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Next-Generation Farming: Leveraging IoT Sensors for Sustainable Smart Agriculture

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ABSTRACT

The agricultural industry in India is losing ground daily, which has an impact on the ecosystem's ability to produce. Resolving the issue is becoming more and more important to revitalize agriculture and return it to a path of higher growth. An extensive agricultural system requires a lot of maintenance, expertise, and supervision. The Internet of Things (IoT) is a network of linked devices that may communicate and receive information via the Internet and perform tasks without the need for human intervention. Increased crop yields are the outcome of the abundance of data analysis parameters provided by agriculture. The modernization of communication and information is facilitated by the use of IoT devices in smart farming. It is reasonable to expect that moisture, minerals, light, and other elements will improve crop development.

In this study, we are discussing to development of the agriculture system in India. An advanced version of agriculture for farmers who can grow, develop and cares of the crops. The aim of next-generation agriculture by IOT sensors is to merge intelligent technologies to produce an agricultural environment that is more precise, effective, and sustainable. This system is based on advanced sensor technologies, like weather sensors, temperature sensors, humidity sensors, rainfall, wind, and soil sensors, which monitor temperature, pH, and moisture level. Also, livestock sensors to monitor the health of crops and the movement of pests, insects, and animals

Wireless communication technologies such as LPWAN (local power wide area network), including LoRa and NB-IoT, are utilized for data collection and transfer in faraway agricultural areas due to their long-range and low power consumption. Farmers can increase resource use, improve production, and reduce their impact on the environment. To support seamless data collection and transmission in remote agricultural areas, wireless communication technologies such as LPWAN (Low Power Wide Area Network), including LoRa and NB-IoT, are utilized for their low power consumption and long-range capabilities. These technologies enable continuous monitoring and real-time decision-making, allowing farmers to optimize resource use, increase yield, and reduce environmental impact. Overall, next-generation IoT-based agriculture combines sensor data with connectivity and analytics to transform traditional farming into a smart, data-driven practice.

Keywords- IoT in agriculture, Smart agriculture, Soil monitoring, Environmental Monitoring, Communication.

I. INTRODUCTION

Traditional farming lacks real-time data and efficiency. Manual observation, historical knowledge, and sporadic intervention make up the majority of traditional agricultural methods, which frequently lead to inefficient resource use and a delayed reaction to environmental changes. When it comes to irrigation, fertilizer, and pest management, farmers usually rely on their experience or visual signals. But this method isn't accurate enough or timely enough to meet the demands of modern agriculture. It is difficult to maximize agricultural growth conditions, stop crop diseases early, or react quickly to climate unpredictability when real-time data is unavailable. It is therefore challenging to maintain productivity and profitability in the face of rising global food demands and environmental challenges because old methods frequently result in excessive use of water and fertilizers, lower crop yields, and higher operating expenses[1][2].

One of the technologies that is expanding the fastest in the modern world is artificial intelligence (AI). These days, artificial intelligence is widely used in many different industries, from robotics development to environmental monitoring[3], [4]. Unquestionably, artificial intelligence (AI) has applications in healthcare systems, self-driving cars, satellite imaging, terrain mapping, climate change monitoring, and medical equipment. AI has accelerated the development of robotics worldwide, which has improved people's quality of life and made living easier. AI-mediated automation in several industries, including agriculture, will produce high-quality goods with fewer adverse environmental effects[1], [5].

IoT-based technologies are used in precision farming to track agricultural variables. For improved environmental protection and the ongoing sustainability of agricultural production, IoT offers real-time critical data about crop, soil, water, and air conditions. To expedite the irrigation process, irrigation can be converted into a smart irrigation system. Unmanned aerial vehicles (UAVs) are one piece of equipment that is utilized to quickly gather vital data about crucial agricultural elements like pest attack, soil quality, and water availability over a wide area [6]. Even in remote locations, UAVs equipped with spectrum analysis technology may detect pest infestations in farms by taking high-resolution pictures that are saved in cloud server databases for additional analysis [6].

India is mostly an agricultural nation. These days, farmers manually irrigate the land at regular intervals. Crop dryness may come from increased water consumption or from longer transit times bringing the water to its destination. Monitoring humidity and temperature in real-time is essential in many agricultural fields. However, there are several application constraints due to the rigidity of the outdated wired detection control approach. One important solution to this issue is irrigation automation, which this project accomplishes. A Raspberry Pi helps do this by controlling the temperature and moisture sensors in response to input. For this reason, an automatic plant watering system is built using moisture sensors. The primary aim of this study is to simplify supervision and steer clear of ongoing monitoring. In this study, a system has been developed that can achieve smart agriculture. IoT-based agriculture monitoring is part of this system. The Internet of Things (IOT) is revolutionizing the agricultural industry and tackling the massive challenges and barriers that farmers face in the field today. To find out if the soil is wet or dry, a soil moisture sensor is inserted into it. Regular monitoring of the relay unit connected to the motor switch is necessary if the soil's moisture content is low. It will activate the motor when the soil is dry and switch off the engine when the soil is wet.

