A Systematic Review of Irrigation Methods for Onion Cultivation in Developing Countries: Case of Senegal

Mass. Gning*[1,*,‡], Doudou. Dione[2], Demba. Faye[3] and Idy. Diop[4]

[1] *Cheikh Anta Diop University of Dakar, Sénégal*
[2] *École Supérieure Polytechnique (ESP), UCAD, Sénégal*

Abstract
Onion cultivation faces major challenges related to inefficient irrigation management. These problems are amplified by increasing water scarcity due to inadequate management, climate variability, and unregulated deep water exploitation. Traditional irrigation systems result in significant water losses, while precision irrigation systems do not allow for informed decision-making. This poor irrigation management produces onion bulbs with high water content, reducing their storage capacity and making them vulnerable to biological degradation and pathogens. To address this, innovative solutions have emerged, combining traditional and modern precision irrigation methods. In this article, we review the study of irrigation systems based on traditional methods and precision for onion cultivation. We analyze their advantages, limitations, and challenges, highlighting the potential of technologies based on adequate and sustainable precision irrigation. This analysis also highlights the importance of adopting innovative approaches to optimize onion production and preserve water resources.

Keywords: Onion; irrigation; IoT; Machine Learning (ML)

1. Introduction

Oignon(Allium cepa L.) is a biennial herbaceous plant of the Alliaceae family, widely cultivated for its medicinal and dietary properties. The latter contribute to the prevention of cardiovascular diseases . From a nutritional point of view, it is an important source of carbohydrates, proteins, lipids, mineral salts and vitamins [1].Ranked as the second most cultivated vegetable in the world after the tomato, its global production will reach approximately 111 million tonnes per year in 2023, dominated by China, India and the United States.In Africa, the main producing countries are Egypt, Algeria, Sudan, Nigeria, Morocco and South Africa (FAOSTAT, 2023) [2]. However, onion cultivation faces major challenges related to inefficient irrigation management, with negative consequences on the quality of onion bulbs [3].

To address these challenges, innovative solutions have been developed in recent years, combining traditional and precision irrigation techniques. These techniques enable more precise monitoring of environmental parameters and more tailored irrigation, thus reducing water waste and improving crop resilience to climate variations.

In this article, we review irrigation systems based on traditional and precision methods for onion cultivation. We analyze and compare these methods, highlighting their advantages, limitations, and challenges. The objective is to determine the extent to which these technologies can improve irrigation efficiency, thereby contributing to more sustainable agriculture, aimed at increasing crop yields and strengthening resilience to current environmental challenges.

Faced with these challenges, a thorough assessment of existing research is essential to better understand the potential and limitations of irrigation technologies applied to onion cultivation.

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**Corresponding author.
‡ mass2.gning@ucad.edu.sn (Mass Gning) ; doudou2.dione@ucad.edu.sn (Doudou Dione) ; demba.faye@esp.sn (Demba Faye) ; idy.diop@esp.sn (Idy Diop)
§ 0009-0008-5087-5856 (Mass Gning)

This review aims to answer the following questions:

- To what extent do current irrigation practices affect the quality and yield of onion crops, particularly in resource-constrained regions?
- What are the comparative strengths and weaknesses of traditional versus precision irrigation methods for onion cultivation?
- How can emerging irrigation technologies be adapted and optimized to meet the specific agro-climatic conditions of onion-producing regions in Africa?
- What are the main obstacles to the large-scale adoption of efficient irrigation systems, and how can they be addressed to support sustainable agriculture?

By exploring these dimensions, this analysis intends to provide insightful perspectives on sustainable onion production while identifying the key levers for improving irrigation efficiency and resilience.

The article is structured as follows: Section 2 provides an overview of onion cultivation in Senegal. Section 3 lists traditional and precision irrigation techniques developed by researchers in recent years. Section 4 provides a critical analysis of the identified solutions and their limitations, while Section 5 examines Challenges and Discussion only. Finally, the last section concludes the article.

