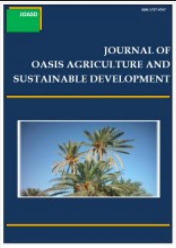
REVIEW ARTICLE



JOURNAL OF OASIS AGRICULTURE AND SUSTAINABLE DEVELOPMENT

www.joasdjournal.org

JOASD

p-ISSN: 2724 – 699X
e-ISSN: 2724-7007

A Review of IoT Applications for Monitoring Plant Growth and Adaptation to Climate Change

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Article info

Article history:
Received: 26 May 2025
Accepted: 22 December 2025

Keywords: IoT, Agriculture, Plant Monitoring, Sensor Technology, Water Use Efficiency

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Conflict of Interest: The authors declare no conflict of interest.

Abstract

Climate change significantly impacts agriculture by altering plant growth, productivity, and resource efficiency. The Internet of Things (IoT) offers a data-driven framework to monitor plant and environmental conditions in real time, supporting more resilient agricultural systems. This review synthesizes recent advances in IoT-based plant monitoring, focusing on sensor technologies, communication protocols, and integrated platforms for assessing plant stress, nutrient uptake, and water use efficiency. Studies show that IoT implementation can improve irrigation efficiency by up to 30% and reduce fertilizer waste by nearly 20% through precise monitoring. Despite these benefits, widespread adoption remains limited by high deployment costs, inconsistent connectivity in rural areas, and complex data management requirements. The review also identifies research priorities, including the development of low-cost, energy-efficient sensors, interoperable data systems, and AI-driven decision-support tools. Overall, IoT-based monitoring provides an essential pathway for improving crop productivity and adaptive capacity under changing climatic conditions.

1. INTRODUCTION

The Internet of Things (IoT) has emerged as a game-changing technology that has the potential to alter agriculture (Laghari et al., 2021). IoT offers real-time monitoring of environmental conditions and plant growth by connecting physical equipment to the internet and collecting data from sensors (Narayana et al., 2024). This technology has the potential to improve agricultural productivity and sustainability, as well as to assist farmers in adapting to the difficulties of climate change (Elijah et al., 2018).

Climate change offers a huge threat to agriculture, affecting plant development and yield due to rising temperatures and shifting precipitation patterns (Malhi et al., 2021). It is critical to monitor plant development and adaptability in real time in order to counteract the consequences of climate change and preserve food security. By providing continuous monitoring of environmental parameters such as temperature, humidity, soil moisture, and nutrient levels, IoT provides a valuable tool for doing so (Almalki et al., 2021).

This review is guided by the overarching research question: How can IoT technologies be effectively applied to monitor plant growth and support adaptation to climate change? To address this, the paper is structured around three main aspects: types of IoT sensors and devices for plant monitoring, applications for assessing plant stress, nutrient uptake, and water use efficiency under climate variability, and challenges and opportunities associated with implementing IoT systems in agriculture.

While previous reviews have primarily focused on general IoT applications in precision agriculture, this review fills a specific gap by emphasizing plant-level monitoring under climate change conditions. It integrates discussions of sensor technologies, platforms, physiological measurements, and real case studies to highlight how IoT can directly enhance plant adaptability and productivity in variable environments.

By providing a comprehensive and climate-focused perspective, this review aims to offer new insights into how IoT contributes to sustainable plant growth monitoring and to inform researchers, practitioners, and policymakers about both the current state-of-the-art and emerging opportunities for applying IoT in climate-resilient agriculture.

2. CLIMATE CHANGE AND ITS IMPACT ON PLANT GROWTH

Climatic change is a worldwide process that is altering the earth's weather patterns and climatic systems(Marí-Dell'Olmo et al. 2022). Changes in temperature, precipitation, and other environmental conditions have dramatic effects on plant development and productivity, making climate change one of the most significant impacts on agriculture (Table 1) (Raza et al. 2019).

growth. As temperatures rise, many plants suffer from heat stress, which can result in diminished photosynthesis, growth, and, ultimately, yield (Akter and Rafiqul Islam 2017). Furthermore, increased temperatures might increase the prevalence of pests and diseases, reducing crop productivity (Skendžić et al. 2021).

