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Automation in drip irrigation system: A comprehensive review with mathematical modeling and optimization algorithms

Jeet Chand[1+]
Rupesh Acharya[2]
Roshan Pandey[3]
Milan Paudel[4]
Sanjeeb Bimali[5]

[1]*Prime Minister Agriculture Modernization Project, Khumaltar, Lalitpur, Nepal.*
[1]*Email: jeetchand06@yahoo.com*
[2,3]*Green Eye Engineering Solutions Ltd. /Inspire Agriculture, Kathmandu, Nepal.*
[2]*Email: rupeshacharya1200@gmail.com*
[3]*Email: pandeyrosan100@gmail.com*
[4]*Water Resource and Irrigation Development Division, Gorkha, Gandaki province, Nepal.*
[4]*Email: k6milan@gmail.com*
[5]*Centre for Agricultural Infrastructure Development & Agricultural Mechanization Promotion, Hariharbhawan, Lalitpur, Nepal.*
[5]*Email: sanzibbimali@gmail.com*

(+ Corresponding author)

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ABSTRACT

This study aims to review and document literature related to drip irrigation and its advancement towards automation in agriculture so that farmers can benefit from the optimum use of input resources, primarily water and fertilizer. Additionally, this review examines technological improvements such as sensor integration, wireless connectivity, and systems because the Internet of Things, microcontrollers, artificial intelligence, and real-time monitoring are critical tools for enhancing agricultural productivity and environmental sustainability. Mathematical models and formulations related to intelligent drip systems were reviewed, along with a deeper exploration of optimization algorithms employed, especially in terms of improving irrigation efficiency, resource optimization, and system performance. Furthermore, a critical analysis was undertaken in a comprehensive explanation of the system design, including real-world applications, with clear mathematical formulations and optimization models. This study found that among different irrigation methods, an intelligent drip system has the highest application efficiency, distribution uniformity, better crop yields, and input resource savings. Also, this study postulates that drip automation allows for accurate water and nutrient distribution, reducing fertilizer runoff and environmental harm. In contrast, drip irrigation has been found to be characterized by higher capital costs and the need for skilled personnel to manage the system, which are, however, equalized by higher yields and savings of production inputs. Reviewed literature indicated that high-valued cash crops are most appropriate for drip automation and suggest extensive application of automated drip systems for environmental sustainability in agriculture. This study recommends further research to make drip irrigation cost-effective, intelligent, and more farmer-friendly.

Contribution/Originality: This study has contributed to the advancement of drip automation and intelligent irrigation systems for resource conservation and agricultural sustainability. Mathematical modeling and optimization algorithms have been reviewed, marking the first time a study has focused on the drip automation system.

1. INTRODUCTION

The goal of irrigation science is to provide a uniform water supply on the farm to satisfy crop water requirements at the right times using different methods depending on topography, water sources, and economics (Thapa & Chand, 2024). Studies have been undertaken to correlate irrigation application methods to crop yield and sustainable economic return per unit of water (Chand et al., 2024; Liu, 2011; Qu, Li, Hu, & Jiang, 2020). The major irrigation methods commonly applied are surface, sub-surface, and micro irrigation. Among them, drip irrigation is a relatively new micro-irrigation initiative that minimizes losses due to evaporation, deep percolation, and surface runoff (Biswas, Akanda, MS, & Hossain, 2016; Liu et al., 2023). The water application efficiency of a well-designed drip system is reported to be around 90% or more, which is higher compared to other irrigation methods (Montazar, Cahn, & Putman, 2019; Qu et al., 2020). Drip irrigation not only provides the highest efficiency but also increases the quality of agricultural products (Chand, Hewa, Hassanli, & Myers, 2023). For example, several studies by Hao et al. (2013) and Chand, Jha, and Shrestha (2022) concluded that drip irrigation plays an important role in increasing the number of fruits, fruit size, as well as soluble solid content in greenhouse-based tomatoes and cucumbers. Seventy percent or more of the root systems of major cash crops, including tomatoes, cucumbers, and capsicum, are located in the upper 20 cm of the soil; therefore, a drip system equipped with a fertigation device is always recommended for the proper use of nutrients and maximum profitability for growers (Bansal et al., 2021; Haifa, 2018). Thus, despite limitations like clogging emitters, high initial capital cost, and intensive management (Chand et al., 2023; Oliver, Hewa, & Pezzaniti, 2014). Drip irrigation serves as an integrated part of commercial agriculture in both open and facility agriculture environments. The application of microirrigation has progressed continuously from being a novelty that was employed by researchers to being widely accepted, efficient methods of irrigating crops in many countries around the world. Drip irrigation encompasses two main methods: a) surface drip, commonly employed in gardens and orchards, and b) subsurface drip, which is frequently used in intensive agriculture (Bansal et al., 2021; Saxena, 2021). Trickle or drip irrigation systems are further categorized into four types based on the emitters that regulate the quantity and rate of water discharge (Rambabu, Bridjesh, Prabhu Kishore, & Shiva Sai, 2023). Point-source emitters, in-line drip emitters, basin bubblers, and micro spray sprinklers are ideal for irrigating trees, shrubs, and similar vegetation. Drip irrigation, also popularly known as precision irrigation, has some key components needed to ensure a well-designed and reliable system, as presented in Figure 1.

