Role of Wireless Sensor Networks and IoT in Sustainable and Smart Farming Systems

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Abstract—**The growing world food demands, and a corresponding diminishing natural resources, climate changes and water shortages have led to a change in the traditional, labor intensive, agriculture practices to technology centered smart farming systems which are sustainable. The paper survey is a review of the combination of the Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) as disruptive technologies in contemporary agriculture. WSNs are low-power, distributed sensor network systems that are continually used to monitor soil moisture, temperature, humidity, nutrient concentration (NPK) pH, crop well-being and microclimatic conditions and send real-time data to IoT cloud platforms to be stored, analyzed and visualized. The IoT systems permit precision farming, automated greenhouse, livestock tracking, resource management, and wastewater and fertilizer reduction by 20-50 percent, pollution by chemicals, and yield by 10-20 percent. The use of drones, autonomous tractors, wearable sensors, and others, increases sustainability by prescribing specific interventions, identifying diseases, and improving operational efficiency. The global trends in adoptions show the increasing market, with the IoT in agriculture projected to reach USD 22.65 billion by 2028 and WSN-based precision farming showing high reliability with the error margin of the NPK sensors of 8.47%. High initial costs, low rural connectivity, and energy are among the challenges that are being solved with the development of AI, machine learning, 5G, LoRaWAN, and predictive analytics.**

Index Terms—**Smart Farming, Wireless Sensor Networks, Internet of Things, Precision Agriculture, Sustainable Agriculture, IoT Sensors, NPK Monitoring, Smart Irrigation, Crop Yield Optimization.**

I. INTRODUCTION

The growing world food demand, the depletion of natural resources, the global warming, and the diminishing availability of water have necessitated the need to transform the ancient, labor-intensive systems of farming to the modern, technology-based smart farming systems. In this regard, the collaboration of Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) is transforming the contemporary agriculture in terms of real-time monitoring, data-driven decision-making, and automated farm management. WSNs are represented by low-power, spatially distributed sensor nodes, which gather continuously essential information about soil moisture, temperature, humidity, pH level, nutrient content, crop health, microclimatic conditions, and so on. This is sent to cloud-based systems to be stored, analyzed, and visualized when used with IoT platforms so that the farmers can monitor their fields remotely and act in time to their surroundings. Smart farming based on IoT enables precision agriculture in terms of scheduling irrigation, fertilizers, and pest management to minimize the use of water, excessive use of chemicals, and to minimize cost and waste and increase the yield and quality of crops. These technologies are important in the process of sustainable agriculture by limiting the wastage of resources, lowering the emission of green house gases, preventing the chemical runoff into the ecosystem, and encouraging the efficiency in the use of energy. Moreover, predictive analytics, artificial intelligence, and machine learning combined with IoT systems allow identifying the stress, diseases, and pest infestations in crops in time, which substantially decreases the loss of crops. Unmanned labor and remote control using smartphones or computers also deal with shortage of labors and minimize human exposure to risky agricultural practices.

II. RESEARCH OBJECTIVES

- To assess the role of WSNs in real-time monitoring, precision irrigation, and sustainable resource management.
- To examine the impact of IoT on automation, crop monitoring, productivity, and environmental sustainability.
- To explore challenges and future prospects of integrating AI and predictive analytics with WSNs and IoT for smart agriculture.