II. RELATED WORK

A survey identified several loopholes. First, rather than offering a complete, end-to-end solution, many studies concentrate on certain elements, including soil sensing or weather monitoring. Second, even though power management and energy efficiency are essential for off-grid and isolated areas, they are frequently disregarded. Third, although data collecting is becoming more and more important, fewer studies examine efficient data analytics and real-time decision-making for insights that may be put to use [7]. Figure 1 shows the IoT-Based Sensor Data Uses in India.

There is a need for an affordable, scalable, and integrated IoT-based smart farming system that can track several environmental variables, function in real time, and deliver useful information via a single platform. The proposed approach fills these gaps by creating an end-to-end agricultural monitoring system that integrates sensor networks, wireless communication, edge computing, cloud storage, and user-friendly interfaces [5]. This system seeks to serve both small- and large-scale farming operations by emphasizing affordability, modular architecture, and real-time analytics, thereby increasing the accessibility and sustainability of precision agriculture.

In recent years, many devices have been developed that are connected with technology. Most of them are IoT-based devices that sense the data and give results. Internet of Things (IoT) technologies are increasing productivity, efficiency, and sustainability in the field of agriculture [1]. There are some examples of developed agriculture systems, are SmartFarmNet, OpenAg, and Agri-Tech. IOT has increased the ability to monitor soil moisture, temperature, humidity, and other key parameters to support the IoT-based sensor [5].

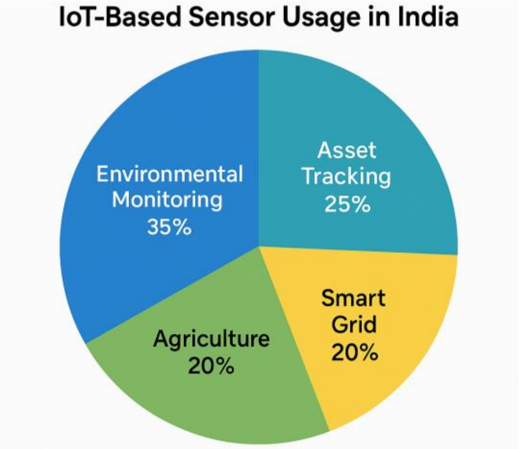

Figure 1. IoT-Based Sensor Data Uses in India

1. System Architecture and Design

a. Hardware Components:

- **Acoustic based sensors:** The electrical instruments used to identify variations in sound frequencies are called acoustic-based sensors.

Figure 2. Acoustic based sensors

- **Soil moisture**: Detect soil for water supply if soil needed it. With the help of this we can detect the water.

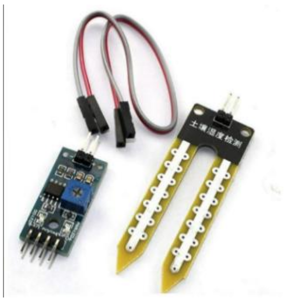

Figure -3. Sol moisture sensor

- **Soil temperature**: Determines the soil's thermal state. Farmers can more efficiently schedule planting and fertilizer application by keeping an eye on this characteristic [3].

Figure 4. Soil temperature

- **Air temperature and humidity**: Gathers information about the humidity and temperature of the surrounding air. Extreme humidity or temperatures can cause stress, lower yields, or disease outbreak.

Figure 5. Air temperature and humidity sensor

- **Soil pH**: Indicates soil fertility and helps in crop selection [1].

Figure 6. Soil pH sensor

b. Communication Layer:

The communication layer is the part of the system that transmits sensor data to the CPU or cloud server. Ensuring that field data enters the system immediately, without interruptions, and without data loss is crucial. A wireless, low-power, and reliable communication method is needed since sensors are commonly located in large or remote farming regions[5].