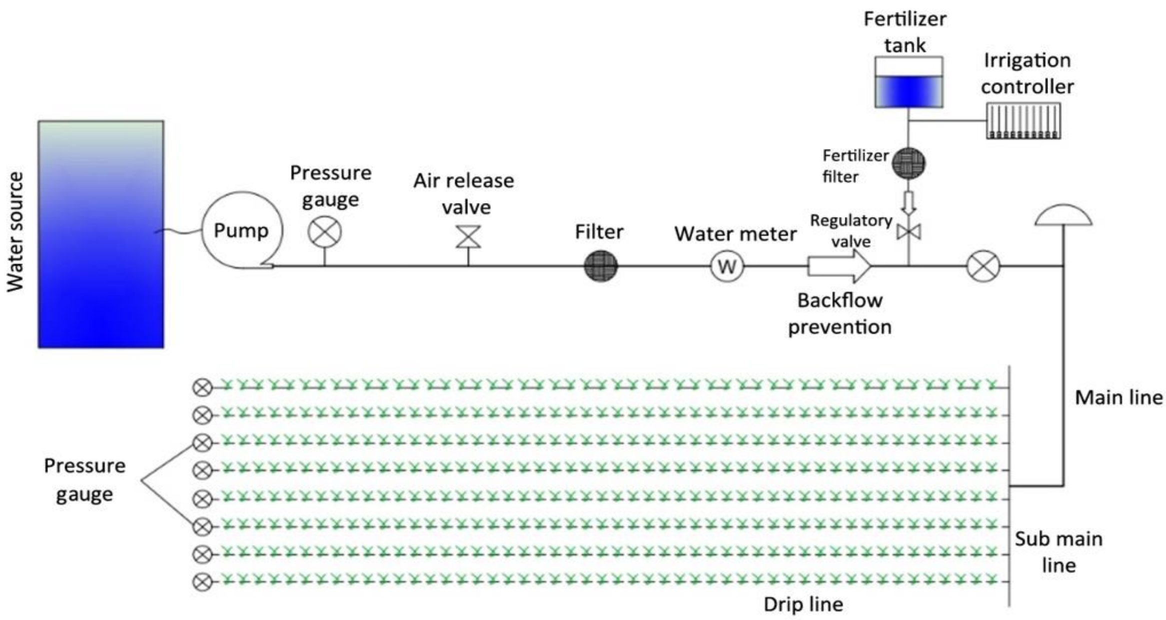

Figure 1. Specific layout with components of drip irrigation [Image Designed from AutoCAD].

Source: Shock (2013).

2. METHODOLOGY

A systematic approach was used to collect and analyze information about automated drip irrigation systems to prepare this review article. The primary goal was to study the subject's breakthroughs, problems, and practical applications. To guarantee complete coverage, the authors reviewed various sources, including peer-reviewed journal publications, technical reports, conference papers, and reliable blogs. Critical databases such as Google Scholar, ScienceDirect, and SpringerLink were utilized to find academic articles, while industry reports and specialist blogs supplied practical information. The materials were chosen based on their relevance to the topic, publication date (with an emphasis on works published within the last decade), and credibility. Studies on irrigation system automation, sensor integration, the Internet of Things (IoT), and energy saving were prioritized. Abstracts were reviewed to identify relevant studies, and full texts were assessed for scientific accuracy and significance of results. This allowed the authors to include high-quality and significant studies.

Automation technologies, system efficiency, environmental sustainability, and economic feasibility were the focus of the study. Each study was assessed critically based on its objectives, techniques, and findings. Comparisons were made between studies to detect consistent trends, divergent findings, and prospective research gaps. Where applicable, findings from blogs and industry reports were cross-checked against academic literature to ensure accuracy. By combining data from multiple sources, this evaluation provides a comprehensive overview of the current state and future possibilities of automated drip irrigation systems. This methodology ensured a balanced viewpoint that included both theoretical advances and actual implementations in the sector.

