# Cloud-based IoT Solutions for Precision Farming and Agricultural Sustainability and Efficiency

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#### Abstract

Agricultural sector has been beset by numerous challenges, such as resource management inefficiencies, susceptibility to climate change, and supply chain opacity. These have necessitated the search for innovative solutions that can increase productivity and sustainability. In recent years, advancements in technology have opened up new horizons for agriculture, with the Internet of Things (IoT) emerging as a key driver of what is being termed the 'digital revolution in farming'. This research delves into the transformative potential of Internet of Things (IoT) devices in modern agriculture, particularly in precision farming, automated irrigation, livestock monitoring, smart greenhouses, predictive analytics for crop diseases, and supply chain efficiency. IoT devices provide a platform for farmers to meticulously monitor the needs of individual plants and refine their farming techniques, consequently optimizing resource utilization and enhancing productivity. By employing sensors to scrutinize variables like soil moisture, plant health, temperature, and humidity, farmers can gain real-time data essential for informed decision-making. Our study also explores the efficacy of IoT devices in automated irrigation systems. These devices manage watering schedules predicated on data from soil moisture sensors, regulating the volume of water delivered to each plant or field, thus diminishing water consumption and ameliorating plant health. In the domain of livestock monitoring, IoT applications have emerged as valuable tools in tracking health and wellbeing parameters, with systems capable of sending real-time notifications about livestock health, location, and overall welfare. The research also delves into IoT applications within smart greenhouses. These advanced structures leverage IoT technology for automatic climate control and monitoring, significantly reducing manual intervention and resource usage. Further, our study examines the role of machine learning in predictive analytics for crop diseases. Here, algorithms utilize IoT-generated data to predict potential disease and pest infestations, empowering farmers to undertake preventive measures proactively. We scrutinize how IoT can enhance supply chain efficiency. By tracking the supply chain from the farmer to the retailer, IoT applications can assure product freshness, mitigate waste, and equip consumers with transparent information about the source of their food.

**Keywords**: Precision Farming, Internet of Things (IoT), Automated Irrigation, Predictive Analytics Supply Chain Efficiency

## Introduction

Precision farming, also known as precision agriculture or smart farming, is an innovative approach to agricultural management that utilizes advanced technologies and data-driven techniques to optimize crop production and resource utilization on a field-by-field basis [1], [2]. This method involves the integration of various technologies such as Global Positioning System (GPS), Geographic Information System (GIS), sensors, drones, and automated machinery to gather real-time data on soil conditions, weather patterns, crop health, and other critical factors. Analyzing this data helps farmers make informed decisions, precisely tailoring irrigation, fertilization, pest control, and other practices to the specific needs of individual plants or sections of a field [3]. The ultimate

goal of precision farming is to increase crop yields, minimize resource wastage, and promote sustainable agricultural practices.

The concept of precision farming can be traced back to the 1980s when the use of GPS technology in agriculture started gaining traction. Early adopters recognized the potential of GPS for accurate positioning of farm equipment, enabling straighter rows, efficient tilling, and reduced overlap. However, it wasn't until the late 1990s and early 2000s that precision farming began to emerge as a comprehensive approach [4].

The evolution of precision farming was significantly propelled by advancements in computing power, remote sensing technologies, and data analytics [5]. As computers became more powerful and affordable, the capacity to process and analyze large datasets improved, leading to more sophisticated precision farming systems. Additionally, the advent of remote sensing technologies, such as satellites and aerial drones, offered farmers unprecedented access to high-resolution data on their fields, enabling better crop monitoring and analysis.

Furthermore, the integration of precision farming with the Internet of Things (IoT) and Artificial Intelligence (AI) brought in a new era of smart agriculture. IoT devices, such as soil moisture sensors and automated irrigation systems, facilitated real-time data collection, enabling farmers to make prompt decisions for optimizing resource use. AI-driven algorithms empowered farmers to predict crop yields, detect diseases early, and automate tasks, further enhancing the precision farming approach [6].

With the world's population projected to reach over 9 billion by 2050, the demand for food is escalating rapidly. Traditional farming methods may struggle to meet this demand, especially considering the diminishing availability of arable land and the impact of climate change on agriculture. Precision farming offers a ray of hope by leveraging technology to boost productivity and ensure the sustainable production of more food per unit of land.

