A Review of Drone Based Irrigation System for Large Farms

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Received 15 May 2025; Accepted 01 July 2025

Abstract

Agricultural sustainability and resource optimization are critical in addressing the growing challenges of food security and climate change. Conventional irrigation practices often lead to excessive water usage and inefficient crop management. This review paper presents a comprehensive overview of drone-based smart irrigation systems that integrate wireless communication, sensor networks, and automation to enhance precision agriculture. The review highlights the hardware-software architecture, real-time monitoring data methods, communication flow, and system working. It further explores the possible benefits, including water preservation, enhanced crop health, and minimized human involvement. Finally, the paper highlights future directions such as AI integration, remote monitoring dashboards, and multi-drone coordination, the underscoring potential of drone-based irrigation in transforming conventional agricultural practices into intelligent, data-driven systems.

Keywords: Drone-based irrigation, Raspberry Pi, NPK sensor, soil moisture sensor, based water control, weather API, integrated irrigation, smart farming, relay control irrigation.

Journal of Graphic Era University, Vol. 13_2, 323–338.
doi: 10.13052/jgeu0975-1416.1325

1 Introduction

Irrigation is an essential component of agriculture, playing a key role in determining crop output, soil health, and sustainable farming practices. Conventional irrigation methods – such as flood irrigation, furrow system, and manual watering – are still widely used, particularly in developing countries. However, these methods often lead to over-irrigation, nutrient runoff, water wastage, and inconsistent distribution of soil moisture, thereby reducing both water use efficiency and crop yield. With the rising demand for food production and the strain on freshwater availability, there is a growing necessity for efficient and technology-enabled irrigation solutions.

Over the past few years, the development of smart irrigation systems has transformed the way water is supplied to crops. These irrigation systems use real-time data from soil and environmental sensors, weather forecasting, and automation technologies to ensure the right amount of water is applied at the right time and location. Among the developing smart irrigation techniques, drone-assisted irrigation systems present a highly flexible and scalable approach, particularly for large and remote agricultural fields.

This review examines a drone-based smart irrigation framework, which integrates embedded systems, wireless communication, and sensor data to boost irrigation performance.

This paper analyzes the system hardware and software components, data flow design, and communication procedures. Moreover, it evaluates the benefits of adopting drone technology in smart irrigation and highlights future upgrades, extensibility, and the scope for merging machine learning and GIS-based mapping in future advanced smart farming solutions.

2 Literature Review

Kamath et al. (2019) implemented a wireless visual sensor network (WVSN) using Raspberry Pi 3 Model B boards equipped with camera modules to capture paddy field images over a 25-day period. The study employs Bluetooth 4.0 for node-to-base communication and Wi-Fi for base-to-remote transmission, powered by solar cells. At the remote station, images are processed to extract shape features – Hu's invariant moments, size-independent descriptors, and chain code perimeters – which are then classified using Random Forest (RF) and Support Vector Machine (SVM) algorithms. The experimental setup spans a 10 m^2 paddy field, testing the system's feasibility for weed detection.

Mateo-Aroca et al. (2019) proposed a Remote Image Capture System (RICS) designed to monitor crop conditions using static imaging nodes. Unlike UAVs or satellites that face challenges such as high cost, weather dependency, and flight restrictions, the RICS system offers a low-maintenance alternative by capturing periodic images of specific zones in lettuce fields. These images are processed to assess key crop parameters like the percentage of green cover (PGC), which is further used to estimate crop evapotranspiration (ETc) and detect water stress areas. Each image node operates independently and transmits data to a central processing unit via ZigBee-based wireless modules (XBee). The system is powered by solar panels, ensuring independent functioning over extended periods without manual intervention. The real-time data acquired is utilized to make automated decisions regarding irrigation and harvesting, offering a practical solution for areas with limited access to remote sensing technologies.

This research shows that combining ground-level image acquisition with sensor-based environmental data can enhance the reliability and responsiveness of irrigation decisions, especially in regions experiencing water scarcity.

Krishna et al. (2020) demonstrated a viable, farmer-centric smart irrigation system, leveraging Raspberry Pi for automation and resource optimization. While effective for small-scale applications, its limitations highlight areas for further development, making it a valuable reference for advancing IoT irrigation technologies.

