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IoT Applications for Sustainable Agriculture: A Holistic Review

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Abstract: *The integration of Internet of Things (IoT) tech- nologies in agriculture has enabled data-driven and sustainable farming practices. IoT devices, such as sensors, actuators, and cloud-based monitoring systems, provide real-time information on soil health, weather conditions, and crop growth, allowing farmers to optimize resource usage, increase productivity, and reduce environmental impact. This paper reviews recent devel- opments in IoT-based sustainable agriculture, analyzes existing solutions, highlights challenges in implementation, and discusses future research directions for scalable and cost-effective adoption.*

Keywords*:* IoT, Sustainable Agriculture, Precision Farming, Smart Farming, Sensors, Data Analytics

I. INTRODUCTION

Sustainable agriculture aims to produce food efficiently while minimizing environmental impact and preserving natural resources. Conventional farming methods often rely on manual monitoring and experience, which can lead to inefficient resource use and inconsistent yields [1]. The Internet of Things (IoT) offers solutions by connecting devices that collect, transmit, and analyze real-time data from agricultural fields. This enables precision farming, reduces waste, and improves crop management, making agriculture more sustainable [2].

The Internet of Things (IoT) technology is being utilized in many sectors across the world. These sectors are agriculture, home automation, automobiles, and the medical industry. The IoT uses elements like sensors and other elements to sense data like heat, temperature, and other important factors from the outside world [3]. This IoT in agriculture can read the data from the outside world and send an alert message to the farmers. Crop yields can be increased by using infor- mation recorded and inferred in the farm field, as well as weather information from online repositories [4]. Agriculture production needs to be improved with advanced technology to help the entire ecosystem. In order to improve the production system, the most important things to measure are temperature, humidity, and soil signals [5]. This data will be transmitted by the wireless networks through an M2M (machine to machine) support platform. The IoT uses both wired and wireless tech- nology to communicate between the sensors, microcontrollers, and actuators [6].

Based on the problem noticed in agriculture, the IoT tech- nology was selected to overcome the problem. Different IoT techniques use sensors to transmit the data from a ground point to a destination point, called a ”farmer communication point [7].” When a farmer receives an alert message, he performs the alternative task to avoid damage to his field. IoT in agriculture can also change many developing countries into developed countries [8]. Smart agriculture has recently been advocated as a way to improve agricultural modernization and considerably increase food output. In particular, smart agriculture systems incorporate numerous modern computer and information technologies such as the Web of Things, machine intelligence, and cloud technology [9]. IoT is mostly used to gather agricultural data and transfer it to data centers, while artificial intelligence methods are utilized to evaluate the data for smart decision-making [10]. One example is looking at the data on the agricultural ecosystem to figure out how much water is needed for irrigation [11]. Researchers have deployed a novel and revolutionary wireless sensor network within an IoT system designed to boost agricultural production while addressing the challenging impacts of climate change [12]. Portable devices are employed to gather data on various factors such as temperature, humidity, soil moisture, and plant development stages. This

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information is then processed and analyzed by a cloud-based sys tem, offering farmers real- time updates on crop growth and health. By aiding farmers in making informed decisions regarding pest control, fertilizer application, and irrigation systems, food yields are enhanced while conserving resources. This parallels the proposal in [13], which introduces an IoT system for managing automated farming across diverse communication platforms [14]. The system incorporates factors such as data transmission speed, communication method, security, range, delay, throughput, and power consumption to develop a robust, secure, and dependable system [15]. Comprising sensors that oversee and regulate processes such as watering, pest control, fertilization, and harvesting, it offers flexibility to align with the resources available to individual farmers, facilitating seamless integra- tion into their operations. An IoT based automated system is designed to streamline every aspect of farming, from seed sowing to post-harvest cleanup [16]. Sensors are deployed to measure soil moisture, temperature, humidity, and other environmental factors. The collected data is transmitted to the cloud for analysis, enabling farmers to receive real-time recommendations on when and how to water, fertilize, and protect their crops [17]. Additionally, the device can manage the systems responsible for watering, fertiliza tion, and pest removal. For scalability, the system can incorporate additional UAVs, cameras, farm bots, and other systems as needed. This enables complete automation of farming tasks, reducing the need for daily manual intervention. Consequently, efficiency in farming is enhanced, leading to reduced labor costs and increased farm productivity [18]. The integration of wireless sensor networks (WSNs) and IoT appli cations has revolu- tionized how farms collect and monitor information compared to traditional methods [19]. With these technologies, farmers now can remotely monitor various aspects of their farms using tracking de vices. This allows for real-time surveillance and management of different farm areas, marking a significant departure from previous methods of data collection and ob- servation [20]. The IoT-based setup analyzes, and processes remotely obtained data through the cloud, providing valuable insights to farmers for decision-making. With tech nological advancements, it becomes feasible to develop self-installable, personalized landslide warning systems deployable in haz- ardous areas without user intervention [21]. These systems can autonomously adjust communication lines for effectiveness and address node failures. Addi tionally, the concept of an IoT management system has emerged, capable of monitoring various environmental factors such as air, wind, water, and soil across large areas [22]. By utilizing affordable electronic devices and communication technologies, IoT enables remote environ mental monitoring, allowing individuals to observe the environment without direct physical presence [23]. Through IoT, detailed maps of noise, air quality, water pollution, current weather conditions, and radiation levels can be generated and updated in real-time. Additionally, outdoor factors can trigger data transmission to users, alerting them through messages or notifications from designated officers [24].