2.1. Drip Irrigation Economics

An Israeli engineer, Simcha Blass, invented contemporary drip irrigation in the 1950s after noticing a tree thrived with a minor leak in a water line, gaining momentum in current commercial agriculture as a climate-smart and resources-efficient initiative. The selection of an irrigation system is an important economic decision in commercial agriculture because of the various costs involved in the production process, including installation, operation, and maintenance, along with an array of annual costs like water, energy, management, and depreciation (Moursy, ElFetyany, Meleha, & El-Bialy, 2023). Limiting investment and operation costs and maximizing income are generally the most important factors that farm managers consider when selecting an irrigation scheme (Bansal et al., 2021; Pedras & Pereira, 2009). The high installation, operation, and maintenance costs of micro-irrigation systems remain a major constraint to their expansion. However, many industries, companies, and governments have invested huge budgets to foster the advancement and practicality of micro-irrigation (Moursy et al., 2023). High-value cash crops in commercial growing environments are generally recommended to implement micro-irrigation technology (Yang et al., 2023).

Based on the study of Ayars, Bucks, Lamm, and Nakayama (2007), micro irrigation system costs for flower and vegetable production in Japan were as high as $16,000 per hectare. In contrast, many of the countries indicated an average installation cost for drip irrigation ranging from $2,000 to $4,000 per hectare (Chand et al., 2023), along with annual operation and maintenance costs ranging from $100 to $800 per hectare. The large variation in cost estimates might be due to variable labor costs, the design and technology adopted, and system automation.

Micro irrigation provides opportunities to improve both the farm-level net returns and the public net benefits generated with limited water resources (Bajpai & Kaushal, 2020; Wichelns, 2007). The potential farm-level benefits include reductions in water deliveries and labor costs, higher crop yields, and a broader set of production opportunities in regions where water supplies are particularly scarce or saline, whereas potential public benefits include higher farm-level net returns, and the net values generated in agriculture and in other uses with water made available when farmers replace alternate irrigation methods with micro-irrigation. However, the costs and benefits of micro irrigation vary based on farm size, crops grown, topography, availability of inputs, and technology adopted for production and post-harvest processing (Chand et al., 2023; Wichelns, 2007). Commercial growers readily adopt drip irrigation if they can recover the costs of installing, maintaining, and operating a system through water and labor savings, improve crop yield or quality, expand crop activities, or reduce the cost of performing cultural practices (Bansal et al., 2021; Wichelns, 2007).

As the micro-irrigation industry continues to develop, its economics is getting more attention to reduce overall system costs and invent low-cost systems for use in developing countries (Lamm, Ayars, & Nakayama, 2007; Liu et al., 2023). In China, thin-walled, low-cost drip fertigation is gaining momentum among farmers growing commercial horticultural commodities and agronomic crops like maize. Improvements in the reliability, durability, and longevity of the system components and materials (high-quality equipment and parts of the drip system) and the introduction of innovative designs have reduced the cost of micro irrigation to levels that enable small-scale producers in both industrialized and developing countries (Ayars et al., 2007; Liu et al., 2023).

In their study, Pedras and Pereira (2009) concluded that the performance of micro irrigation system depends essentially on the type and quality of the equipment and on the quality of the system design, and fortunately, better control of negative environmental impacts of irrigation is achieved when the system performance is high; however, attaining a high performance usually requires higher investment cost. There should be continuous improvement and modernization in drip irrigation to equalize the high initial capital cost of installing a drip system on farms. Drip automation is one of the improvements in the initiative of agricultural mechanization, modernization, and industrialization. It is the latest technology for managing and optimizing costly resources in the farming system.

2.2. Drip Automation

The concept of drip irrigation dates to ancient times, but modern drip irrigation systems emerged in the mid-20th century. An Israeli engineer, Simcha Blass, invented the contemporary drip irrigation system in the 1950s after noticing a tree thrived with a minor leak in a water line, prompting him to design slow but regular watering techniques. By the 1960s, Blass and his team at Netafim invented the first commercially viable drip irrigation system, employing plastic emitters to efficiently distribute water to plant roots and prevent loss (My Olive Tree, 2017). Over the decades, drip irrigation has evolved with advancements in materials, emitters, and integration with automation technologies. A review by Lakhiar et al. (2024) examines Precision Irrigation Water-Saving systems (PISs) as a potential way to improve agricultural sustainability in the face of climate change and lessen global water scarcity. It emphasizes the creation, application, and advantages of PISs in raising crop output, lowering environmental effects, and increasing water usage efficiency. Future technological developments and artificial intelligence will be crucial in maximizing irrigation techniques (Lakhiar et al., 2024).

