrigation in rural areas. This system addresses the real-world challenges and makes the system in a low-cost platform, online & offline access and user friendliness. Also, the chatbot is familiar and easy to use and enables this system to be deployed in small, medium, and large-scale agricultural fields.

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