II. LITERATURE REVIEW / BACKGROUND

Several studies have explored IoT applications in agricul- ture:

• Sensors and Monitoring Systems: Soil moisture sen- sors, temperature sensors, and nutrient detectors provide continuous field data [25].

• Automated Irrigation Systems: IoT-enabled irrigation systems adjust water supply based on real-time soil and weather data, saving water and energy [26].

• Crop Health Monitoring: Image-based sensors and drones can detect pest infestations or nutrient deficiencies early [27].

• Data Analytics and Cloud Computing: Collected data can be analyzed for predictive insights and long-term planning, integrating AI algorithms for decision-making [28].

These systems improve yield quality, optimize resource utilization, and reduce environmental degradation.

III. RELEATED WORK

IoT techniques make use of the cloud by collecting data from the fields and utilizing machine learning to predict future instances to overcome upcoming disasters. Using the GSM module, the client receives the SMS or alert message [29]. In many countries, like China, Thailand, and other countries, there is a successful implementation of IoT in farming. IoT sensors are able to gather data from the agricultural field and respond to user-input via wireless networks, making them ideal for farmers [30]. The aim of the IoT in agriculture is to make fields talk to each other. It uses the sensors to grab the data, and that data can be used to analyze the situation. As a result, no output resource is utilized less efficiently, and most production resources are also more efficiently used as yield levels rise as control parameters are optimized more. An experimental setup with a large number of sensors for monitoring the farming area's status is designed. The suggested system employs an infrared camera to detect the presence of insects based on the heat they emit. To validate the pest's existence in the field, image processing is utilized to take photos of the pest [31]. A new technique for analyzing humidity, temperature, and light in a potato field using a wireless sensor network has been developed. Based on the data acquired, farmers may be able to find a recovery technique for increasing the fertility of the soil. The major aspect of IoT in agriculture is situational monitoring. Several kinds of farming are: crop farming, aquaponics, forestry, and livestock farming. The parameters monitored are water, fuel, and animal feed using IOT. Many countries are not able to develop this type of IoT- based application because of development costs. A multi-agent system is developed with precision agriculture for intelligent systems in the industry. Precision agriculture seems efficient because it is tightly matched with scientific theories of soil, crop, and pest management. Automatic irrigation systems also provide a better system because it works based on temperature, water content in the air, and humidity sensor [32].

IV. ARCHITECTURE OF THE PROPOSED SMART FARM MANAGEMENT SYSTEM

The proposed architecture of the smart farm management system is depicted in Figure. 1. The goal is to facilitate communication between the various components of the system.

Figure 2: Arduino Mega 2560 board.

Figure 3: (A) The soil moisture sensor,

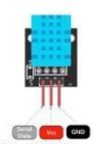

Figure 3: (B) The pH sensor, Figure 3: (C) The DHT11 sensor.

This communication can be identified in several steps. The key components of the system consist of an Arduino MEGA 2560 board, a water pump, sensors like soil pH sensor, soil moisture sensor, and temperature and humidity sensors (DHT11), a cloud service, and a web and mobile application [33].

1. Description of the Architecture Studied crops field: The crop farm being studied incorporates IoT devices, including an Arduino MEGA 2560 board (refer to Figure. 2) and a water pump. It also utilizes sensors such as a soil moisture sensor (refer to Figure. 3. A), a soil pH sensor (refer to Figure. 3. B), and DHT11 sensors for temperature and humidity (refer to Figure. 3. C). These sensors gather essential data on soil moisture, acidity, ambient temperature, and air humidity, which are then transmitted through the Gateway for real- time management or to cloud computing services for in- depth analysis [34]. The network technologies considered for transmitting this data include: Wi-Fi : between farm equipment and the Gateway; G/5G : between the Gateway and the Cloud service. Real-time farming management: A web or mobile application allows farmers to access real-time information about the farm under study [35]. The data is presented in different formats, including graphical representations of am- bient humidity and temperature, with other data shown in percentages. Additionally, the algorithm proposed in this work provides a classification of the most suitable crops or seeds based on soil pH to increase yield. Furthermore, some tasks such as watering can be managed through the application [36]. Cloud computing services: It provides administration services for the proposed system's

applications, database, and operating algorithm. Then, users may remotely access these data using a computer or a smartphone. The cloud service will enable additional analysis of the data gathered from the farm being studied [37]. Remote farming management: the farm management services of the proposed system can also be accessed remotely via a web or mobile application housed in the cloud and especially for further analysis of the data captured [38].