Changes in precipitation patterns are another important aspect in how climate change affects plant development. Climate change is causing more frequent and intense droughts and floods in many locations, which can have devastating consequences on crop productivity (Durodola 2019). Droughts, in particular, can cause water stress in plants, leading to reduced growth, smaller yields, and in some cases, plant death (Legg 2021).

Climate change can also affect other environmental parameters such as soil moisture,

Table 1. Impacts of Climate Change on Plant Growth and IoT Solutions

Aspects of Climate Change	Effects on Plant Growth	IoT Solutions for Monitoring	References
Increased Temperature	Heat stress, reduced photosynthesis, stunted growth	Temperature sensors to track variations and adjust irrigation	(Ilyas et al. 2021)
Irregular Precipitation	Soil erosion, over-irrigation, water stress	IoT-based irrigation systems and weather forecasts	(Ahmed et al. 2023)
Increased CO2 Levels	Fertilizing effect, but variation in water and nutrient efficiency	CO_2 sensors to monitor changes in carbon assimilation	(Dier et al. 2018)
Changes in Growing Seasons	Altered flowering and harvesting periods	Predictive IoT systems to optimize planting cycles	(Ali et al. 2023)
Extreme Weather Events	Crop damage, plant mortality	IoT-based early warning systems	(Nayak et al. 2020)

Global warming is expected to reduce food yields by up to 2% every decade over the next century, according to a recent report by the Intergovernmental Panel on Climate Change (IPCC) (Yadav et al. 2021). This decrease in yield is mostly caused by changes in temperature and precipitation patterns, which have an impact on plant growth and development.

Temperature is an important component in plant growth, with different plants having optimal temperature ranges for development and

carbon dioxide content, and nutrient availability, which can have a substantial impact on plant development and yield (Kumar 2016). Climate change is having a substantial impact on agriculture, with temperature, precipitation, and other environmental elements influencing plant growth and yield (Malhi et al. 2021). Understanding these implications is critical for establishing effective climate change mitigation strategies and ensuring food security for future generations.

3. IoT AND PLANT MONITORING

The Internet of Things (IoT) is a network of physically connected gadgets and sensors that collect and transmit data over the internet (Perwej et al. 2019). IoT sensors can be used to collect data on a variety of environmental factors, such as temperature, humidity, soil moisture, light intensity, and atmospheric gases (such as carbon dioxide and oxygen), all of which can have an impact on plant growth and development (Mohamed et al. 2021). Sensors can be linked to Internet of Things (IoT) devices such as gateways or edge computing devices, which send data to the cloud or a central system for analysis and display (Yu et al. 2017).

Plant monitoring can be accomplished with a variety of IoT sensors and devices, including (Fig. 1):

- Environmental sensors are devices that monitor variables such as temperature, humidity, and light intensity. They can be placed in the soil or the air around plants to monitor their growth (Yin et al. 2021).
- Soil sensors monitor soil parameters like moisture, pH, and nutrient levels. They can be utilized to improve irrigation and fertilizing methods (Zhang et al. 2017).
- Plant sensors are used to detect plant factors such as growth rate, leaf area, and photosynthesis. They are useful for determining plant health and yield (Lee et al. 2021).

In agriculture, IoT technologies for plant monitoring are already in use. For example, Chen et al. (2022) published a study in which they developed an IoT system for greenhouse tomato production that used multiple sensors to monitor environmental conditions and plant growth. The system enabled real-time monitoring and control of the greenhouse environment, which resulted in increased tomato yield and quality.

Another example is Dhal et al. (2023) IoT-based system for monitoring lettuce growth in a hydroponic system. The system collected data on environmental conditions and plant growth using various sensors, and the data was evaluated using machine learning techniques to forecast plant growth and production.