Digital agriculture with automation is a new initiative that contributes to narrowing down the problem of global food hunger (Abiri, Rizan, Balasundram, Shahbazi, & Abdul-Hamid, 2023). Automation enables remote communication between equipment and wireless networks, and hence farming operations become digital and advanced (Silva et al., 2021). Smart irrigation, also called intelligent irrigation, is important for modernizing the agricultural profession and maximizing farm benefits by conserving input resources, including seeds, water, and fertilizers (Ray & Majumder, 2024). Automation in technology reduces waste, labor costs, and environmental impacts, resulting in better crop development and higher productivity (Kumar, Didawat, & Kumar, 2023).

The use of water on or below the soil surface through point or line sources, also known as emitters, at a shallow discharge of about 1-30 l/h per emitter and a slight operating pressure of 20-200 kPa is referred to as drip irrigation (Dasberg & Or, 2013). This system irrigates and fertilizes plants efficiently by delivering water and fertilizer directly to the effective root zone area through emitters (Bajpai & Kaushal, 2020; Moursy et al., 2023; Yang et al., 2023). As a result, fertilizer leaching and soil salinity can be minimized (Yang et al., 2023). Currently, the Asia-Pacific markets are expected to dominate in most drip irrigation uses, including significant usage in China, India, and Israel (Global Drip Irrigation Market, 2023).

Drip irrigation systems provide efficient root-to-root irrigation with significant water savings but are more expensive and have a lifespan of around ten years (Markets, 2024). They are commonly employed in developed nations such as the United States, Canada, the United Kingdom, and Germany. Automated versions, which are more efficient and have a longer lifespan, are widely utilized in countries such as the United States, Canada, Brazil, and Spain for vegetable and row crop farming. At the same time, government projects in India and China use drip systems due to their low maintenance and higher efficiency.

2.3. Mechanism

The design of an irrigation system is crucial for efficient water distribution and application. Drip system must match supply requirements and irrigation management, including tapes, tubes, and emitters. Factors like depth, distance, and emitter spacing must be considered. Drip tubing is typically used for perennial crops. The design also finds land topography, water distribution uniformity, and power and water source limitations. Filters and pumps are essential for system performance and accuracy. Sand media, screen, and disk filters are common alternatives, providing filtration to 200 mesh and serving as pre-filters or secondary filters before irrigation water enters the drip tube (Shock, 2013). The microcontroller-based drip irrigation system (Figure 2) consists of various components: a pump, water filter, flow meter, control valve, chemical injection unit, and drip lines with emitters, moisture and temperature sensors, and the microcontroller unit. The system is automated by measuring soil moisture and temperature, which are measured using RTD like PT100 and Tensiometer. Once the soil has reached the desired moisture level, the sensors send a signal to the microcontroller to turn off the relays controlling the valves (Prathyusha & Suman, 2012). The microcontroller unit uses amplifier stages to boost the sensor's signal, which is then fed to A/D converters for digital input. A 16X1 line LCD module monitors current readings of all sensors and valve status. The microcontroller also controls solenoid valves through relays. A chemical injection unit mixes fertilizers, pesticides, and nutrients with water, and the pump motor's speed can control water pressure. A flow meter is attached for water consumption analysis, which can be transferred to the centralized computer for further study. In case of sensor failure, the microcontroller unit turns off valves after a threshold level of time.