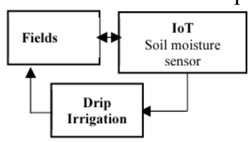

Figure 1. Drip irrigation

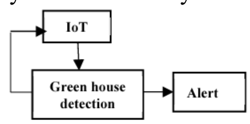

Figure 2. IoT based greenhouse detection

V. METHODOLOGY USED

Various methodologies are implemented to achieve the highest yield, and technology plays an efficient role in the agriculture sector. The accuracy of a methodology is calculated by considering the advantages of using that methodology, response time, and many others. The different methodologies are briefly discussed in the following section. 1. Drip Irrigation using IoT Sensors Drip irrigation is the process of watering the field or plants, and it saves 40–50% of the water that was going to be wasted. These sensors are used in agricultural lands to detect water content in the soil. Depending on the values read by the sensor, the IoT technology decides whether to send water to the crops in the field or not. It uses the Arduino board with the combination of a soil moisture sensor. The IoT sensors continuously check the reading from the soil [39]. With the combination of IoT and drip irrigation, water saving is increased by up to 50–60% . The goal of this system is to make a reliable, advanced, cost-effective, and smart drip irrigation control system gadget that can look at the land's humidity, heat, and moisture levels and deliver water close to the roots of the plants to make sure all crops get enough water for healthy growth while reducing labor-intensive tasks [40]. 3.2. Greenhouse Agriculture IoT Green house detection Alert Figure 2. IoT based greenhouse detection The goal is to provide agriculturists with field data about greenhouse factors such as carbon dioxide (CO_2), soil moisture, humidity, and light. The water content of the soil is monitored in order to control how the conservatory windows and doors roll on and off [41]. This prevents agriculturists from physically visiting the fields. Crops, farm animals, soil, moisture conditions, and the effects of current technologies are being investigated. IoT is commonly used to link devices and collect data, as shown in Figure 2. The device is meant to monitor various greenhouse characteristics such as CO_2, moisture, heat, and light [42]. Gardeners may gather this data using a cloud application and internet access. Conservatory windows and doors roll open and shut based on how much moisture is in the air. By doing so, all the physical tasks can be controlled automatically [43].

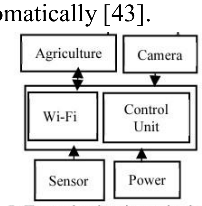

Figure 3. IoT monitoring in agriculture

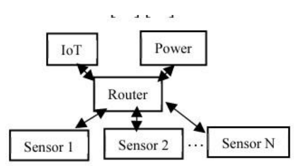

Figure 4. Wireless network in agriculture

3. IoT based Monitoring System in Agriculture The system's core components are a microprocessor, a network processor, and an area network unit. It is lightweight, battery-operated, and provides a secure and quick connection [44]. Variations in environmental circumstances will have an impact on the crop's total production. For maximum development and yield, the health of the plants needs to be maintained. Systems are used to detect the state of the crop field, which is highly important [45]. The temperature is measured using an infrared thermostat sensor with a built-in digital control and math engine. It measures temperature in real time and uses a moisture sensor to detect the relative humidity levels in the farming field [46].

4. Wireless Sensor Network in Agriculture IoT Power Router Sensor 1 Sensor 2 . . . Sensor N Figure 4. Wireless network in agriculture A wireless sensor network requires little, if any, architecture. It is made up of multiple sensor nodes that work together to observe a certain area, as shown in Figure 4. The sensors in the system may be kept unvarying for information-sensing and computation without causing any disruption [47]. The network sensor nodes can

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be installed on an ad hoc basis. Because there are so many nodes in a structure with fewer wireless sensor nodes, maintaining and detecting errors is extremely tough [48]. Data obtained from the sensor browser information system is managed by the command center [49]. The geo-spatial consortium also establishes a framework for interoperable interfaces and data compression, allowing for real-time synchronization. Anyone with a website can see the most important information and the characteristics of the network [50].