Conventional farming practices have often led to negative environmental consequences, including soil degradation, water pollution, and greenhouse gas emissions. Inefficient use of resources like water and fertilizers also contributes to these challenges. Precision farming presents a viable solution by optimizing resource allocation through targeted application and reducing waste. By using data-driven insights, farmers can implement site-specific practices that conserve resources, protect ecosystems, and reduce the overall environmental impact of agriculture. One of the most significant advantages of precision farming is its ability to enhance crop yield and overall farm efficiency. By accurately tailoring inputs such as irrigation, fertilizers, and pesticides based on real-time data, precision farming helps maximize the potential of each field. This targeted approach minimizes input costs and maximizes output, increasing profitability for farmers. Moreover, the precise identification of problem areas within a field allows for timely interventions, such as pest control, which can mitigate losses and further contribute to higher yields.

The foundation of precision farming lies in the utilization of GPS technology and satellite imaging. GPS provides precise positioning data, enabling farmers to precisely navigate their equipment and machinery while performing various tasks in the field. By integrating GPS with Geographic Information System (GIS), farmers can create detailed maps of their fields, allowing them to identify variations in soil types, topography, and other crucial factors. Satellite imaging complements GPS by providing high-resolution aerial images of the fields, aiding in the assessment of crop health, nutrient levels, and pest infestations [7]. Together, GPS and satellite imaging empower farmers with real-time, location-specific information to make informed decisions and implement site-specific agricultural practices.

The Internet of Things (IoT) has revolutionized precision farming by enabling seamless connectivity and communication between agricultural equipment and smart devices. IoT devices, such as soil moisture sensors, weather stations, and plant health monitors, collect vast amounts of data on various environmental and crop-related parameters. These sensors transmit data to central systems, where it is processed and analyzed. This data-driven approach allows farmers to monitor conditions in real-time, assess plant health, and evaluate resource availability. By understanding the specific needs of each crop, farmers can optimize irrigation schedules, apply the right amount of fertilizers, and implement targeted pest control measures, leading to improved resource efficiency and enhanced crop productivity.

Precision farming embraces the use of unmanned aerial vehicles (UAVs), commonly known as drones, to provide rapid and comprehensive aerial data. Drones equipped with high-resolution cameras, multispectral sensors, and LiDAR technology can capture detailed information about crop health, growth patterns, and field variability. With drones, farmers can cover large areas efficiently and monitor crops more frequently, enabling early detection of potential issues. Additionally, automation plays a crucial role in precision farming, as it facilitates autonomous operation of machinery and equipment. Automated tractors, planters, and harvesters can follow pre-defined paths accurately, reducing human error and increasing overall operational efficiency [8].

The abundance of data generated by various precision farming components necessitates sophisticated data analysis techniques. Big Data analytics plays a crucial role in processing and synthesizing vast amounts of information collected from sensors, GPS, drones, and other sources. Artificial Intelligence (AI) algorithms then process this data to identify patterns, correlations, and trends, facilitating predictive analysis and informed decision-making. AI-powered systems can predict crop yields, detect anomalies or diseases in plants, and recommend optimal planting and harvesting schedules [9].

## **Cloud-based Internet of Things (IoT) solutions**

The integration of Internet of Things (IoT) devices into agriculture has ushered in a new era of smart farming practices, enabling farmers to gain unparalleled insights into their crops' needs. By employing IoT-enabled sensors, farmers can now monitor the specific requirements of individual plants with unprecedented precision. These sensors can measure critical environmental factors such as soil moisture, plant health, temperature, humidity, and more. The real-time data generated by these sensors provides farmers with timely and accurate information, allowing them to make informed decisions about irrigation schedules, fertilization, pest control, and other farming techniques. This level of precision and data-driven decision-making has the potential to revolutionize traditional farming practices, leading to resource savings and significant boosts in farm productivity.