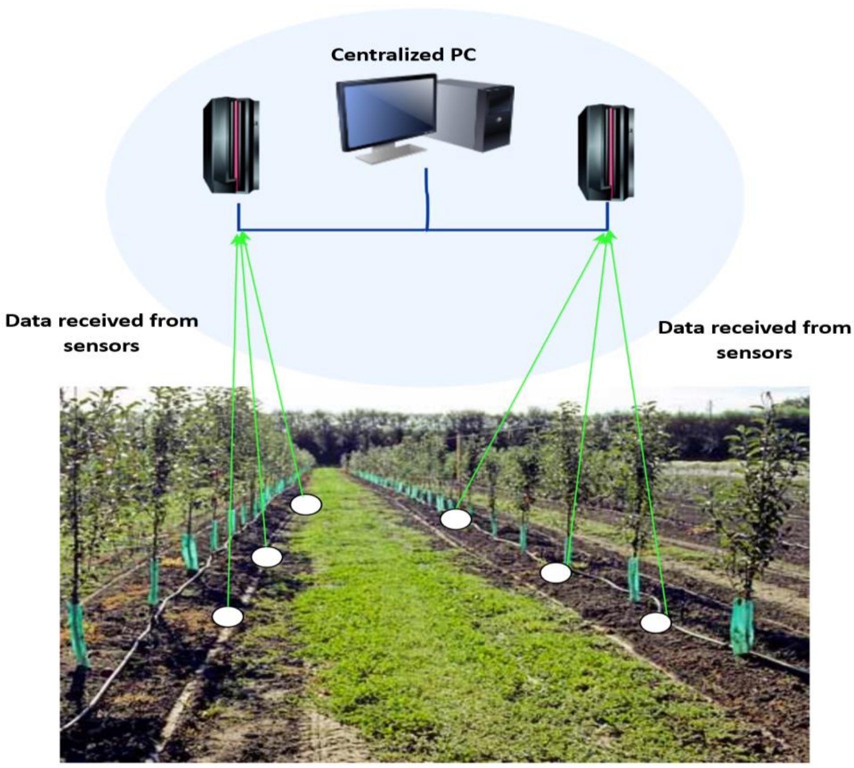

Figure 2. Modified illustration of the general application of automatic drip irrigation (*Image credit*).
Source: Blaho (2015).

2.4. Water Application Rate

2.4.1. Application Rate Calculation in Automatic Drip System

Since it controls the amount of water given over time per unit area, the application rate is a crucial component in drip irrigation systems. A precise application rate calculation is necessary to prevent either over- or under-irrigation, which can result in water waste, nutrient leaching, or less than ideal crop performance (Dasberg & Or, 2013). Depending on the crop requirements and system configuration, there are a number of different ways to calculate the application rate.

The most commonly used formula to calculate the application rate in drip irrigation is Equation 1 as follows:

$$\text{AR} = \frac{Q \times 60}{A \times T} \qquad (1)$$

Where:

- AR: Application Rate (mm/hour)
- Q: Flow rate per emitter (liters/hour)
- A: Area covered per emitter (m^2)
- T: Irrigation duration (minutes)

This formula is practical for determining the rate at which water is applied to the soil surface, considering the system's flow rate and spatial layout (Barkunan, Bhanumathi, & Sethuram, 2019; Dasberg & Or, 2013).

2.4.2. Mathematical Modeling in Drip Irrigation

The design and optimization of automated drip irrigation system depends extensively on mathematical modeling which is systematically explained by Abiri et al. (2023) in their research.

2.5. The Penman-Monteith Equation

It is a fundamental model used in irrigation research to determine evapotranspiration (ET) rates as expressed in Equation 2.

$$\text{ET} = \frac{0.408\,\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

Where:

- R_n: Net radiation at the crop surface ($MJ/m^2/day$)
- G: Soil heat flux density ($MJ/m^2/day$)
- T: Mean daily air temperature (°C)
- u_2: Wind speed at 2 m height (m/s)
- $e_s - e_a$: Saturation vapor pressure deficit (kPa)
- Δ: Slope of the vapor pressure curve (kPa/°C)
- γ: Psychrometric constant (kPa/°C)

2.6. Richards' Equation

$$\frac{\partial\theta}{\partial t} = \nabla.[k(h)\nabla h] + S \qquad (3)$$

The Richards' Equation, basically explains the movement of water through unsaturated porous media where θ is the volumetric water content, K(h) is the unsaturated hydraulic conductivity (dependent on the water head "h"), ∇ represents the gradient operator, and S is a source/sink term for water content over time "t". This equation models water movement in unsaturated soils, aiding in the design of emitter placement and irrigation timing (Dasberg & Or, 2013; Nimmo, 2009; Toshiyuki & Ghezzehei, 2022).

2.7. Green-Ampt Infiltration Model

$$I = K_s\left(\frac{\varphi_f \Delta\theta}{I} + 1\right) \qquad (4)$$

This model is used for estimating infiltration rates and ensuring uniform water distribution in the drip irrigation system (Barkunan et al., 2019). Adapted for drip irrigation, the Green-Ampt infiltration model estimates water infiltration rates from discrete sources like as drip lines by using the idea of a sharp wetting front passing through soil. It is useful for forecasting infiltration in simplified scenarios since it makes the assumption that soil profiles are uniform, and hydraulic conductivity is constant (Tao et al., 2025). Important soil factors used by the model include porosity, wetting front suction head, saturated hydraulic conductivity, and beginning water content (HEC-RAS Hydraulic Reference Manual, 2025; Mohammadzadeh-Habili & Heidarpour, 2015).

2.7.1. Optimization Algorithms for System Efficiency

Through the reduction of water consumption and the preservation of crop quality and production, optimization algorithms improve irrigation efficiency. In the field of irrigation, algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GAs) are frequently employed. These methods address multi-objective issues with system scheduling, resource allocation, and performance improvement (Bhavsar, Limbasia, Mori, Aglodiya, & Shah, 2023).