2. An overview of onion cultivation in Senegal

In Senegal, onion cultivation is practiced in several agro-ecological zones. The Niayes horticultural zone in Senegal is located between Dakar and Saint-Louis. This densely populated coastal strip is made up of dunes and inter-dune depressions where onion cultivation thrives. As Senegal's primary horticultural production area, the Niayes zone is of major importance to the country's economy and food security. The major challenges center on profound changes that affect the availability and quality of water resources. The proliferation of drilling is leading to overexploitation of groundwater and, in some places, an advance of the saline wedge originating from the seawater table [4].

According to the Directorate of Agricultural Analysis, Forecasting, and Statistics (DAPSA STAT, 2023), onion production in Senegal was estimated at 400,000 tons in 2023, while a target of 600,000 tons had been set. The following figure shows the evolution of production compared to the target that was set.

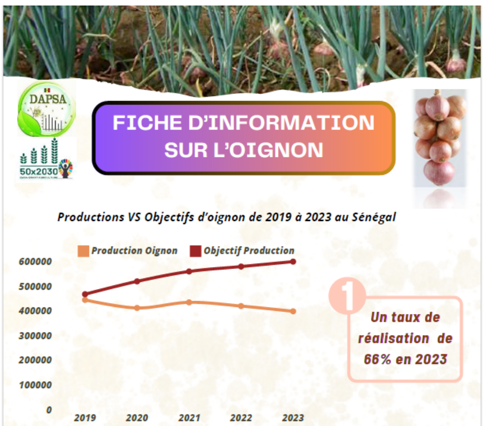

Figure 1: Evolution of onion production compared to the target set [5]

The main production areas are the Niayes region, which accounts for approximately 50% of production, the Senegal River Valley (VFS), which accounts for 30%, and the Northern Zone (Gandon-Potou axis), covering the remaining 20% [5]. This distribution is visible on the map in the following figure:

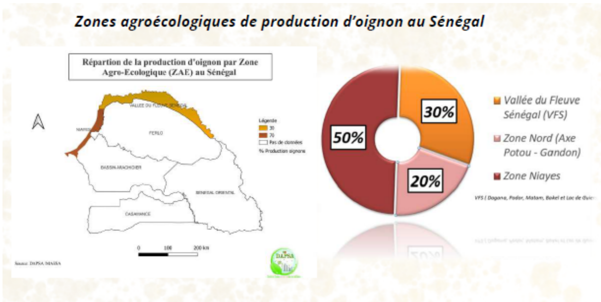

Figure 2: Agroecological zones of onion production in Senegal [5]

This production is largely hampered by poor water management. Irrigation plays a key role in onion cultivation, which is characterized by a superficial root system requiring regular and moderate water inputs to avoid water stress. Good irrigation management thus optimizes growth and yield, while preserving water resources [6].

3. Traditional and precision irrigation methods

3.1. Traditional irrigation methods

Water is an essential resource for food production, and agricultural consumption accounts for nearly 69% of total freshwater consumption. Under these conditions, the need to use available water economically and efficiently is essential. Therefore, irrigation management must be improved according to the actual needs of crops, in order to reduce crop water input while achieving high yields.[8].

Table 1 presents the traditional irrigation techniques.

Table 1
Traditional irrigation techniques used in different studies

Years	References	Irrigation
2018	[2]	Controlled deficit
2018	[7]	Alternating irrigation
2019	[4]	Continuous irrigation
2020	[29]	Cyclical irrigation
2022	[8]	Surface irrigation
2022	[9]	Combination of different water regimes
2023	[10]	Water deficit
2023	[11]	Sprinkler irrigation
2024	[28]	Treatment by irrigation case

This table illustrates the annual evolution (2018 to 2024) of the number of scientific studies on traditional irrigation techniques.