Sun and Imran (2020) presented an IoT-based prototype developed on the Arduino platform to monitor soil moisture and Nitrogen (N), Phosphorus (P), and Potassium (K) (NPK) levels for indoor plants. The system utilizes a Grove Moisture Sensor and optical transducers (LEDs and photodiodes) to measure nutrient absorption based on light wavelengths (e.g., 470 nm for N, 568 nm for P, 624 nm for K), applying Beer's Law to calculate absorbance. Data is transmitted via The Things Network (TTN) and stored on the Ubidots platform, providing real-time feedback through a user-friendly dashboard and smartphone app. The prototype classifies NPK levels into five categories, triggers email notifications, and controls hardware responses (e.g., LED indicators) when thresholds are breached, aiding in precise irrigation and fertilizer application. Testing over two days demonstrated its ability to detect moisture drops and nutrient imbalances, though limitations include sensitivity to indoor light and lack of specificity for certain plants (e.g., cacti). The study suggests future enhancements, such as integrating pH sensors and automated irrigation systems, to improve functionality. This work highlights

IoT's potential in reducing waste and enhancing decision-making in smart agriculture and home gardening.

Abioye et al. (2020) offered a detailed overview of monitoring and control techniques for accurate irrigation. They emphasized the use of IoT-based systems, wireless sensors, and embedded controllers like Arduino and Raspberry Pi for real-time data acquisition. The study classified irrigation control into open-loop and closed-loop systems and highlighted the role of cloud platforms and mobile dashboards in managing irrigation remotely. It also discussed the integration of soil, weather, and crop-based sensors for automated irrigation decisions.

A Drone Monitored Solar Irrigation System is designed by Ismail Alnaimi and Mabdi (2021) – which integrates valves controllers into the system It details a solar-powered irrigation framework for Lemon Myrtle crops. A drone equipped with Bluetooth surveys leaf health, directing a microcontroller to adjust water output (0–6 L) at a steady 0.07 L/s. This green approach cuts energy costs and water waste, yet its single crop focus and lack of scalability evaluation suggest room for wider application testing.

A study by Meivel and Maheswari (2021) explores the application of drone-based remote sensing for precision agriculture, emphasizing the use of the Normalized Difference Vegetation Index (NDVI) and Near-Infrared (NIR) sensors to monitor agricultural land. The research integrates multi-spectral and hyperspectral imaging with a quantum geographic information system (QGIS) and GPS-enabled drones to assess plant health, water stress, and nutrient management. Key vegetation indices such as NDVI, Green Normalized Difference Vegetation Index (GNDVI), Soil-Adjusted Vegetation Index (SAVI), and others are employed to evaluate plant growth and leaf conductance, with a significant correlation reported ($p \leq 0.01$, $r = 0.77$ and -0.77). The study highlights the use of thermal and NDVI sensors for real-time monitoring of water content and temperature, achieving a standard irrigation level of 60% for optimal plant growth. Drones equipped with these sensors provide high-resolution imagery and data, facilitating precise irrigation and fertilization strategies. The methodology includes drone setup, flight preparation, image acquisition, and data processing using QGIS, supported by a deep neural network algorithm to measure biomass densities and nitrogen levels. The findings underscore the cost-effectiveness and flexibility of drones in enhancing agricultural productivity, though challenges remain in managing heavy payloads and atmospheric variations.

Karar et al. (2021) – presented a practical implementation of a smart irrigation system based on an IoT-enabled UAV framework. In this study, the authors utilized environmental sensors – temperature, humidity, and soil moisture – connected to Arduino boards and Wi-Fi modules. These sensors collected data from different parts of the field and transmitted it via UAVs to a cloud platform. Based on the cloud-analyzed data, irrigation pumps were controlled automatically. An Android-based interface was also developed to allow farmers to monitor field conditions remotely. The system achieved significant efficiency in water management and demonstrated the applicability of IoT and UAV integration in smart farming scenarios.

Shaikh et al. (2022) conducted a comprehensive analysis of how the IoT systems are redefining agriculture. Their study emphasizes the role of intelligent systems in enabling real-time monitoring, predictive analysis, and autonomous decision-making for various agricultural operations. Key applications include disease detection, environmental monitoring, precision irrigation, and yield forecasting. The fusion of AI and IoT, known as A IoT, allows the deployment of smart sensors, drones, and data-driven models to make field operations more efficient and adaptive to climatic and soil variations.