2.8. Genetic Algorithms (GAs)

GAs optimize irrigation plans by simulating the process of natural selection. The system assesses fitness based on crop production and water use efficiency (WUE) by encoding decision variables (such as water volume and timing) as chromosomes. For instance, compared to traditional techniques, GA-optimized irrigation schedules have shown water savings of up to 25% (Barkunan et al., 2019).

2.9. Particle Swarm Optimization (PSO)

PSO algorithms mimic the social behavior of particle swarms to optimize system parameters. Based on both individual and communal experiences, each particle, which represents a possible solution, modifies its location in the search space. PSO improves fertigation schedules, flow rates, and emitter location in automated drip systems, which lowers fertilizer leaching and increases nutrient uptake (Zhao, Yu, Lei, & Liu, 2023).

2.9.1. IoT-Based Flow Optimization Model

Modern drip irrigation systems often integrate IoT technologies for real-time monitoring and optimization. An example formula for flow optimization is represented in Equation 5:

$$Q = \frac{\sum_{i=1}^{n} S_i \times E_i}{T} \qquad (5)$$

Where,

- S_i: Sensor readings (e.g., soil moisture)
- E_i: Efficiency factors
- T: Time interval

This ensures precise water distribution based on real-time data from sensors and cloud-based systems (Bhavsar et al., 2023).

2.9.2. System Design and Optimization Process

Automated drip irrigation systems are designed by combining sophisticated software algorithms with hardware components to provide exact control over the flow of nutrients and water. Important phases in the design process consist of:

2.10. Component Selection

The system's components include pumps, filters, flow meters, control valves, sensors (temperature, moisture content of the soil), microcontrollers, and emitters. Durability, efficiency, and compatibility are the main considerations when choosing components. The design is tuned to guarantee even water distribution and reduce pressure losses (Dasberg & Or, 2013).

2.11. IoT and Real-Time Monitoring Integration

Internet of Things (IoT) technologies allow for remote control and monitoring. Real-time data is sent by sensors to a centralized platform, where algorithms examine patterns and offer useful insights. According to crop-specific needs, this integration guarantees timely irrigation. IoT technologies allow for remote control and monitoring. A centralized platform receives real-time data from sensors, and algorithms examine patterns to produce useful insights. In accordance with crop-specific needs, this integration guarantees timely watering (Bhavsar et al., 2023).

2.12. Modeling and Simulation

To forecast system performance under various conditions, mathematical models are used to simulate the system prior to implementation. To improve design parameters, tools like MATLAB and ANSYS model the dynamics of water flow and pressure distribution (Zhao et al., 2023).

Operational Parameter Optimization: Using multi-objective optimization models, irrigation plans are matched to crop development phases, resource availability, and weather. The Non-dominated Sorting Genetic Algorithm III (NSGA-III), for example, has been used to balance water use and irrigation thresholds.

2.13. Operational Parameter Optimization

Multi-objective optimization models match crop development stages, resource availability, and climate to irrigation schedules. To find the best irrigation thresholds that balance agricultural output and water use, for example, the Non-dominated Sorting Genetic Algorithm III (NSGA-III) has been used (Zhao et al., 2023).

2.14. Applications in the Real World

System performance is confirmed by case studies. For instance, an automated drip system combined with artificial neural networks (ANNs) increased goji berry yields by 10.7% and decreased water consumption by 20% in a study carried out in the Ningxia region of China (Zhao et al., 2023).

The efficiency and sustainability of automated drip irrigation systems are improved by combining mathematical modeling, optimization algorithms, and sophisticated system design methodologies. Since they tackle urgent issues of food security, environmental degradation, and water scarcity, these developments are essential instruments for contemporary agriculture.

2.15. Market Forecast

Due to growing concerns about water conservation and sustainable agriculture methods, the worldwide drip irrigation market has been expanding significantly. With a 2021 valuation of USD 5.12 billion, the market's importance in contemporary agriculture was highlighted. Between 2021 and 2030, the industry is expected to grow at a Compound Annual Growth Rate (CAGR) of 10.08%. Several causes, such as improvements in irrigation technologies, increased understanding of resource-efficient practices, and government programs encouraging sustainable water use, are responsible for this strong growth trajectory (Global Drip Irrigation Market, 2023). The market is anticipated to grow to a staggering USD 12.15 billion by 2030, demonstrating the extensive use of drip irrigation systems in many different geographical areas. This expansion is especially noteworthy in regions experiencing water scarcity, as the technology is essential for increasing crop yields while optimizing water consumption (Global Drip Irrigation Market, 2023).