One of the key advantages of IoT-enabled farming is the ability to optimize resource utilization effectively. With precise data on soil moisture levels, farmers can tailor their irrigation systems to supply water only when needed, preventing overwatering and reducing water wastage. Additionally, real-time monitoring of temperature and humidity allows farmers to adjust environmental conditions inside greenhouses or controlled environments, optimizing crop growth and minimizing energy consumption. This resource-efficient approach not only benefits the farmer's bottom line but also contributes to sustainable agriculture practices by conserving water and energy resources.

The application of IoT in agriculture goes beyond monitoring and data collection [10]. IoT devices can be integrated with automated farming equipment and autonomous machinery, resulting in increased efficiency and reduced labor demands. For instance, IoT-enabled tractors equipped with GPS technology can precisely follow pre-determined routes for planting, fertilizing, and harvesting, reducing overlap and minimizing soil compaction. Moreover, smart machinery can be programmed to perform tasks based on real-time data received from IoT sensors, such as adjusting seed planting depth or pesticide application rates according to specific plant health conditions. This level of automation not only saves time and labor but also leads to more consistent and accurate farming practices [11]–[13].

Another critical advantage of IoT devices in agriculture is their ability to enable remote monitoring and control of farming operations [14]. Farmers can access the real-time data collected by the IoT sensors through mobile applications or web interfaces from virtually anywhere. This capability empowers farmers to keep a close eye on their crops and make informed decisions even when they are away from the fields. Whether they are managing multiple farms or need to respond to sudden changes in weather conditions, IoT technology grants farmers greater flexibility and peace of mind in managing their agricultural operations.

The insights gained from IoT data can also drive data analytics and machine learning applications in agriculture [15], [16]. By accumulating vast amounts of data over time, farmers can analyze historical trends and patterns to identify correlations and optimize farming techniques further. Machine learning algorithms can be applied to this data to develop predictive models for crop yield estimation, disease outbreak forecasting, and more. Consequently, farmers can anticipate challenges, plan ahead, and implement strategies to mitigate potential risks, leading to higher crop yields and more resilient agricultural systems [17], [18]. As IoT technology continues to evolve, its integration into farming practices will continue to reshape the agricultural landscape, making it more data-driven, efficient, and sustainable than ever before.

Automated irrigation systems powered by IoT devices have emerged as a game-changer in modern agriculture. By integrating soil moisture sensors with smart irrigation technology, farmers can optimize watering schedules with unparalleled precision [19]. These IoT-enabled systems gather real-time data on soil moisture levels, allowing them to tailor irrigation to the specific needs of each plant or field. Gone are the days of blanket irrigation practices that often led to overwatering or underwatering. With automated irrigation, water usage is significantly reduced, alleviating water scarcity concerns while promoting more sustainable farming practices. This targeted approach not only conserves water resources but also contributes to improved plant health, as crops receive the ideal amount of moisture needed for optimal growth.

The benefits of automated irrigation extend beyond water conservation and plant health. By streamlining the irrigation process, farmers can achieve substantial labor savings. The time and effort required for manual irrigation management are greatly reduced, allowing farmers to allocate their resources more efficiently across other essential tasks. Moreover, automated irrigation systems often incorporate weather forecasting data, allowing them to adjust watering schedules based on upcoming weather conditions. By taking into account rain forecasts or periods of high humidity, the system can make informed decisions to avoid unnecessary irrigation, further maximizing water efficiency.

In addition to water conservation and labor efficiency, automated irrigation systems bring about increased flexibility and convenience for farmers. Through the use of mobile applications or webbased platforms, farmers can remotely monitor and control their irrigation systems from anywhere. This level of accessibility empowers farmers to make on-the-go adjustments to watering schedules or respond promptly to unexpected changes in environmental conditions. Whether it's fine-tuning irrigation levels or overriding pre-set schedules during unforeseen weather events, IoT-driven automated irrigation provides farmers with a level of control and adaptability that was previously unattainable.

The data generated by IoT-driven automated irrigation systems also opens up new avenues for agricultural optimization. By analyzing historical watering patterns and correlating them with crop performance data, farmers can gain valuable insights into the impact of irrigation on different crops and varieties. This knowledge helps refine irrigation strategies over time, leading to more efficient resource utilization and higher yields. Additionally, the data collected by these IoT devices can be integrated into larger agricultural analytics systems, contributing to broader research efforts in sustainable water management and precision agriculture.