Jalajamony et al. (2023) proposed an automated irrigation system using a specifically designed multirotor drone integrated with an infrared imaging device (FLIR Lepton 3.5) and a geolocation module to allow targeted watering of specific dry zones in farmlands. Supported by the National Science Foundation (Grant 2100930), the study aimed to address issues of overwatering and underwatering – which account for over 70% of freshwater use in agriculture – by integrating drone-assisted thermal mapping with edge intelligence and machine learning (ML).

The drone captures georeferenced TIR and RGB images, which are processed onboard using a Raspberry Pi 4 to identify dry spots based on temperature variations. These data are transmitted via LoRa WAN to a terrestrial edge unit (also Raspberry Pi 4-based), which employs a Random Forest ML model (MSE = 0.063) to generate irrigation patterns by optimizing sprinkler control parameters – head rotation angle (θ) and flow valve angle (Ø) – for solar-powered smart sprinklers.

The field is divided into hexagonal areas (10–15 m diagonal) to decrease overlap, with sprinklers positioned centrally. Experiments conducted on a 40 m $\times$ 40 m grassland determined an optimal drone altitude of 12 m for effective dry spot detection (7.5 cm^2/pixel resolution), ensuring a balance between area coverage and image accuracy. Video stabilization and RGB channel separation further enhance image reliability under varying environmental conditions.

The results demonstrate reduced water consumption and precise irrigation, with LoRa WAN enabling long-range communication (up to 778 m with SF 12, 125 kHz BW). However, limitations include the resolution constraints of the low-cost TIR camera at higher altitudes and potential irrigation deviations (α factor) due to external influences such as wind. The authors conclude that this scalable, low-latency system advances precision agriculture by optimizing water use across diverse terrains and crop types.

Rane et al. (2023) proposed a dual system for automated crop health management with Drone and Rover where in a drone detects pests with 98% accuracy using a convolutional neural network, and a rover applies pesticides via ROS and SLAM navigation. Tested in simulated fields, it reduces chemical use through precise targeting, aided by RTK positioning. However, it neglects nutrient management and requires safeguards against ecological risks.

Tomaszewski et al. (2023) demonstrated that the integration of 5G and future mobile communication networks enhances the capabilities of drones by enabling ultra-reliable, low-latency communication and massive IoT connectivity – critical for executing time-sensitive tasks like water release in variable rate irrigation (VRI) zones.

Vijayakumar et al. (2024) targeted blockage detection in micro-irrigation system using Drones in their work they employed a drone equipped with high-resolution cameras to identify blocked drip emitters across a 5 km area in just 25 minutes. IoT connectivity transmits the findings to farmers via cloud platforms, thereby enhancing water conservation. While promising, the system lacks mechanisms to resolve blockages or comprehensively monitor crop health.

Their study aimed to construct a budget-friendly, flexible, and automated irrigation setup using Arduino UNO as the central controller, integrated with a soil moisture sensor, relay, water pump, and LCD display. A structured methodology – comprising problem definition, requirements analysis, system design, implementation, and testing is employed to develop a prototype that automates irrigation based on soil moisture thresholds in the range of 300–750.

Basheer et al. (2024) focused on designing a low-cost, scalable irrigation system using Arduino UNO as the primary controller, integrated with a soil moisture sensor, relay unit, irrigation pump, and LCD display.

Sharma et al. (2024) proposed a data-driven smart irrigation approach that leveraged multispectral imaging and artificial intelligence for optimizing water usage in agriculture. The study employed the Parrot Sequoia+

multispectral sensor mounted on an unmanned aerial vehicle (UAV) to capture high-resolution vegetation and soil imagery. This imagery was processed using Random Forest algorithms in a cloud computing environment to classify crop health and determine precise irrigation needs. Based on the analysis, IoT-enabled sprinkler systems were activated to deliver water specifically to stressed crop regions. The system was implemented across 30 hectares of agricultural land and achieved an irrigation decision accuracy of 92%, with a notable 35% reduction in water consumption compared to conventional practices. The study highlighted the potential of combining drone-based remote sensing with AI and IoT for enhancing precision in irrigation scheduling. However, one of the major limitations identified was the high operational cost, primarily due to dependence on commercial UAV platforms and cloud-based data processing. The authors suggested that future research should explore on board AI processing capabilities to reduce reliance on remote servers and improve the system's affordability and real-time responsiveness.