Smart Farming Systems

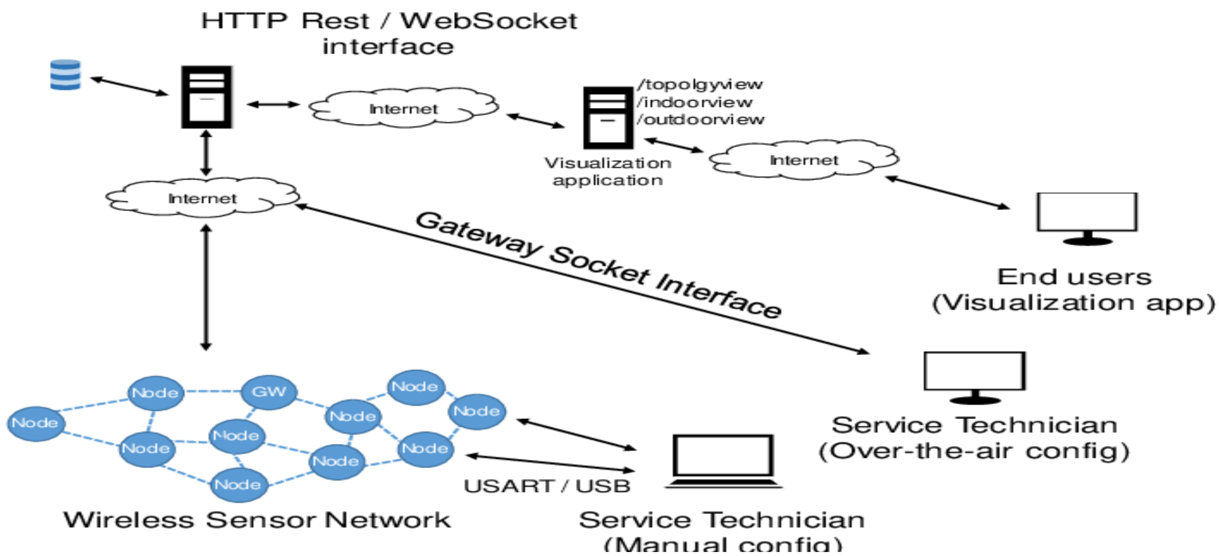
Smart agriculture systems combine complex technologies in the form of IoT sensors, drones, robotics, artificial intelligence, and data analytics to convert the traditional system of agriculture into a highly effective, accurate, and sustainable production system. Through constant gathering of real-time information about the state of the soil, the health of crops, weather conditions, and the health of livestock, the systems allow farmers to make informed and factual decisions in order to maximize the utilization of vital resources like water, fertilizers, energy, and labor. IoT sensors are used to track such important parameters as soil moisture, temperature, nutrient content, and pH, and drones and UAVs can give an aerial perspective on crops, their health, and where exactly inputs should be applied. Tasks like planting, harvesting, and weeding are automated by using autonomous machinery and robotic equipment, which decrease the amount of human labor and operational expenses. State-of-the-art data analytics and AI-based models are applying large quantities of information to provide actionable information, forecast crop yields, and identify diseases or pests at their initial signs of existence. Smart greenhouses have automated climate control which satisfies the optimal climate conditions and livestock management systems which have wearable sensors which monitor the health of animals, their feeding habits, and movements.

Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) are distributed networks made up of small, low power, and autonomous sensor nodes that are launched to oversee physical or environmental conditions and relay the information gathered wirelessly to a central system to process and evaluate the information. A sensor node is usually made up of sensing units, a microcontroller to process the data, a communication unit, and a source of power, most often a battery or energy-harvesting device. WSNs can be used under dynamic and even harsh environments with minimum human intervention and thus they are very applicable in cases where continuous monitoring is a requirement.

Data sensing and communication is the main activity of a WSN. Parameters are monitored by sensors to the temperature, humidity, pressure, light intensity, soil moisture, vibration, chemical concentration, or motion. This data received is either sent directly to a base station or through multi-hop communication where the nodes address other sensors in the given area sending data to other nodes that can be in range of other sensors to enhance the area coverage and lower the power usage. In the WSNs, efficient routing schemes and data aggregation strategies are important so as to reduce the energy consumptions and extend the lifetime of network because sensor nodes are usually highly power limited.

WSNs have a number of strengths, such as high scalability, flexibility, and affordability. They are able to be implemented across extensive geographical locations and easily extended by new nodes. The wireless feature of them eliminates the complex cabling requirement, which minimizes the costs of installation and maintenance. Moreover, breakthroughs in microelectronics and wireless communication now allow making sensor nodes small and cheap and with growing computational power.