This figure shows the evolution of the Precision Irrigation Technology Adoption Timeline covering the period 2018-2024.

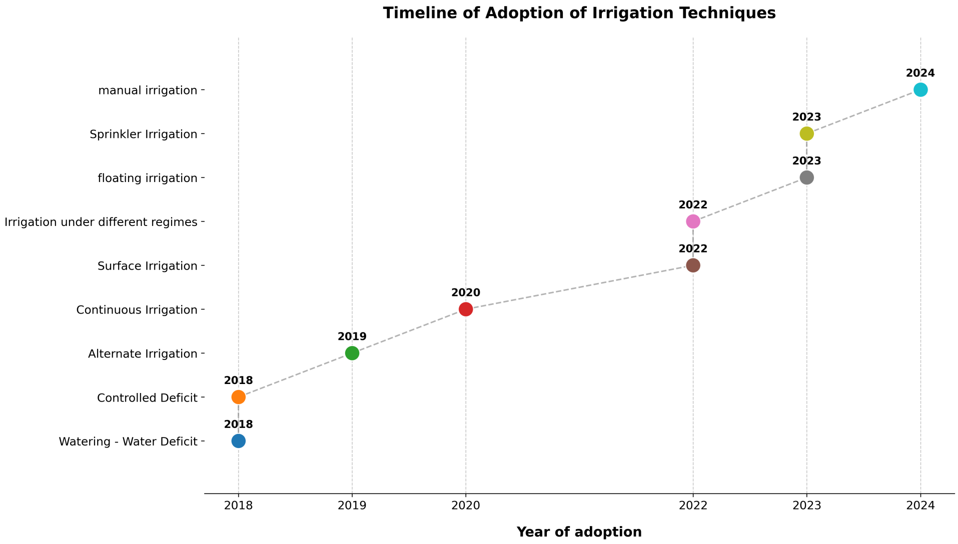

Figure 3: timeline of adoption of irrigation techniques

3.2. Precision irrigation methods:

According to [14], traditional methods used by farmers are no longer sufficient to meet the growing food demand. Therefore, adapting precision irrigation technologies, such as drones, soil moisture and temperature sensors, crop sensors, robots, etc., is a solution to help farmers meet the challenges posed by population growth, water scarcity and waste, and climate change. Agricultural experts estimate that water-sensing technology can reduce irrigation water consumption by 20%. Furthermore, smart soil moisture sensors can measure soil moisture and water levels and regularly transmit data updates to a cloud system, where farmers receive information. The farmer or producer receives continuous information on the amount and areas to be irrigated. Lloret2021. Artificial intelligence (AI) has now enabled and improved agricultural production. This can reduce excessive water consumption or increase water production. This will facilitate real-time monitoring of harvesting, processing, and marketing. [15].

Table 2
Precision irrigation methods used in different studies

Years	References	Irrigation techniques
2018	[26]	IoT and Raspberry Pi
2018	[17]	IoT Commands
2018	[21]	Soil and Environmental Sensors
2018	[27]	LSTM on Groundwater
2019	[18]	Neural Networks for ETc
2020	[14]	Drip irrigation system with IoT
2020	[23]	GSM with wireless sensors
2021	[12]	A wireless sensor network
2024	[20]	Arduino board with sensors and ML

This Table illustrates the annual evolution (2018 to 2024) of the number of scientific studies on precision irrigation techniques.