The adoption of automated irrigation through IoT devices is not limited to large-scale commercial farms; it can also benefit small-scale and subsistence farmers. In regions where water access is scarce or unreliable, IoT-driven irrigation solutions can be particularly transformative. By providing smallholder farmers with the means to conserve water and improve crop yields, these technologies contribute to poverty alleviation, food security, and the empowerment of rural communities. As IoT technology continues to evolve and become more accessible, the potential for automated irrigation to drive positive change in agriculture worldwide is vast, promoting a more sustainable, productive, and resilient farming future.

Livestock Monitoring: The integration of IoT applications in livestock management has brought about a paradigm shift in how farmers care for their animals. IoT devices, such as wearable sensors and GPS trackers, allow farmers to remotely monitor the health, location, and well-being of their livestock in real-time. This data-driven approach enables farmers to gain valuable insights into the

individual and collective health status of their animals, ultimately leading to more proactive and targeted healthcare interventions.

The real-time monitoring capabilities of IoT devices in livestock management provide farmers with instant notifications in case of any irregularities or signs of distress in their animals. For instance, sensors can detect abnormal changes in body temperature, heart rate, or feeding patterns, alerting farmers to potential health issues. By promptly addressing these concerns, farmers can prevent the spread of diseases, reduce treatment costs, and improve overall animal welfare.

The GPS tracking functionalities of IoT devices offer another layer of benefits in livestock management. Farmers can use these devices to monitor the movement and location of their livestock, especially in extensive grazing systems or during transportation. This feature is particularly valuable in preventing theft and minimizing the risk of losing animals due to natural disasters or accidents. With the ability to track the location of each animal, farmers can respond swiftly to potential security threats and ensure the safety of their livestock.

IoT-driven livestock monitoring also facilitates more data-driven decision-making in animal husbandry. By aggregating and analyzing the data collected from multiple sensors and devices, farmers can gain insights into broader trends related to animal health, behavior, and performance. This data can inform breeding programs, feeding strategies, and management practices, leading to better overall productivity and efficiency in livestock operations.

Moreover, the benefits of IoT-based livestock monitoring extend beyond individual farms. Data from multiple farms can be aggregated and analyzed on a larger scale, contributing to research efforts in animal health, genetics, and sustainable livestock production. Such data-sharing initiatives can pave the way for advancements in animal science, disease control, and the promotion of best practices across the livestock industry.

Smart Greenhouses: The integration of IoT technologies in greenhouse operations has revolutionized the way plants are cultivated in controlled environments. By deploying a network of interconnected sensors and actuators, smart greenhouses can autonomously regulate and monitor critical climate conditions, resulting in increased efficiency, reduced manual intervention, and optimized resource usage [20], [21].

One of the key advantages of smart greenhouses is their ability to maintain precise control over environmental factors such as temperature, humidity, light levels, and CO2 concentration. IoTpowered sensors continuously collect data on these parameters and feed the information to a centralized control system. This system can then adjust various greenhouse components, including ventilation systems, shading, and irrigation, to create an ideal growth environment for the cultivated plants. The automation of these processes reduces the need for manual monitoring and intervention, allowing growers to focus on higher-value tasks and strategic decision-making [22].

In addition to minimizing manual labor, smart greenhouses significantly improve resource efficiency. By closely monitoring and controlling environmental conditions, IoT technologies can optimize resource usage, such as water and energy. For instance, automated irrigation systems can deliver precise amounts of water directly to the plants based on their specific needs, reducing water wastage and conserving this valuable resource. Likewise, the smart control of heating, cooling, and lighting systems ensures that energy is utilized only when necessary, leading to substantial cost savings and a more sustainable greenhouse operation.

The real-time data collected by IoT sensors in smart greenhouses enables growers to gain valuable insights into the performance and health of their crops. By analyzing this data, farmers can identify patterns, trends, and potential issues that may arise in the growing process. Early detection of problems such as pests, diseases, or nutrient deficiencies allows for timely interventions, preventing significant crop losses and reducing the reliance on chemical inputs. This data-driven approach to greenhouse cultivation fosters more efficient and environmentally friendly agricultural practices.