Structure of a wireless sensor network (WSN) system

Wireless Sensor Networks is a very important component in a wide variety of applications. WSNs can be used in the field of environmental monitoring to monitor climate conditions, forest fires, air and water quality, and wildlife habitat studies. They serve monitors of patients and wearable health devices in the sphere of healthcare. Equipment condition monitoring, predictive maintenance and automation of processes are industrial applications. WSNs play a central role in smart farming to which they are applied in agriculture to monitor soil moisture, temperature, nutrient content, and crop condition so that irrigation can occur more precisely and resource like nutrients can be used more efficiently.

Although WSNs have advantages, they have various challenges. Persistent concerns are limited battery life, security of data, network reliability, scalability and interference. Energy-efficient protocols, secure communication mechanisms, and integrating WSNs with new technologies, including the Internet of Things (IoT), artificial intelligence, and cloud computing are addressed by researchers to solve these problems.

The Internet of Things (IoT)

Internet of Things (IoT) is a system, a network of interrelated physical objects, or things, which have embedded sensors, software, and communication technologies helping such objects to gather, transmit, and exchange data through the internet. These devices, including household appliances or industrial equipment, will collect real-time data about the surrounding environment, e.g. temperature, movement or video and send it to cloud systems or other devices to be analyzed and act upon. The IoT systems are based on five fundamental elements, namely, sensors and devices to capture data, a connection facilitating a smooth transmission of data through wired or wireless networks (including 5G), software to process data and activate automated responses, user interfaces to monitor and control IoT, and security to ensure the safety of data transmission and its integrity and privacy. The main uses of IoT include smart homes, where smart devices such as thermostats, lights, and locks can be controlled remotely; Industrial IoT (IIoT) in manufacturing, where smart devices can be used to predict the maintenance of equipment and optimize processes; healthcare systems with wearables and connected monitors that can be used to track patients in real-time; and smart cities and agriculture, where smart sensors are used to manage infrastructure, monitor traffic, waste and crop health. IoT changes the way things were done by making operations in industries more automated, more efficient, and decision-making easier and convenient. Nevertheless, when the variety of connected devices is increasing, there is a need to have strong security measures and privacy provisions in place to secure sensitive information against cyber attacks in order to ensure that IoT networks operate safely and in a reliable manner.

Wireless Sensor Networks (WSNs) in Sustainable and Smart Agriculture

The main component of the present-day Precision Agriculture (PA) and Smart Farming is Wireless Sensor Networks (WSNs) that allow moving away with the traditional practices that require a lot of resources and moving to the data-driven agriculture that is sustainable and offers a lot of opportunities. WSNs are autonomous sensor nodes deployed in a distributed manner and that can detect the environmental and crop conditions such as soil moisture, temperature, humidity, nutrient, and light intensity, and send the same wirelessly to a central server or network cloud. This long-term data collection enables farmers to make accurate real-time management reducing the amount of water, fertilizers, and pesticide usage, minimizing waste and harm to the environment.

III. KEY ROLES OF WSNS IN SUSTAINABLE FARMING

1. Precision Irrigation Management: WSNs provide real-time soil moisture monitoring at the root zone, enabling automated, demand-driven irrigation. Studies show that such systems can reduce water wastage significantly, addressing the fact that agriculture consumes 80–90% of freshwater resources**.**
2. Nutrient and Fertilizer Optimization: Sensors measuring Nitrogen, Phosphorus, and Potassium (NPK) levels allow site-specific fertilizer application, reducing overuse and preventing soil and water contamination.
3. Pest and Disease Detection: Data on humidity, temperature, and leaf wetness enable early detection of pest infestations or disease outbreaks. Targeted interventions reduce the need for broad pesticide application, protecting the ecosystem.
4. Yield Prediction and Monitoring: By continuously monitoring microclimate conditions directly in the field, farmers can predict yields accurately and adjust farming practices to optimize productivity.