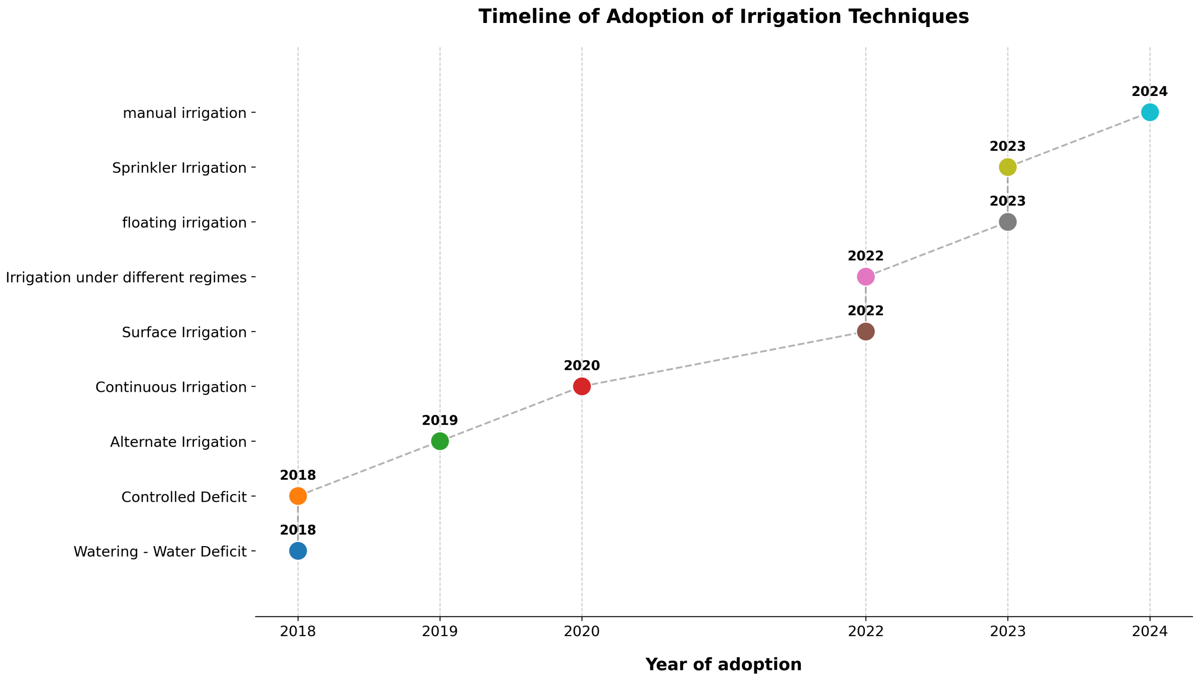

Figure 4: Precision Irrigation Technology Adoption Timeline (2018-2024)

Figure 3 illustrates the distribution of traditional and precision-based irrigation methods. It includes traditional methods, such as watering, surface irrigation, floating irrigation, and manual irrigation. Then there are precision-based methods, which have been adopted by farmers in recent years.

These are irrigation systems based on wireless technologies, controlled by microcontrollers (Arduino, Raspberry Pi) and communicating via GSM, etc.