Furthermore, smart greenhouses facilitate remote monitoring and management through connected devices such as smartphones or computers. Growers can access greenhouse data and control systems from anywhere, allowing for flexible management and quick responses to changing conditions. Whether it's adjusting environmental parameters, analyzing historical data, or remotely troubleshooting issues, the IoT-powered smart greenhouse empowers growers with enhanced agility and accessibility.

Predictive Analytics for Crop Diseases: The integration of machine learning algorithms with data collected from IoT devices has brought a new dimension to disease and pest management in agriculture. By leveraging the power of predictive analytics, farmers can now anticipate and mitigate potential crop diseases and pest infestations, leading to more effective preventive measures and improved overall crop health.

IoT devices, such as weather stations, soil sensors, and surveillance cameras, continuously gather data on various environmental parameters and crop conditions. Machine learning algorithms <sup>1</sup> analyze this vast amount of data to identify patterns and correlations between environmental factors and disease outbreaks [23]. By learning from historical data, the algorithms can build models that predict the likelihood of specific diseases or pests occurring under certain conditions.

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The predictive capabilities of machine learning algorithms enable farmers to take timely and targeted actions to prevent or minimize the impact of crop diseases and pests. When the algorithm detects an increased risk of a particular disease outbreak, farmers can implement preventive measures proactively. This might include adjusting irrigation practices, applying biopesticides or beneficial insects, or adopting cultural practices that discourage pest development. By acting preventively, farmers can reduce the reliance on chemical pesticides and curtail the spread of diseases, leading to healthier crops and increased yield potential [24].

Predictive analytics for crop diseases also contribute to more efficient resource allocation. By identifying high-risk areas or fields in advance, farmers can allocate their resources more effectively. For instance, they can prioritize scouting and monitoring efforts in regions with a higher likelihood of pest infestations or deploy disease-resistant crop varieties in susceptible areas. This optimized resource allocation results in cost savings and ensures that limited resources are directed where they can have the most significant impact [25].

The integration of predictive analytics for crop diseases also facilitates knowledge sharing and collaboration in the agricultural community. Aggregated data from multiple farms can be used to improve the accuracy and robustness of predictive models. Farmers can participate in data-sharing initiatives that allow them to benefit from the collective knowledge of the community, enhancing their disease management strategies collectively. Furthermore, researchers and agricultural experts can use this shared data to gain deeper insights into regional disease patterns and develop more effective and region-specific disease management approaches [26].

Supply Chain Efficiency: The integration of IoT technology into the agricultural supply chain has transformed how food is tracked and managed from the farmer's fields to the retailer's shelves. By leveraging IoT devices and sensors, the supply chain can be closely monitored and optimized, resulting in improved freshness, reduced waste, and increased transparency for consumers about the source and journey of their food.

IoT-enabled tracking devices are deployed at various points in the supply chain, starting from the farm where the produce is grown. These devices monitor critical parameters such as temperature, humidity, and location throughout the transportation and distribution process. Real-time data is transmitted to a centralized system, enabling stakeholders to closely monitor the condition and movement of the food items. This level of visibility helps to identify potential issues that might compromise food quality and allows for timely interventions to maintain freshness and reduce spoilage.

One of the significant advantages of IoT-based supply chain monitoring is the reduction in food waste. By closely monitoring environmental conditions during transportation and storage, the supply chain can proactively respond to any deviations that might lead to spoilage. For instance, if temperature thresholds are breached, automated alerts can be triggered, enabling swift actions to rectify the situation or reroute the shipment. This real-time responsiveness ensures that perishable goods arrive at their destination in optimal condition, reducing the likelihood of waste and enhancing overall supply chain efficiency.

Transparency and traceability are crucial considerations for modern consumers, who increasingly seek information about the origin and handling of the food they purchase. IoT technology addresses this demand by providing consumers with access to detailed information about the source, production methods, and transportation of the food products. By scanning QR codes or using

mobile apps, consumers can trace the journey of their food from the farm to the store shelves. This transparency builds trust and confidence in the food supply chain while empowering consumers to make informed choices about the products they buy.