- **LoRa**: Long-range, low-power, ideal for large farms.
- **Wi-Fi**: ideal for place where infrastructure is already in place.
- **Zigbee**: Low-power mesh network that works well for installation of many sensors.
- **NB-IoT**: Cellular-based solution for dependable connectivity and large coverage.

c. Processing Layer

- **Arduino Uno/Nano:** Arduino is the company behind the Arduino Uno microcontroller board. The Atmega328 microcontroller serves as its foundation. Massimo Banzi and David Cuartielles launched the initial Arduino project in 2003 as an affordable and adaptable method of learning embedded programming [8].
- **Raspberry Pi 4B**: This more potent minicomputer gathers, processes, and transmits all of the sensor data to other devices or the internet. It gathers information from several Arduinos or sensors, saves it, processes it, and can even transmit it to a mobile app or the cloud. It can manage intricate activities like image processing, data logging, and network connectivity since it runs a full operating system, much like a little PC [8].

d. Data Storage Layer

- **Local storage:** The Raspberry Pi may store data on tangible media such as USB drives or SD cards. When internet access is restricted, this is helpful [9].
- **Cloud storage:** Other options include sending the data to cloud platforms (such as AWS, Google Cloud, or Firebase), where it is safely kept on the internet. In addition to helping with long-term storage and backup [9].
- **Databases:** To arrange and manage the data, databases like as MySQL, MongoDB, or InfluxDB are utilized, whether locally or in the cloud. Over time, this facilitates information search, filtering, and analysis [9].

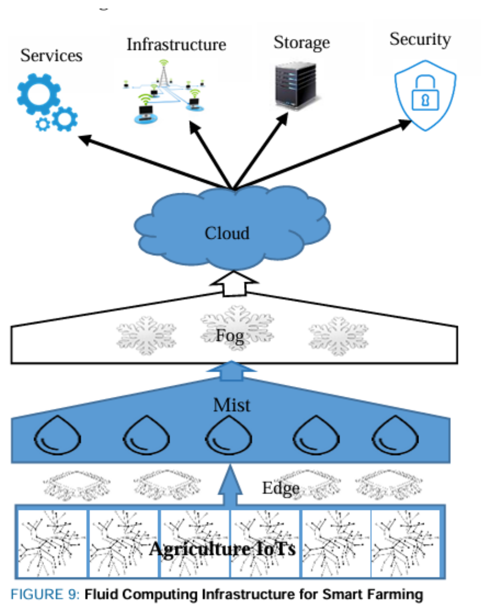

Figure 7. Fluid Computing Infrastructure for Smart farming

2. Challenges and Limitations

The price burden associated with deploying and installing IoT-tagged sensors and peripheral devices across a large portion of agricultural land is one of the main barriers. Furthermore, the amount of benefits made and the cost of implementation are unclear. The cost of purchasing hardware, installing software and running the systems are significant expenses associated with implementing IoT-enabled technologies. Energy consumption, system maintenance, service registration and the cost of personnel required to operate the integrated hardware devices and related software will all bring additional expenses. Another issue that can have a detrimental effect on the widespread deployment of IoT and smart systems is data privacy and security. Attackers can tamper with data saved on cloud servers to harm the automated agricultural systems of farms. Such attacks can further impact the productivity of the entire farm and poor management of environmental elements. Consequently, one of the main reasons for the slow adoption of smart farming technology is concerns about IoT data security[1]. A trustworthy encryption solution is necessary for smart farming to keep digital systems and critical data safe from international cybercriminals. Strong keys combined with cryptography can mitigate cyber attacks on cloud servers [5].

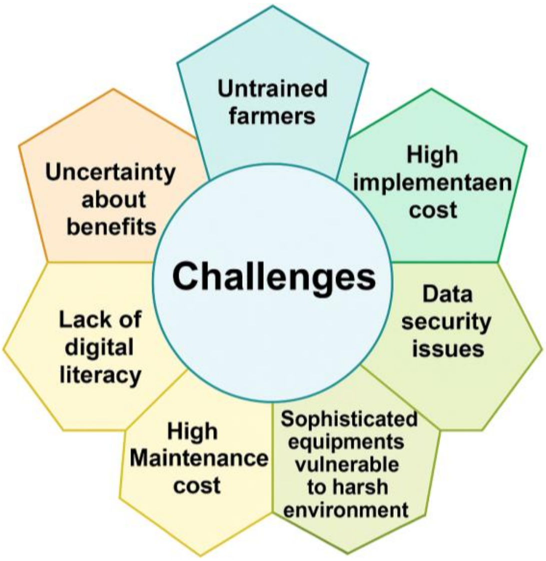

Figure 8. Challenges [4]

Limitation:

- Limited range of wi-fi modules
- Power dependency
- Local storage
- High cost and maintenance
- Setup complexity
- Interference from environment
- Risk on data loss

3. Future Scope

The application of machine learning and artificial intelligence is a significant advancement. These technologies can help analyze data collected by sensors to predict things like when to water crops, potential diseases, or estimated harvesting times. This will reduce waste and help farmers make better choices. Additional sensor types may be introduced in the future, including sensors that detect air, CO2, or soil nutrient levels. This will allow farmers to know more specific details about their fields. Better security technologies should be implemented to keep data safe as security is also important [10].