This research significantly contributes to the advancement of sustainable agriculture by demonstrating how multispectral imaging and intelligent automation can work together to improve water management and crop productivity in large-scale farming.

Bhatia et al. (2025) explored the integration of advanced sensing and machine learning technologies within a smart irrigation framework tailored for large-scale agricultural applications. The researchers developed a precision irrigation model that utilized thermal imaging cameras for real-time monitoring of crop water stress, combined with a Support Vector Machine (SVM) algorithm to analyze temperature variations across crop canopies. This intelligent system was coupled with a drip irrigation mechanism and deployed over a 14-hectare agricultural field. The study achieved an impressive 93% accuracy in irrigation scheduling and demonstrated a 32% reduction in water consumption when compared to traditional irrigation techniques. The system's data acquisition and processing relied heavily on 5G connectivity, enabling low-latency communication between field devices and computational units. Additionally, edge computing infrastructure was employed to facilitate real-time decision-making without dependency on cloud-based processing, thus improving system responsiveness. However, the researchers acknowledged certain limitations, particularly the dependence on high-speed internet and advanced edge computing infrastructure, which may pose challenges in rural or low-connectivity regions. Despite these constraints, the study provides a significant contribution to the field of smart agriculture by showcasing the potential of combining AI, IoT, and next-generation wireless technologies to improve irrigation efficiency and water resource management in precision farming systems.

Joice et al. (2025) conducted a systematic review that explored the versatile role of Raspberry Pi in supporting various aspects of precision agriculture. As a compact and affordable single-board computer, Raspberry Pi enables field-level data collection, processing, and control. The review identified applications across multiple domains including automated irrigation systems, disease detection, weather monitoring, and crop health analysis.

One of the major advantages of Raspberry Pi lies in its ability to support various types of sensors such as soil moisture, temperature, humidity, and water level sensors, making it suitable for low-cost implementation in remote or resource-constrained farming environments. Moreover, the study highlighted the growing trend of implementing Tiny Machine Learning (TinyML) algorithms on Raspberry Pi devices, which allows for on-site data analysis without relying on cloud infrastructure. This significantly improves the speed and privacy of decision-making in smart agriculture systems. Raspberry Pi can serve as a central control unit that connects environmental sensors with decision-making algorithms, enabling real-time responses to field conditions with minimal human input.

Al-Najadi et al. (2025) conducted an experimental study to evaluate the effectiveness of Drone-Based Thermal Imaging (DBTI) in optimizing Controlled Environment Agriculture (CEA) under arid climatic conditions. In their research, a drone equipped with a thermal sensor was used to monitor canopy temperature (Tc) of plants grown under three different irrigation regimes (deficit, optimal, and excess).

The thermal data collected via UAV were compared with conventional in-situ sensor data (thermocouples) and analyzed to calculate Crop Water Stress Index (CWSI) and stomatal conductance (Ig). The findings indicated that DBTI effectively detected stress levels, with a high correlation ($R^2 = 0.959$) between drone-derived and ground sensor-based Tc values. Plants under water-deficit conditions exhibited higher CWSI values and lower stomatal conductance, while over-irrigated plants also showed physiological stress, revealing the dual impact of irrigation mismanagement.

This research contributes to the growing evidence supporting UAV-based sensing for automated irrigation monitoring. However, it also identifies the need for additional developments such as multi-crop validation, integration with IoT-enabled ground sensors, and real-time control algorithms for adaptive irrigation systems.

Hassan et al. (2025) proposed an innovative approach combining UAV-assisted data collection with wireless power transfer (WPT) to enhance the efficiency and sustainability of WSNs in smart irrigation systems. The study introduced a two-region clustering mechanism where UAVs serve as mobile sinks and energy providers. This method effectively mitigated the hotspot problem – where nodes near the base station deplete energy faster – by optimizing cluster head selection based on residual energy, reducing transmission hops, and wirelessly recharging helper nodes. The proposed scheme demonstrated a 20% reduction in water usage and extended network lifetime by over 9.6% compared to conventional clustering methods.