2.16. Benefits

According to the reviewed works of literature, the major benefits of automated drip irrigation over traditional drip irrigation are:

2.16.1. Efficiency

The optimization of the irrigation schedule with direct and suitable quantities of water to the plant roots minimizes evaporation, runoff, and overspray. As a result, irrigation becomes more effective and efficient (Azulay et al., 2023).

2.16.2. Improved Crop Yields

A study by Kumar et al. (2021) in the Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi, suggests that adopting an automated drip irrigation system resulted in the highest crop and irrigation water productivity among automated and various manually controlled irrigation methods.

2.16.3. Water Savings

Drip irrigation has significant water savings compared to other irrigation methods. The right amount of water in the right amount of time can reduce water loss in an automated manner. Thus, water savings will be higher when irrigating with automated drip irrigation.

2.16.4. Cost Savings

Despite the higher initial cost of installation, reducing water usage and increasing crop yields can lower operating costs and increase long-term cost savings (Azulay et al., 2023).

2.16.5. Environmental Sustainability

As drip irrigation with automation saves 30% water and nutrients, environmental sustainability in agriculture gets improved (Thapa & Chand, 2024). After effective application of smart drip, chances of soil erosion and losses will be significantly decreased (Jha, Doshi, Patel, & Shah, 2019).

If these benefits are properly applied at the farm level, the attractiveness, competitiveness, and profits of the agriculture business increase to the next level, contributing to its sustainability and food security. Most of the farming communities throughout the globe are in low-profile professions that demand technological improvement and profit maximization through mechanization and automation in agriculture.

2.17. Major Findings

According to the review on drip irrigation impact in China, when applied at 100 to 120% water levels, drip irrigation increases crop output by 28.9%, 14.5%, 8.03%, 2.3%, and 5.2% compared to floods, border, furrow, sprinkler, and micro-sprinkler irrigation (Yang et al., 2023). This method improves water use efficiency, minimizes fertilizer leaching, and lowers soil salinity, making it a promising solution for addressing global water scarcity and ensuring sustainable agricultural production. For real-time irrigation control in water-scarce areas, Vandôme et al. (2023)

designed the Pilowtech, an open-source, low-cost soil moisture sensor. When tested in Tunisia, it performed better than commercial sensors and offered a practical, affordable way to use water in agriculture (Vandôme et al., 2023).

To improve crop productivity, water use efficiency (WUE), and environmental footprints, Imran Ali Lakhiar et al. reviewed the research that suggested and validated the use of smart tools (IoT and WSN) for crop irrigation water delivery and monitoring. Numerous smart drip irrigation systems that use Internet of Things (IoT) technologies—including Wi-Fi, GSM, and LoRaWAN—are highlighted in the review to automate water delivery based on real-time data from sensors like pH, soil moisture, and climate. One study Barkunan et al. (2019) suggests an automated drip irrigation system for paddy farming that combines a microcontroller with a GSM module and a smartphone-based soil moisture-detecting approach. The experimental findings demonstrated water savings of roughly 41.5% when compared to conventional flood irrigation and 13% when compared to conventional drip irrigation (Barkunan et al., 2019).

In the case study of lemongrass farming, the experiment suggested an Internet of Things-enabled soil monitoring system and Message Queuing Telemetry Transport (MQTT) protocol for automated drip watering. As explained by Jain, Chiu, Hassani, Orlov, and Shi (2023), using cloud-based analytics and real-time data transfer, the system reduces water waste and improves irrigation efficiency by automating water supply management. The research that focuses on optimizing lower irrigation limits with the Non-dominated Sorting Genetic Algorithm III (NSGA-III) and Artificial Neural Network (ANN) shows that accurate water management can improve the yield and quality of the medicinal and commercially valuable plant Lycium barbarum, also referred to as goji berries. The experiment conducted in China's water-scarce Ningxia area demonstrated the efficacy of the suggested model for sustainable irrigation methods by growing fruit yield by 10.7% and improving fruit quality by 8.8% (Zhao et al., 2023). The authors stress the importance of affordable, easily navigable tools that provide farmers with remote monitoring and management skills to promote sustainable farming methods and lessen the effects of water scarcity (Imran et al., 2024). A sensor-based soil moisture meter integrated with a drip irrigation system increased crop yield and quality, with promising outcomes noted in the 2020 field season, based on a study highlighting the production of tomatoes and watermelons in North Dakota using mulches and automatic drip irrigation.

In comparison to other treatments, the results demonstrated that drip irrigation in conjunction with clear plastic mulch for watermelon and black plastic mulch for tomatoes produced the highest yields, as well as enhanced fruit quality, morphometric, and taste parameters (Vaddevolu, Lester, Jia, Scherer, & Lee, 2021).