Metrics in WSN-Based Agriculture

The adoption of WSNs in agriculture is growing rapidly, with the global wireless sensor market projected to reach $15.3 billion by 2025**,** largely driven by agricultural applications. NPK sensors connected via LoRaWAN have demonstrated an average margin of error of just 8.47% compared to laboratory-based manual testing, proving the reliability of WSNs for field-scale precision agriculture.

Table 1: Common WSN Sensors and Applications in Smart Farming

Sensor Type	Parameters Monitored	Role in Sustainability
Soil Moisture	Volumetric water content	Reduces water consumption through targeted irrigation
NPK/Nutrient	Nitrogen, Phosphorus, Potassium	Minimizes fertilizer overuse and soil nutrient pollution
Air Temp/Humidity	Ambient climate conditions	Prevents disease outbreaks; optimizes greenhouse environments
Light (PAR)	Photosynthetically Active Radiation	Optimizes shading and artificial light in greenhouses
Electrochemical	Soil pH and salinity	Enhances soil health and nutrient availability

Table 2: Comparison of WSN Communication Technologies

Technology	Range	Data Rate	Power Usage	Suitability
ZigBee	10–100 m	Low	Very Low	Small/medium farms, dense node networks
LoRa/LoRaWAN	>10 km	Very Low	Extremely Low	Large-scale, remote, long-term monitoring
WiFi	20–100 m	High	High	Small greenhouses, high-data applications

Benefits for Sustainability

- Reduction in Input Costs: Targeted fertilization and irrigation reduce water and chemical usage by 20–40%**,** lowering operational expenses.
- Environmental Protection: Minimized runoff of fertilizers and pesticides protects surrounding ecosystems.
- Increased Productivity: Real-time monitoring ensures optimal growth conditions, boosting crop yields by 10–20%**.**

Role of Internet of Things (IoT) in Sustainable and Smart Agriculture

Smart Farming or Agriculture 4.0 is the integration of the Internet of Things (IoT) in agriculture that is transforming how farming is practiced as it allows farmers to monitor the farm in real-time, automate their farms, and manage their resources precisely. IoT can change the agricultural industry, which is labor-based and focused on efficiency, to data-driven, sustainable, and highly efficient model, meeting the food needs of the globe and minimizing environmental impact. Through the gathering, conveying, and processing of data, IoT will help farmers make wise choices that will lead to high levels of productivity, reduce instances of wastage and enhance ecological sustainability.

Role of IoT in Sustainable Farming

IoT systems use sensors, drones, and connected machinery to continuously monitor soil conditions, crop health, weather patterns, and livestock behavior. This data is integrated with cloud-based AI analytics to provide actionable insights for precise resource management. Key applications include:

- Precision Agriculture: IoT enables site-specific application of water, fertilizers, and pesticides instead of uniform distribution, reducing resource wastage and chemical runoff.
- Smart Irrigation: Soil moisture sensors activate irrigation only when necessary, reducing water usage by up to 50%, a crucial factor in regions facing water scarcity.
- Greenhouse Automation: Environmental sensors manage temperature, humidity, and light to optimize crop growth while reducing energy consumption.
- Livestock Monitoring: Wearable sensors track health, behavior, and movement, enabling early disease detection, minimizing mortality, and optimizing feed efficiency.

Impact of IoT in Agriculture

The adoption of IoT in agriculture is growing rapidly. The global IoT in agriculture market was valued at USD 13.73 billion in 2023 and is projected to reach

USD 22.65 billion by 2028. IoT-enabled smart farming has demonstrated significant improvements in resource management, productivity, and sustainability:

- Water Saving: Smart irrigation reduces water use by 25–50%.
- Resource Efficiency: Precision farming lowers fertilizer consumption by up to 30%.
- Productivity Increase: Farmers report 10–20% higher yields within the first year of IoT adoption.
- Pest Control: IoT-enabled cameras and drones detect pests with >96% accuracy, reducing chemical usage.