3 Comparative Study

Among the reviewed studies (Summarized in Table 1), the most recommended work is by Bhatia et al. (2025), which combines 5G technology and distributed computing with infrared imaging to achieve 93% irrigation accuracy and 32% water conservation. Its use of innovative communication (5G) and machine learning (SVM) enables real-time, high-performance decision-making, making it highly suitable for future-ready precision agriculture.

Alternatively, the least preferred work is by Krishna et al. (2020), which uses Raspberry Pi but lacks details on sensors, communication standards, or step-by-step instructions. Its limited scope and lack of potential for improvement or scalability make it less effective compared to other studies.

Multiple studies have used 5G technologies, such as Tomaszewski et al. (2023) and Bhatia et al. (2025), highlighting its role in optimizing data speed and time-sensitive agricultural practices. However, these works also point out infrastructure limitations in rural areas.

Studies like Basheer et al. (2024) and Sun & Imran (2020) applied Arduino-based platforms, focusing on cost-efficient, soil moisture-based smart irrigation systems with simple control setups. In contrast, Raspberry Pi was used in studies such as Joice et al. (2025) and Kamath et al. (2019), emphasizing edge AI (TinyML), vision-based weed identification, and data independence from cloud platforms.

Overall, research on 5G and AI integration highlights the strong potential for growth and accuracy, while Arduino-based systems remain suitable for low-cost, localized implementations. Raspberry Pi-based studies bridge the gap by providing system flexibility for relatively complex tasks in smart agriculture.

Table 1 Comparative summary of smart irrigation systems from existing literature

Computing Platforms	Studies	Technology/Platform	Focus/Application	Key Features	Common Limitations	Research Gaps
Raspberry Pi-Based Systems	Kamath et al. (2019), Krishna et al. (2020), Joice et al. (2025)	Raspberry Pi (with vision-based, TinyML)	Weed identification, automated irrigation, disease detection	Edge computing intelligence, Image recognition, on premise AI	Poor system extensibility, Sensor data unavailability	Partial sensor integration, Limited scalability of deployment
UAV / Drone-Based Systems	Alexandros et al. (2021), Ismail Alnaimi & Mabdi (2021), Jalajamony et al. (2022), Rane et al. (2023), Tomaszewski et al. (2023), Vijayakumar et al. (2024), Al-Najadi et al. (2025), Hassan et al. (2025)	UAV, drones, thermal/multispectral imaging, imaging sensor, 5G, wireless energy transmission (WPT)	Water stress detection, irrigation control, pest identification, crop condition assessment	High-definition imaging, live data streaming, 5G network integration	Expensive, limited load-bearing, infrastructure requirements, Power limitations	Expensive implementation, limited automation loops, energy and payload restrictions, rural infrastructure gaps
Arduino-Based Systems	Sun & Imran (2020), Basheer et al. (2024)	Arduino + Sensors (Grove, soil moisture, relay)	Interior plant cultivation, soil moisture-based irrigation	Economical, Easy management, Automatic irrigation control	Indoor-specific, minimal crop and weather integration	Insufficient real-time responsiveness, Restricted combination of weather and crop information, Scaling issues

IoT and Cloud-Based Systems	Abioye et al. (2020), Shaikh et al. (2022), Tomaszewski et al. (2023), Joice et al. (2025)	Internet of Things frameworks, Cloud computing, Smart IoT systems, 5G	Automated irrigation, Smart farming, AI-driven insights	Real-time sensing, AI-powered analysis and action, Cloud-based connectivity	Expandability, Architectural dependency	Multi-sensor fusion, Extended field experimentation, Connectivity constraints in remote areas
Imaging and Sensing Technologies	Mateo-Aroca et al. (2019), Kumar et al. (2024), Bhatia et al. (2025), Bendig et al. (2012), Alexandris et al. (2021), Al-Najadi et al. (2025)	Infrared imaging systems, Detailed spectral analysis, Vegetation health index	Agricultural field monitoring, Soil fertility levels, Irrigation optimization	Accurate prediction, Crop strain detection and Plant health assessment	Budget-heavy implementation, Big data processing, Restricted dynamic response	Intensive processing load, High-capacity storage requirement, Absence of dynamic feedback loop
Communication Technologies	Kamath et al. (2019), Alnaimi & Mabdi (2021), Mateo-Aroca et al. (2019)	Bluetooth, Wi-Fi, ZigBee/XBee, LoRaWAN, 5G	Agricultural data communication for irrigation and crop monitoring	High-speed transmission, Real-time communication	Short-range connectivity, Poor rural connectivity	Insufficient wireless access, Power efficiency issues, Communication inconsistency