Every state in India has different soil types and there is still a lot to learn about Indian agriculture, which has a lot of untapped potential. Adopting this scheme will provide significant benefits to farmers. IoT-based smart agriculture systems have a lot of potential for the future and can become more user-friendly. Some future scopes are mentioned below[10].

1. To detect the movement of any animal on the farm, we can incorporate motion sensors in the system.
2. To make the system easier for farmers to use, voice command functions supporting multiple regional languages can be added.
3. GPS (Global Positioning System) can be incorporated in the system to get accurate location data of farmers and weather reports of the farm.
4. To enhance its utility, we can add a rain detection sensor.
5. We can also incorporate a webcam in the system, and the app will show the pictures taken.

4. Model Development & Implementation

To verify its efficacy and functioning, a small-scale test plot was used to deploy the suggested Internet of Things-based agricultural monitoring system. The system was made up of several sensor nodes spread out throughout a 10 m x 10 m tomato-growing area. A collection of sensors was installed on each node, including a rain detection sensor, a light-dependent resistor (LDR) for light intensity, a pH sensor (SEN0161), a temperature and humidity sensor (DHT11), and a soil moisture sensor (YL-69). An ESP32 microcontroller, selected for its low power consumption and built-in Wi-Fi functionality, was used to interface these sensors. Lithium-ion battery packs and solar panels were used to power the nodes, guaranteeing continuous field operation.

Using Wi-Fi connectivity and the MQTT protocol, sensor data was sent to a cloud server at 10-minute intervals. A Wi-Fi repeater was placed in the middle of the field to increase the coverage area. The gathered data was transferred to the Thing Speak cloud platform, which offered graphical dashboards for real-time analytics and visualization. Trends in historical data were utilized to improve irrigation decision-making by Analyz environmental patterns. The IFTTT platform was used to set up alerts that would send consumers an email or SMS when important thresholds, such low soil moisture, were identified.

The implementation also included an automatic irrigation system. The ESP32-controlled relay module opened a solenoid valve to start irrigation when the soil moisture content fell below 30%. To guarantee using the Arduino IDE. The device showed notable increases in irrigation efficiency throughout a 30-day testing period, resulting in a 25% reduction in water usage. Because of the automated features, physical labour was reduced and soil moisture levels stayed within the ideal range of 30 to 60%. Additionally, the tomato plants' health improved, as seen by their more consistent growth across the test plot.

Despite the positive results, there were some difficulties in putting the plan into practice. Data smoothing techniques were used to address the rain detection sensor's first false positives caused by morning dew and the periodic calibration needed to maintain accuracy. Additionally, using a repeater to enhance the network fixed sporadic Wi-Fi signal problems. Overall, the deployment established the foundation for future scalability and predictive analytics integration while validating the viability and efficacy of utilizing IoT-based sensors for smart agriculture.

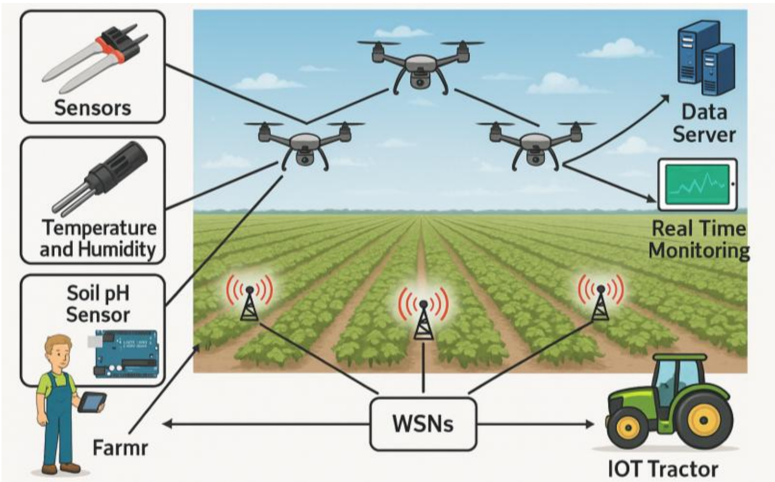

Figure 9. Model Development & Implementation

5. Circuit diagram of IoT-based Smart agriculture System

The IoT-based Smart Farming System integrates various sensors and microcontrollers to enable real-time environmental and soil monitoring. This circuit employs a combination of a Raspberry Pi and an ESP32 microcontroller to gather and transmit data to the cloud for remote access and analysis.