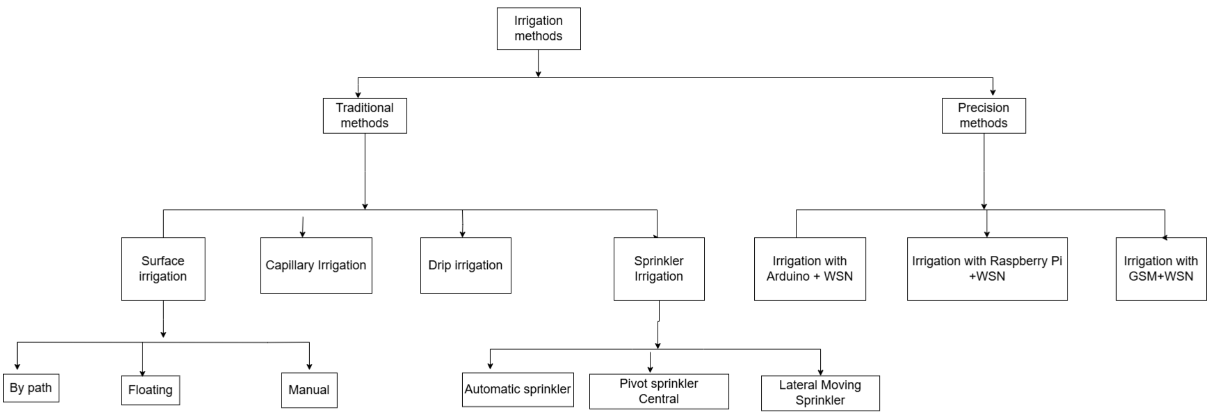

Figure 5: Distribution of traditional and precision irrigation methods

WSN: stands for Wireless Sensor Network

4. Critical analysis of proposed irrigation methods and their limitations

In recent years, several research projects have been conducted to improve crop yields, particularly onions. Most of this research focuses on water management, which is divided into several methods, including traditional irrigation methods and modern irrigation methods.

4.1. Critical Analysis of Traditional Irrigation Methods

One of the most pressing concerns remains water resource scarcity, exacerbated by inadequate water management and climate variability. Many farmers, using outdated equipment, exploit groundwater inefficiently, increasing the risk of water resource depletion [3]. Furthermore, traditional irrigation methods are often inefficient, leading to significant water losses and uneven distribution of water resources.

The authors of [9] developed an optimal irrigation regime for onion (Allium cepa L.) production and reached the following conclusions: the highest total bulb yield, 34,000 kg/ha, was obtained with the control treatment. However, this difference was not statistically significant compared to the treatment combination applying 100% ETc with a 5-day irrigation interval. They demonstrated that shorter irrigation intervals combined with higher irrigation level gave the best performance for all parameters studied, while treatments with higher water stress showed lower performance.

ETc: refers to *crop evapotranspiration*, which is the total amount of water lost through soil evaporation and plant transpiration.

However, the technique used suffers from a lack of precision regarding the water content of the onion bulbs, excessive content being able to cause them to rot.

In [12] and [11], The authors aimed to increase agricultural production by maximizing IWUE (irrigation water use efficiency) and improving yield per unit of water used. They evaluated the response of onion growth, plant water status, bulb yield, irrigation water use efficiency, and bulb quality, applying three continuous water deficit strategies with irrigation levels of 100%, 75%, and 50% of water requirements over a period of three seasons. They concluded that the productive response depends on climate and rainfall. Under average conditions, marketable yield increased linearly with increasing irrigation water applied, while irrigation water use efficiency decreased.

However, the techniques used lacked precision in assessing water use efficiency at 100%, 75% and 50% evapotranspiration levels and in considering environmental parameters, including soil temperature, relative humidity, pH and other key variables and chlorophyll content of the onion crop. Better control of these parameters would help optimize drip irrigation for each treatment carried out, to avoid under- or over-irrigation, which could lead to onion bulb rot and ultimately yield reduction.

The authors of [10], [6], and [26] sought to determine the effect of deficit irrigation on onion yield components and crop water productivity, as well as the impact of different conventional, alternating-furrow, and fixed-furrow irrigation techniques on these same parameters.

They demonstrated that, when irrigation is reduced, conventional furrow irrigation techniques result in the smallest decrease in bulb yield. Furthermore, onion bulb yield increases when the irrigation level increases from a 40% deficit regime to a full 100% application. Fixed-furrow irrigation with irrigation levels of 100% and 80% resulted in the highest bulb yields compared to alternating-furrow irrigation (AFI).

However, there is no control over the amount of water produced during furrow irrigation on the technique used, which can promote rotting of onion bulbs. The technique used did not focus on the consequences of water stress. Indeed, although water stress saves a significant amount of water, it causes several irregularities, including promoting a decrease in the yield of onion crops. In addition, the authors overlooked climatic parameters and agronomic variables, which are fundamental factors for optimal irrigation control and improved onion yield. As well as temperature analysis and the evaluation of other types of soils and climates, which would have broadened the scope of research and improved onion yields according to the specific characteristics of each study area.