Table 3. IoT Technologies and Applications in Smart Farming

IoT Technology/Device	Application in Smart Farming	Contribution to Sustainability
Soil Sensors	Measure moisture, NPK levels, pH, temperature	Optimizes fertilizer/water use, reduces runoff
Agricultural Drones (UAVs)	Crop health monitoring, multispectral imaging, precision spraying	Minimizes chemical runoff, protects ecosystems
Smart Irrigation	Automated watering based on soil moisture & weather	Conserves water, reduces energy usage
Livestock Wearables	Track health, location, and activity of animals	Improves welfare, early disease detection
IoT Cameras/Imaging	Detect weeds, disease, and fruit ripeness (>98% accuracy)	Reduces broad-spectrum pesticide use
Autonomous Tractors	GPS-guided precision tilling and harvesting	Reduces fuel consumption (~6%)

IV. CHALLENGES AND FUTURE DIRECTIONS

Although it has advantages, the challenges to the IoT adoption are the initial high cost of sensors, drones, and infrastructure, and the lack of internet connectivity in rural regions. With the development of 5G and satellite internet, and the decrease in the price of technologies, IoT will continue to increase the level of precision, sustainability, and resilience in agriculture. The combination with AI, machine learning, and predictive analytics in the future will allow making decisions automatically, predicting yields better, and managing pest/diseases.

V. RESULTS AND FINDINGS

The adoption of Wireless Sensor Networks (WSNs) and Internet of Things (IoT) in the agricultural sector have already proven to be more efficient, productive, and sustainable in terms of resources, which is an evident transformation of the conventional approach to smart farming that is data-driven. WSNs are able to conduct real time monitoring of vital parameters like soil moisture, temperature, nutrient concentration, pH, and condition of crops and provide precise irrigation, fertilization, and control of pests. Research indicates that WSN-enabled precision irrigation can save 50 percent of water, and NPK sensors permit application of fertilizers site-specifically reducing chemicals by 20-40 percent, and eliminating the issue of nutrient runoff. IoT is used to boost this system system by linking sensor information to cloud-based analytics and AI models, which can be used to make decisions and remotely manage farms. It has been demonstrated that IoT applications, such as smart irrigation, crop monitoring drones, autonomous tractors, livestock wearables, and greenhouse automation can enhance crop yields by 1020 percent, and avert pests and diseases at an accuracy of more than 96 percent detecting them. These findings are also backed by market data where the wireless sensor market is projected to reach USD 15.3 billion by 2025 and the IoT in agriculture market is projected to increase to USD 22.65 billion by 2028 indicating a high rate of adoption. In addition, operational efficiencies (in terms of labor needs and energy conservation) lead to lower production costs and greater profitability.

VI. CONCLUSION

Ultimately, the research finds that the combination of the Internet of Things (IoT) and the Wireless Sensor Networks (WSNs) is reshaping the conventional form of agriculture into a highly efficient, sustainable, and data-driven one. WSNs provide around-the-clock checks of soil, crop, and environmental conditions, which can be used to perform accurate irrigation, nutrient control, pest identification and optimize yield. IoT also extends these functions by linking sensors, drones, and machines with analytics and AI on the cloud so that automated decisions may be made in real-time and predictively. These technologies combined cut water and fertilizer consumption by 20 percent or more and 50 percent or more, reduce the runoff of chemicals, boost crop yields by 10 percent or more and 20 percent or more, and also increase operational efficiency and solve labor shortages. Nevertheless, in spite of the obstacles of high initial expenses and lack of connectivity, consistent developments in AI, machine learning, 5G, and satellite networks can offer a resilient, scalable, and sustainable future of climate-sensitive agriculture across the globe.

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