IoT has immense potential in agriculture for monitoring plant development and environmental conditions (Zouari et al., 2024; Dhal et al. 2023). IoT solutions can help farmers enhance crop management procedures and improve yield and quality by delivering real-time data on many environmental elements that affect plant growth (Sreekantha and Kavya 2017).

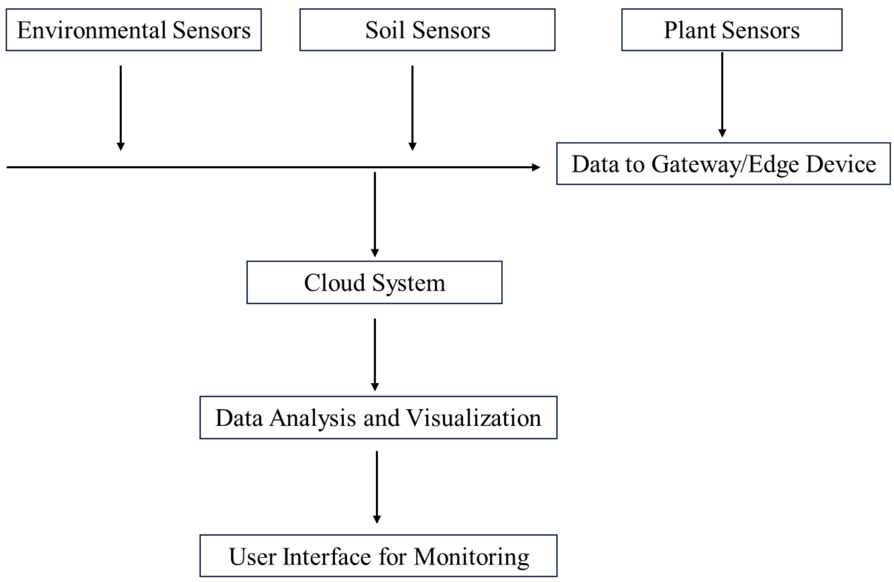

Fig. 1. Architecture of IoT-Based System for Monitoring Plant Growth Using Environmental, Soil, and Plant Sensors

Different IoT sensors and platforms offer unique advantages and face distinct limitations. Environmental sensors provide rapid detection of changes in temperature, humidity, and light intensity, but may require frequent calibration and can be affected by extreme weather conditions. Soil sensors give detailed information on moisture, pH, and nutrient levels, enhancing irrigation and fertilization strategies, yet their installation and maintenance can be labor-intensive for large-scale fields. Plant sensors, such as those measuring leaf area or photosynthetic activity, allow direct assessment of plant health, but are often expensive and limited to specific crop types. Similarly, IoT platforms vary in data handling capabilities: cloud-based systems offer scalable storage and advanced analytics but depend on reliable internet connectivity, whereas edge computing

platforms provide faster, local processing with lower latency but may be limited in storage and complex data analysis. Understanding these advantages and limitations helps researchers and farmers select appropriate IoT solutions tailored to their agricultural scenario, optimizing plant monitoring and resource management under changing environmental conditions.

4. Applications of IoT for Plant Monitoring Under Climate Change

Climate change has significant consequences on agriculture worldwide, affecting temperature, precipitation, and other environmental factors that influence plant development and adaptability (Raza et al., 2019; Akter and Rafiqul Islam, 2017). Monitoring plant growth and environmental conditions in real time is crucial to mitigate these impacts. The Internet of Things (IoT) provides a promising approach, offering farmers real-time data on environmental conditions that affect plant growth (Maraveas and Bartzanas, 2021).