4.2. Critical Analysis of Modern Irrigation Methods

Traditional methods used by farmers are not sufficient to meet the growing demand for food. Therefore, the adaptation of sophisticated precision irrigation technologies is a way forward to help farmers meet the challenges posed by population growth, water scarcity, and climate change. Artificial intelligence (AI) in agriculture has improved crop production and has led to savings on excessive water use and improved real-time monitoring of crops [14].

The authors of [16] designed a smart drip irrigation system that optimizes water use for agricultural crops using wireless sensors and fuzzy logic. The wireless sensor network used consists of several sensor nodes, a hub, and a control unit. The data collected by the sensors is transmitted wirelessly to the hub. The hub processes the information using fuzzy logic to determine the duration of irrigation valve opening. As a result, the drip irrigation system is activated for an optimized period based on the crops' water needs.

Following their study, the authors concluded that the proposed system can quickly and accurately calculate the amount of water needed for crops, thus providing a scientific basis for efficient and water-saving irrigation.

However, beyond this accuracy, the system has certain limitations. It lacks machine learning algorithms that leverage data acquisition such as temperature and humidity to improve decision-making. Furthermore, the lack of an interactive dashboard limits real-time parameter visualization and analysis for dynamic irrigation adjustment.

In [21] and [23], the authors developed a smart and automated irrigation monitoring system using a Raspberry Pi to optimize water use for agricultural crops. They concluded that the proposed system allows live streaming of crops using Android phones and incorporates an automatic motor start and stop mechanism, making irrigation completely autonomous.

However, while the authors emphasized that this system can help farmers monitor the condition of their fields remotely, regardless of their location in the world, they did not consider the integration of machine learning algorithms exploiting parameters such as soil temperature and moisture. The addition of these technologies would further automate decision-making and optimize irrigation based on environmental conditions.

The authors of [18] used a neural network to optimize water use in a smart farm by integrating it into the proposed smart farm automated irrigation system (SFAIS) using an expert system.

After their deliberations, they concluded that the neural network was a relevant tool and provided satisfactory results.

However, the model has a performance limitation, as a near-linear relationship was observed between the expected (or target) data and the results obtained from the network.

In [22], the authors proposed a system aimed at providing a sustainable solution by automatically monitoring and controlling the irrigation process using the Internet of Things (IoT). They used a regression algorithm to predict the amount of water required for daily irrigation based on data collected by various sensors. The predicted information is made available via a mobile application, allowing users to access the current status of the agricultural field.

They concluded that the proposed automated smart irrigation in agriculture improves field production while reducing water waste.

However, the proposed system is limited to remote irrigation via the mobile application, based solely on data provided by soil temperature and moisture sensors. It does not take into account other essential parameters, such as environmental conditions and agronomic characteristics of plants, which could enrich the decision-making process and allow more optimized irrigation management over a wider scope of application.

The authors of [20] proposed an intelligent system based on open-source technology to predict a field's irrigation needs by analyzing several soil and environmental parameters. This system relies on soil moisture and temperature detection, environmental conditions, and weather forecast data obtained from the internet. The system is based on an intelligent algorithm that integrates the detected data with weather forecasts, including precipitation, air temperature, humidity, and UV levels for the coming days.

Following their study, the authors concluded that the proposed algorithm leverages recent past sensor data and weather forecasts to predict soil moisture for the coming days. The predicted values exhibit good accuracy and a low error rate.

However, the authors did not address optimizing the use of available water using their algorithm or minimizing the system's cost. Furthermore, they did not consider the integration of machine learning algorithms to improve decision-making and refine irrigation management.

In [24], the authors developed a time series model based on long-term short-term memory (LSTM) as an alternative to computationally expensive physical models. The proposed model consists of an LSTM layer followed by a fully connected layer, with a dropout method applied to the first LSTM layer. It uses monthly water diversion, evaporation, precipitation, temperature, and time as input data to predict groundwater depth.