4 Discussion/Analysis

Comprehensive research has been performed in the fields of automated irrigation, UAV-assisted agriculture, and IoT-based crop health monitoring; however, several critical gaps remain unresolved. Many existing solutions depend on fixed ground-based sensors with limited scope or operate drones without responsive control and real-time decision-making mechanisms. Studies by Kamath et al. (2019) and Alnaimi & Mabdi (2021) demonstrate the use of drones or Raspberry Pi for area-specific irrigation but lack extensive integration and real-time flexibility. Additionally, dependence on individual sensing techniques, cloud-based decision systems, or costly devices such as hyperspectral cameras limits real-world application, especially in rural and resource-limited regions.

Despite several advancements in smart irrigation systems, major research gaps remain in implementing real-time, drone-based solutions that combine diverse sensors such as NPK, DHT11, soil moisture, and water level using Raspberry Pi. Current studies often do not adequately address the challenges of robust and fast data transfer between ground stations and drone units in rural regions, where insufficient network infrastructure restricts consistent connectivity. Additionally, the accuracy and suitability of weather information accessed through APIs like OpenWeatherMap have not been sufficiently validated for ground-level decision-making. There is also a lack of standardized communication protocols between Arduino and Raspberry Pi for sensor data integration, resulting in unreliable system performance. Furthermore, existing research frequently overlooks the computational and power consumption challenges faced by edge computing devices like Raspberry Pi when handling large volumes of sensor and weather data in real time. Most studies are simulation-based or limited to short-term laboratory tests, with very few instances of long-term field validation. Risk management, data accuracy, and scalability are also underexplored, particularly concerning affordability and convenience for small-scale farmers. Finally, although AI-driven decision-making is commonly discussed, its reliability and performance efficiency under real-time, field-deployed conditions remain insufficiently studied.

For addressing such challenges, a design of a drone-based irrigation system that combines real-time multi-sensor data gathering, involving soil moisture, temperature, humidity, and NPK values – alongside weather data sourced via the OpenWeatherMap API will prove to be reliable, and onboard processing through the Raspberry Pi allows the drone to make real-time automated irrigation decisions.

Such system closes the loop between sensing and actuation by enabling smooth communication between a ground station and a drone-mounted system via socket programming. utilization of cost-efficient sensors and relay-based water control improves system feasibility and scalability, making it a wise, environmentally sustainable, and affordable system suitable for small to medium farms.

5 Conclusion & Future Work

In this paper, we have reviewed, compared, and analysed the advantages and drawbacks of drone-based irrigation systems.

Most existing systems typically either focus on monitoring or using fixed, ground-based sensors with limited operational control over watering processes. Many existing solutions lack real-time feedback irrigation, where sensor data automatically initiates irrigation procedures instantly.

The suggested design of a drone-based irrigation system bridges this gap by combining real-time environmental sensing (soil moisture, temperature, humidity, and NPK values) with weather forecasting data (via the OpenWeatherMap API) and onboard processing (using Raspberry Pi). Unlike established systems, this approach will not stop at monitoring; it immediately controls irrigation using a relay mechanism to trigger solenoid valves according to evaluated data.

The socket programming will enable effective communication between the ground station and the drone-mounted system, ensuring timely actuation. The use of cost-effective sensors and autonomous decision-making increases its applicability in rural and resource-constrained areas. Thus, this system will provide a complete closed-loop smart irrigation solution that is affordable, scalable, and practical for small to medium-scale farms.

In current applications, automated irrigation systems demonstrate significant potential for enhancing farming techniques.

For future improvements, the integration of AI tools to predict soil conditions and enhance irrigation efficiency will make the system more dynamic and smart.

Additionally, the system can be expanded by merging UAV drones, sensors, and devices to form a more extensive network for precision farming that improves system efficiency.

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