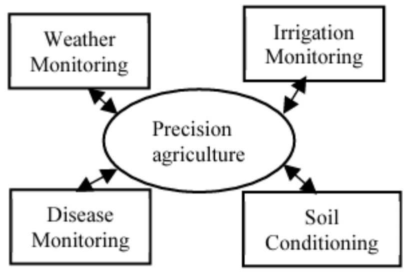

Figure 5. Precision agriculture

5. Poly House, Water-Volume Sensor and Soil PH Sensor in Smart Agriculture [51] The Poly farm-house is the most effec- tive method for increasing crop performance and productivity [52]. An IoT water analyzer keeps track of how much water is flowing through a pipe [53]. Almost every huge organization that deals primarily with fluids or chemical products must continually monitor and quantify the liquids they must manage during the automated processes. A flow sensor is a device that is widely used to monitor the flow of fluid [54]. The flow rate and volume of fluid passing through the pipe are regulated using a microcontroller [55]. In order to achieve a higher yield, one has to provide sufficient water [56]. Data from this water current detector device is sent to the computer, which further takes the proper measures, such as shutting off the pump [57].

VI. IOT TECHNOLOGIES IN AGRICULTURE

IoT encompasses a network of interconnected devices that collect and exchange data. In agriculture, IoT technologies include:

- Sensors: Monitor soil moisture, temperature, pH levels, and crop health.
- Actuators: Automate irrigation, fertilization, and pest control.
- Drones and UAVs: Capture aerial imagery for crop surveillance and health assessment.
- Cloud Computing: Stores and analyzes data for in- formed decision-making.
- Artificial Intelligence (AI): Processes data to predict trends and optimize farming practices [58].

These technologies enable precision agriculture, where inputs are applied precisely when and where they are needed, minimizing waste and maximizing efficiency [59].

VII. APPLICATIONS OF IOT IN SUSTAINABLE AGRICULTURE

A. Precision Irrigation

IoT-based irrigation systems use soil moisture sensors to determine the optimal time and amount of water required, reducing water wastage and ensuring crops receive ade- quate hydration.

B. Crop Monitoring and Management

Sensors and drones provide real-time data on crop health, enabling early detection of diseases and pests. This allows for targeted interventions, reducing the need for widespread pesticide use.

C. Livestock Monitoring

Wearable IoT devices track the health and location of livestock, providing data on feeding patterns, movement, and overall well-being, leading to improved animal hus- bandry practices.

D. Supply Chain Optimization

IoT technologies facilitate the tracking of produce from farm to market, ensuring freshness, reducing spoilage, and enhancing food safety [60].

VIII. BENEFITS OF IOT IN SUSTAINABLE AGRICULTURE

· Resource Efficiency: Optimizes the use of water, fertilizers, and pesticides.
· Increased Productivity: Enhances crop yields through timely interventions.
· Environmental Protection: Reduces chemical runoff and soil degradation.
· Economic Viability: Lowers operational costs and increases profitability.
· Data-Driven Decisions: Enables informed decision- making through real-time data analysis.

IX. CHALLENGES AND LIMITATIONS

– High Implementation Costs: Initial setup and main- tenance of IoT systems can be expensive for small- scale farmers.
– Connectivity Issues: Rural areas often lack reliable internet connectivity, affecting real-time monitoring.
– Data Security and Privacy: IoT systems generate large amounts of sensitive data that require secure handling.
– Technical Complexity: Farmers may need training to operate and maintain IoT devices efficiently.

X. RESEARCH GAPS

– High Initial Costs: IoT setup can be capital- intensive.
– Technical Expertise: Requires skilled personnel for installation and maintenance.
– Connectivity Issues: Remote areas may lack reliable internet access.
– Scalability: Adapting IoT solutions to different farm sizes and types.

XI. FUTURE DIRECTIONS

– Low-cost IoT Solutions: Development of affordable sensors and devices for small-scale farms.
– Integration with AI and ML: Predictive models for crop disease, yield forecasting, and automated decision-making.
– Sustainable Energy Integration: Use of solar or renewable energy to power IoT devices in fields.
– Scalable and Interoperable Systems: Ensuring de- vices from different manufacturers work seamlessly together.

XII. CONCLUSION

IoT has the potential to transform agriculture into a sustainable, data-driven industry. By providing real-time monitoring, predictive analytics, and automation, IoT en- hances productivity while reducing environmental impact. Despite challenges such as high costs and connectivity issues, continued research and innovation are likely to make IoT solutions more accessible, scalable, and effec- tive for sustainable agriculture worldwide.

IoT technologies hold significant potential to revolu- tionize sustainable agriculture by enhancing efficiency, productivity, and environmental stewardship. While chal- lenges exist, ongoing advancements and supportive poli- cies can facilitate the widespread adoption of IoT solu- tions, paving the way for a more sustainable and resilient agricultural future. This paper introduces Mba¨ıMi, an implementation of a smart farm management web and mobile application with a real hardware prototype that uses IoT technology, which provides farmers an effective decision-support tool for their agricultural practices. The system uses soil pH, humidity, temperature, and moisture levels to determine the soil acidity used to provide a real- time categorization of best crops for specific soils, aiding in seed selection and increasing production. The system also offers autonomous irrigation and temperature control, optimizing water resource utilization and encour- aging greenhouse farming.

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