After further study, they concluded that the proposed model can serve as an alternative approach to predicting groundwater depth, particularly in areas where hydrogeological data are difficult to obtain.

However, the proposed model does not provide a sufficiently accurate prediction of groundwater depth, which could limit its effectiveness for informed decision-making.

The authors of [17] developed a strategy of co-locating eddy covariance sensors with weather stations on a farm with different irrigated crops. They used neural networks to train a model based on weather sensors present on the farm to estimate actual evapotranspiration (ET), as measured by the eddy covariance method. They concluded that this method reliably estimates ET from only four sensor parameters (temperature, solar radiation, humidity, and wind speed), with a training time as short as one week. However, the neural network trained using this learning method is only valid under environmental and crop conditions similar to those of the training period.

The authors of [19] evaluated the performance of data-driven models combined with IoT to predict onion yields under different irrigation regimes. Their study concluded that when the total amount of water used for onion cultivation was compared with the results of previous studies using traditional drip irrigation systems, it was found that the AIDIS system's use of Arduino technology optimized water management and maximized crop yields by minimizing irrigation time and quantity, while avoiding over- or under-watering scenarios.

However, the authors did not investigate more complex architectures or the use of ensemble techniques, which could have ensured farmers had access to the best resources for more informed decision-making.

5. Challenges and Discussion only

Irrigation methods proposed to improve crop yields, particularly for onions, have shown promise. However, many challenges remain, including:

Controlling Bulb Water Content The techniques used to date are insufficient to control the water content of onion bulbs [9].

Quantifying water requirements is essential: The techniques used do not allow for accurate deduction of the amount of water required for onion cultivation, and excessive watering can promote onion rot [11, 12].

Measurement of meteorological and environmental parameters: The techniques used so far do not provide accurate values of meteorological and environmental parameters that would allow for precise irrigation optimization [26, 25, 6, 10].

Consideration of agronomic parameters: Some irrigation techniques do not take into account the study of agronomic parameters. This limits water optimization and decision-making, hindering the improvement of crop yields, particularly for onions [22, 14].

Combination with cloud platforms: The techniques used, which take into account both the study of environmental and agronomic parameters and machine learning algorithms, do not incorporate the possibility of using more complex architectures combined with integrated cloud platforms. This could facilitate informed decision-making, regardless of the farmer's location, to improve crop yields, particularly for onions [19]. The central question therefore becomes: how to anticipate the irrigation needs of onion crops, optimizing water use while striking a balance between a slight decrease in yield, slightly lower onion quality, and less than optimal nutrient absorption. This will be achieved by leveraging the Internet of Things (IoT) and machine learning to ensure intelligent and predictive irrigation management.

6. Conclusion

This article provides a review of monitoring and control strategies applied to both traditional and precision irrigation methods. In recent years, we have classified these approaches into two broad categories: those based on conventional techniques and those based on precision irrigation technologies.

In this study, a critical analysis of existing techniques allowed us to identify their limitations and highlight potential challenges. These elements constitute relevant avenues of research for future work aimed at optimizing onion irrigation and improving yields.As part of our research, we plan to develop a smart, automated system based on modern precision irrigation technologies, integrating the Internet of Things (IoT) and machine learning. This system will be equipped with sensors capable of collecting environmental, meteorological, and agronomic data in real time. This data will feed machine learning algorithms, allowing them to accurately predict water needs and yields based on local conditions. In addition, a mobile application will provide farmers with an interactive dashboard to help them make informed decisions. Our work will primarily focus on the Niayes region of Senegal.

Declaration on Generative AI

During the preparation of this work, the authors used chatGPT-5 mini. for the following activities: language refinement, grammar corrections, and occasional structural suggestions. After using this tool, the authors reviewed and edited all generated content as needed and take full responsibility for the publication's scientific integrity and content.

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