Moreover, the data collected from IoT devices along the supply chain offers valuable insights for supply chain optimization and strategic decision-making. By analyzing this data, stakeholders can identify inefficiencies, areas of improvement, and potential bottlenecks in the supply chain. This knowledge allows for process improvements, such as optimizing transportation routes, reducing Page | 24 transit times, and streamlining storage and inventory management. As a result, the IoT-driven supply chain becomes more agile, cost-effective, and sustainable.

## Conclusion

The study embarked on an in-depth exploration into the transformative capacity of Internet of Things (IoT) in contemporary agriculture, covering critical areas such as precision farming, automated irrigation, livestock monitoring, smart greenhouses, predictive analytics for crop diseases, and supply chain efficiency. The findings elucidate a compelling narrative of how digital technologies, particularly IoT, could function as a cornerstone for a resilient, efficient, and sustainable agricultural future. For precision farming, the research established that IoT devices could significantly bolster the capacity of farmers to monitor and meet the exact requirements of individual plants, thereby refining their farming practices. These devices provide real-time data on critical variables such as soil moisture, plant health, temperature, and humidity, which underpin data-driven decision-making processes. The result is optimal resource utilization, minimized waste, and enhanced productivity-an alignment of economic benefits with environmental sustainability that underscores the multi-faceted potential of IoT technology in agriculture. Similarly, in automated irrigation systems, IoT-based technologies have been shown to be pivotal in managing water distribution based on real-time soil moisture data, thus reducing water consumption and improving plant health. The automation provided by these systems not only saves valuable resources but also significantly reduces the burden of manual labor, enabling farmers to focus more on strategic decision-making and other high-value tasks.

Advanced systems that track health and wellbeing parameters in real-time and generate timely notifications about livestock health and location have emerged as invaluable tools. They not only improve animal welfare but also increase productivity and reduce losses, demonstrating the potential for IoT technologies to revolutionize livestock management.

The research also extended its scrutiny to the application of IoT in smart greenhouses. Our findings underscore the effectiveness of such systems in automating climate control and monitoring processes, leading to a significant reduction in manual intervention and resource usage. This technology offers a viable pathway to achieve increased efficiency, crop quality, and yield, while maintaining sustainability.

The study further confirmed the beneficial role of IoT in conjunction with machine learning for predictive analytics in crop disease management. By leveraging algorithms that utilize IoTgenerated data, potential disease and pest infestations can be accurately predicted. This capability empowers farmers to take proactive preventative measures, reducing crop loss and improving overall yield and productivity. The ability of IoT applications to track the supply chain from the farmer to the retailer brings about numerous advantages, including the assurance of product freshness, reduction of waste, and providing consumers with transparent information about the source of their food. This level of transparency not only boosts consumer confidence but also improves the overall efficiency of the agricultural supply chain.

From precise resource management, improved livestock care, and advanced crop disease prediction to efficiency in supply chain operations, the findings underscore the potential of IoT to instigate a digital revolution in farming. The integration of digital technologies and data-driven systems in precision farming generates vast amounts of sensitive agricultural data. This data includes information about crop yields, soil conditions, weather patterns, and even personal farm

management practices. Protecting this data from cyber threats and ensuring privacy becomes a significant concern. Farmers and stakeholders in the agricultural industry must be cautious about data breaches, unauthorized access, or misuse of the information collected. Ensuring robust cybersecurity measures and implementing data privacy policies are essential to build trust among farmers and encourage wider adoption of precision farming technologies [27].

Precision farming heavily relies on access to digital infrastructure, such as reliable internet connectivity and electricity. Unfortunately, not all regions, especially rural and remote areas, have sufficient digital infrastructure in place [28], [29]. This digital divide poses significant challenges for small farmers who may lack access to the technology needed for precision farming implementation. Unequal access to resources hinders the ability of small-scale farmers to compete with larger, technologically-equipped farms, exacerbating the disparities in the agricultural sector. Bridging the digital divide and providing adequate support to small farmers to adopt precision farming technologies are crucial steps to ensure equitable and sustainable agricultural development [30], [31].

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