4.1. Plant Stress Monitoring

IoT can be effectively applied to monitor plant stress caused by climate-related factors such as drought, heat, and cold, which trigger physiological changes that impair growth and yield (Ali et al., 2023). Sensors can continuously track plant physiological characteristics, including photosynthesis and transpiration, providing detailed information on stress levels and overall plant health (Lee et al., 2021). These insights enable the early detection of stress symptoms, allowing farmers to implement timely interventions such as irrigation scheduling or nutrient correction to reduce stress-related losses**.**

4.2. Nutrient Uptake Monitoring

Climate change can alter soil properties, affecting nutrient availability and leading to deficiencies or toxicities (Bungau et al., 2021). IoT sensors enable monitoring of soil parameters such as pH, nutrient levels, and microbial activity, giving precise information on plant nutrient status (Rossel and Bouma, 2016). By integrating this data with predictive models, IoT systems can guide site-specific fertilizer management, optimizing nutrient efficiency and minimizing environmental pollution. This data helps optimize fertilization strategies and maintain plant productivity under varying environmental conditions.

4.3. Water Use Efficiency (WUE) Monitoring

With increasing water scarcity due to climate change, enhancing agricultural water use efficiency is essential (Abioye et al., 2020). IoT devices can monitor soil moisture and plant transpiration rates, providing real-time data to optimize irrigation practices and improve water management (Adeyemi et al., 2017). Smart irrigation systems connected to IoT sensors allow adaptive control of water delivery, reducing waste while maintaining optimal plant health. By adjusting water application based on sensor feedback, farmers can conserve water while sustaining crop yield.

4.4. Case Studies and Applications

Several studies have demonstrated the practical application of IoT in monitoring plant growth under climate variability. Aruna Balla et al. (2019) used IoT systems to monitor maize growth under different soil moisture conditions. Suneja et al. (2022) applied IoT to monitor tomato growth under varying light conditions, optimizing environmental settings for improved yield. Additionally, Zouari et al. (2024) implemented IoT to track tomato turgor pressure and assess growth parameters, crop yield, and nutrient content, thereby enhancing abiotic stress management and agricultural sustainability. These studies collectively show how IoT implementation differs by crop type and region, revealing that effectiveness depends on sensor calibration, data interpretation methods, and local environmental constraints. Overall, IoT enables farmers to optimize crop management, improve yield and quality, and adapt effectively to climate change (Farooq et al., 2019; Bwambale et al., 2022).

5. Challenges and Opportunities

5.1. *Challenges of IoT Implementation*

While IoT has considerable potential for plant monitoring in the face of climate change, there are various hurdles to establishing IoT systems for plant monitoring (Ali et al. 2023; Mishra and Padhy, 2021). Cost, data management, and technical restrictions are among the challenges.

Cost is a major barrier to using IoT systems for plant monitoring (Elijah et al. 2018; Kodali and Sahu, 2016). IoT sensors and devices can be costly, especially when a high number of sensors are needed to cover a big amount of land (Bagwari et al. 2021; Shahpur et al., 2022). Furthermore, in underdeveloped nations, where the cost of technology and infrastructure may be a barrier to adoption, the cost of deploying an IoT system may be higher. In rural areas, additional costs arise from the need to establish reliable communication networks and maintain power supply for sensors and gateways. Many smallholder farmers cannot afford the replacement or calibration of devices, which further limits large-scale IoT adoption.

Data management is another difficulty linked with IoT devices for plant monitoring. Large volumes of data are generated by IoT sensors, which can be difficult to manage and interpret (Jayaraman et al. 2016; Atitallah et al., 2020). To ensure that the data provided by IoT sensors is accurate, trustworthy, and useful, effective data management solutions are required (Yan et al. 2014). In addition to storage and processing challenges, data transmission also depends on the communication technology used. For example, LoRa (Long Range) networks provide wide coverage and low power consumption suitable for rural agriculture but suffer from limited bandwidth and slower transmission speeds. Conversely, Wi-Fi allows faster data transfer but covers shorter distances and consumes more power, making it less efficient for open-field farming. These network limitations affect the consistency and scalability of IoT deployment in agricultural regions.