The automation of certain parameters, including soil moisture, EC, soil salinity, temperature, and water flow, improves irrigation water productivity. This is based on a study that highlights the use of an optimal drip irrigation system utilizing semiconductor sensors (Akbarov, Ruzibaev, Sapaev, Ruzmatov, & Yakubov, 2020). The technology, which was used in a one-hectare agricultural setup, showed economic viability by lowering reliance on imported goods and guaranteeing accurate water management through automated pressure valve control and water flow monitoring. A detailed analysis of intelligent drip irrigation emphasizes the integration of technologies, with particular attention to software, microcontrollers, soil moisture sensors, and communication techniques, as presented in Figure 3.

Based on the study of (Bhavsar et al., 2023), it was found that wireless communication technologies like Bluetooth, Wi-Fi, RF, and LoRa are widely used in conjunction with contemporary microcontrollers and sensors, providing bundled software for improved user experience. For implementing the automatic drip irrigation system in the orchard, a low-cost, solar-powered, wireless-controlled drip irrigation system was developed that uses a wireless sensor network to monitor soil moisture and optimize freshwater usage in agriculture, lowering labor requirements and increasing water efficiency in a cherry orchard in central Anatolia (Dursun & Ozden, 2011). An optimized drip irrigation system utilizing IoT technology for automation improved eggplant crop performance by increasing yield by 12.05% and saving 35.2% more water while also enabling remote monitoring via sensors and a cloud server (Kumar et al., 2024).

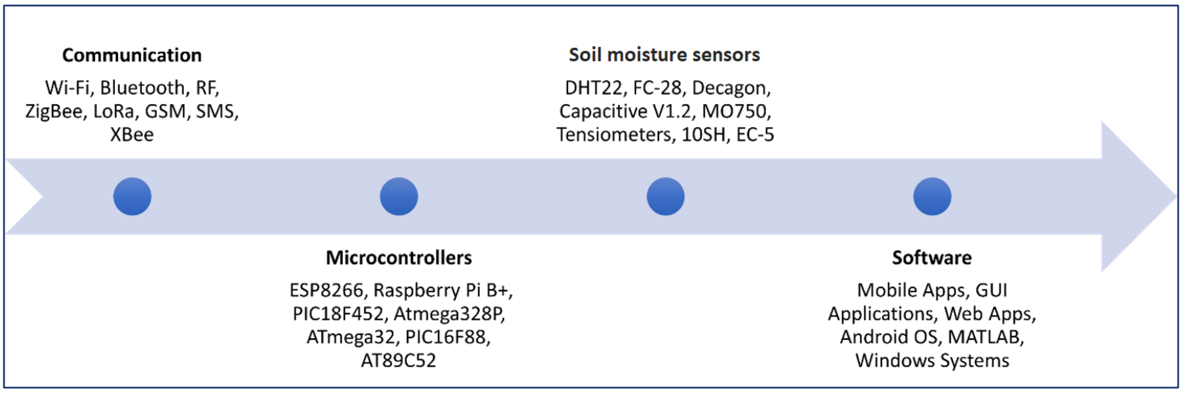

Figure 3. Functional grouping of smart drip irrigation system components.

Source: Bhavsar et al. (2023).

2.18. Challenges and Outlook

Adopting an automated drip irrigation system based on IoT confronts problems such as a need for more awareness, high implementation costs, and reliable internet connectivity and power access, particularly in rural agricultural areas. Furthermore, security concerns, weather-related device vulnerabilities, and the difficulty of processing massive data volumes from IoT devices restrict the general acceptance and practical usage of smart irrigation systems (Bhavsar et al., 2023). Addressing these challenges requires governmental support, subsidies, and training programs to promote the widespread adoption of drip automation. Advancement in technology is the demand of the time. Growers throughout the world need smart, cost-effective, and resource-saving technologies. Making fully automatic services with simple operation, repair, and maintenance in drip irrigation could contribute to the global food security initiative.

3. CONCLUSION

Two-thirds of global freshwater withdrawal goes to irrigated agriculture, where water use efficiency and irrigation management have been listed as major challenging issues. An automated drip irrigation system presents a viable solution to water scarcity, labor shortages, and the need for increased agricultural productivity. Integrating advanced technologies such as sensors, IoT, and automation controllers has transformed traditional irrigation practices, offering precise and efficient water management. The benefits of water conservation, increased crop yields, and labor savings make automated drip irrigation an essential component of modern commercial agriculture. However, to realize its full potential, challenges such as higher initial costs and technical complexities must be addressed through collaborative efforts between governments, technology providers, and the agricultural community. The future of irrigation lies in the continued advancement and adoption of automation technologies, contributing to sustainable agriculture and global food security.

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