At the core of the system is the Raspberry Pi, which acts as the main processing unit. It is directly connected to three local sensors: a soil moisture sensor, a temperature and humidity sensor, and an acoustic sensor. The soil moisture sensor measures the volumetric water content in the soil, enabling the detection of dry or saturated soil conditions. The temperature and humidity sensor (e.g., DHT11 or DHT22) provides crucial data about the surrounding environment, which can influence irrigation and crop health. The acoustic sensor detects ambient sounds, such as rainfall, animal movement, or operational machinery, offering additional contextual awareness.

The system also includes an ESP32 microcontroller, which serves as a remote sensor node placed in distant parts of the field. It is connected to two additional soil moisture sensors to monitor broader areas. The ESP32 transmits its collected data wirelessly to the Raspberry Pi, reducing the need for long physical wiring and enhancing scalability.

Once the Raspberry Pi gathers data from both its local sensors and the ESP32, it transmits the information via the internet to cloud storage. This allows farmers to remotely access real-time and historical data through dashboards or mobile applications. The cloud also enables integration with decision support systems or automated control mechanisms, such as triggering irrigation systems based on soil moisture levels.

This architecture supports scalability, modularity, and energy efficiency, making it suitable for a wide range of agricultural applications. The use of low-cost components and wireless communication makes it a viable solution for small and medium-sized farms aiming to improve resource efficiency and productivity through precision agriculture.

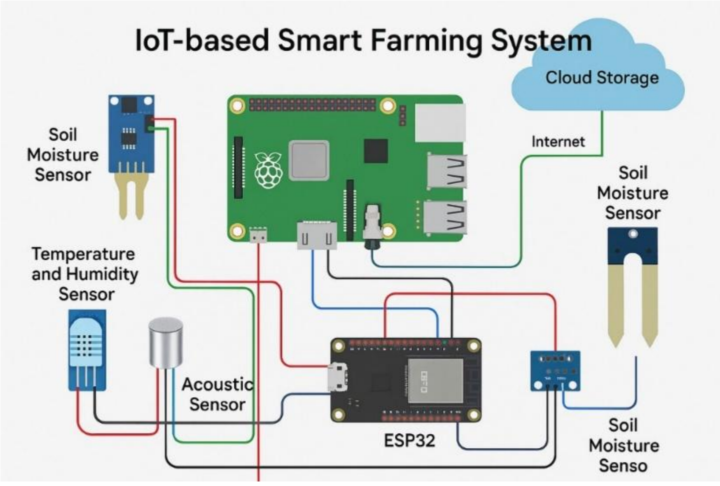

Figure 10. IoT-Based Smart Farming System

III. CONCLUSION

The integration of IoT sensors into agricultural practices marks a transformative shift towards a more intelligent, efficient, and sustainable farming paradigm. As explored throughout this study, next-generation farming harnesses the power of interconnected devices to collect real-time data on critical variables such as soil moisture, temperature, humidity, crop health, and environmental conditions. This data-driven approach empowers farmers to make informed decisions, reduce resource wastage, and optimize crop yields while minimizing environmental impact.

IoT-based smart agriculture not only enhances precision farming techniques but also facilitates predictive analytics, remote monitoring, and automation—hallmarks of a resilient and future-ready agricultural system. By deploying sensor networks and leveraging cloud-based platforms, farmers can monitor their fields in real time, detect anomalies, and respond proactively to potential threats such as pest outbreaks or adverse weather conditions. Moreover, the application of machine learning algorithms to sensor data holds the potential to uncover deeper insights and recommend actionable strategies for continuous improvement.

From a sustainability perspective, IoT sensors contribute to more responsible use of water, fertilizers, and pesticides, thereby preserving natural ecosystems and reducing the carbon footprint of agricultural activities. These technologies also play a crucial role in addressing global challenges such as food security, climate change, and the growing demand for agricultural products driven by population growth.

However, while the benefits are substantial, the adoption of IoT in agriculture also presents challenges, including data privacy concerns, high initial investment costs, connectivity issues in rural areas, and the need for technical expertise. Addressing these barriers through supportive policies, infrastructure development, and capacity-building initiatives will be essential to fully realize the potential of smart farming.

In conclusion, IoT sensors represent a cornerstone of next-generation agriculture, offering a path toward more productive, sustainable, and resilient farming systems. As technology continues to evolve, its thoughtful and equitable implementation will be key to unlocking a future where agriculture not only feeds the world but does so in harmony with the environment.

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