Another issue with IoT devices for plant monitoring is technical limits**.** Distance, interference, and environmental conditions can all have an impact on the accuracy and dependability of data collected by IoT sensors and devices (Yin et al. 2021). Furthermore, the installation and maintenance of IoT devices may necessitate extensive technical expertise, which may be a barrier to adoption for certain farmers. In addition, in low- and middle-income countries, inadequate digital infrastructure, unreliable electricity, and limited training opportunities for farmers and technicians restrict the long-term sustainability of IoT solutions. Policy gaps, such as insufficient support for digital agriculture or weak data governance frameworks, further delay adoption and integration into national agricultural systems.

Several recent studies have emphasized these obstacles. Cost, for example, was recognized as a major impediment to the adoption of IoT systems for plant monitoring in developing nations in a research (Sinha and Dhanalakshmi 2022). Hu et al. (2020) recognized data management as a critical problem connected with IoT-based plant monitoring in another study (Verma and Prakash 2019). The study advocated using cloud-based systems to store and analyze data generated by IoT sensors, which could assist address some of the data management problems.

5.2. Future Directions and Opportunities for IoT-Based Plant Monitoring

Despite these obstacles, there are numerous prospects for additional study and development in the field of IoT-based plant monitoring (Nižetić et al. 2020). The development of low-cost IoT sensors and devices could boost the accessibility and affordability of IoT systems for plant monitoring. Furthermore, advancements in data management and analysis may aid in overcoming the difficulties associated with managing and evaluating massive amounts of data generated by IoT devices (Popa et al. 2019).

Integration of IoT systems with other technologies, such as machine learning and artificial intelligence (AI)**,** offers another option. It may be possible to construct prediction models that can give farmers actionable insights on crop management methods by merging IoT systems with AI and machine learning algorithms (Bagaa et al. 2020).

Thus, addressing these cost, connectivity, and policy challenges through targeted investment, public–private partnerships, and farmer training programs is essential for achieving scalable and sustainable IoT adoption in agriculture.

6. CONCLUSION

In conclusion, while implementing IoT systems for plant monitoring presents challenges such as cost, data management, and technical limitations, there remain numerous opportunities for innovation and research. This review uniquely contributes to the literature by focusing on IoT applications for plant growth monitoring under climate change, integrating environmental, soil, and plant sensors with water-use efficiency and physiological monitoring. IoT solutions have the potential to revolutionize how we track plant development and responses to environmental change. However, several knowledge gaps persist, as current research often targets small-scale or controlled-environment studies, with limited validation in large or long-term field conditions, and there is still insufficient integration between IoT-generated data and predictive modeling for plant physiology and climate adaptation. Future research should focus on developing low-cost, energy-efficient sensors, improving interoperability among IoT platforms, enhancing data analytics through artificial intelligence and machine learning, and expanding field-based validation of IoT systems under real climatic variability. From a stakeholder perspective, policymakers should invest in rural connectivity, digital infrastructure, and training programs to promote IoT deployment, while developers should design modular, user-friendly, and affordable IoT systems tailored to smallholder farmers' needs. Farmers, in turn, can benefit from real-time decision-making, optimized resource use, and greater resilience to climate variability. Ultimately, addressing these challenges through interdisciplinary collaboration and strategic investment will accelerate the transition toward data-driven, climate-resilient agriculture, and this review provides a concise and climate-focused synthesis to guide future efforts among researchers, policymakers, and practitioners working at the intersection of IoT, agriculture, and climate adaptation.

Acknowledgments

The authors would like to thank all colleagues and researchers whose work contributed to the development of this review.

Funding

This work was funded by The MEDITOMATO project is part of the PRIMA Programme supported by the European Union, under Grant Agreement No. 1831.

Credit authorship contribution statement

The first draft of the manuscript was written by Marwa Zouari and Mohamed Hachicha commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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