Integrating Intelligent Irrigation Systems Across Morocco's Cultivated Spaces: A Strategic Assessment for Sustainable Water Management

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Abstract. Managing Morocco's scarce water resources is a major challenge, especially considering the increasing agricultural demands and climate change influencing the region. This research looks at how Intelligent Irrigation Systems (IIS) might be used in four different types of agricultural categories in Morocco: protected agriculture, traditional open-field farming, urban agriculture, and natural ecosystems. This study examined each agricultural category to assess its suitability for IIS, using a thorough evaluation process that includes infrastructural readiness, technological compatibility, economic feasibility, environmental impact, and social consequences. The research shows that traditional farming, which uses 85% of cultivated area and 70% of irrigation water, has the greatest potential for water savings (up to 70%) with precision irrigation technology. Protected agriculture is more technically ready, but traditional open-field farming is the best way for the country to save water since it has the biggest effect and the most room for growth. The study suggest a system architecture that can scaled-up and include meteorological data, modelling crop evapotranspiration, and machine learning-based soil moisture prediction to make intelligent drip irrigation possible in typical agricultural settings. The results show that using targeted IIS in traditional farming might save a lot of water and help Morocco move toward sustainable digital agriculture. This would make this sector the basis for national initiatives to modernize irrigation.

Keywords: Intelligent irrigation; Water management; Precision agriculture; AI Sustainability; Multi-space agriculture.

1 Introduction

Managing Morocco's limited water resources is a major difficulty; this scenario becomes more severe with rising agricultural needs and climate change [1]. Agriculture is a key user and it's the largest consumer of available freshwater resources, making effective irrigation not only a need for maintaining agricultural production but also for protecting the country's environmental and economic stability. In this context, Intelligent Irrigation Systems (IIS)

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have emerged as a promising technology, combining automation, IoT sensors, and data analytics to provide precision irrigation that may remarkably improve water consumption [2].

This study analyses the possibilities for integrating IIS across multiple cultivated spaces in Morocco, including protected agriculture (e.g., greenhouses), traditional agriculture or open-field farming, urban agriculture the small-scale technology-driven farming, and natural ecosystems. In order to assess the feasibility of IIS integration across those different cultivated spaces, the research conduct an examination based on five key dimensions, infrastructure, technical compatibility, economic feasibility, environmental effect, and social ramifications, attempting to give detailed knowledge of how IIS might be adjusted to each cultivated space.

In Morocco, traditional open-field agriculture dominates 85% of cultivated land and consumes over 70% of irrigation water, yet remains largely disconnected from digital technologies [3]. While drip irrigation systems are increasingly promoted as water-saving alternatives to surface irrigation, they are often deployed in standalone, manually operated setups [4]. This exposes a strategic gap: the infrastructure exists to deliver water efficiently, but there is no integrated system to manage when, how much, and under what conditions water should be delivered—especially in response to real-time environmental data. Without intelligent control, drip systems become static tools, unable to adapt to weather variability, crop needs, or soil moisture dynamics. Scaling digital agriculture in open-field settings requires bridging this gap through connected architectures, sensor networks, and AI-driven decision-support systems that can operate at farm-level and across regions [2].

Recent breakthroughs in integrated IIS architectures in Morocco highlight IoT-AI hybrids geared to water-scarce agriculture. For instance, Morchid et al. (2024) presented an embedded system with server-sent conditions for smart irrigation control in the Fes-Meknes region, incorporating sensors and cloud computing for ETc prediction, showing 40% efficiency gains in open-field trials but pointing out challenges in sensor density for large scales [5]. Lachgar et al. (2024) examined AI-embedded IIS adoption via PRISMA, highlighting limitations in drought phenology adaptation for crops like citrus [6], whereas Benzaouia et al. (2024) implemented fuzzy control in oriental Morocco, lowering waste by 30% but calling for reinforcement learning to address climate variability [7]. These Moroccan systems confront continuing challenges, including high initial costs (e.g., 150–300 MAD/ha for IoT nodes), scalability in varied terrains, intermittent LoRa/GSM signals (<70% reliability in rural areas), and socio-technical adoption within smallholders (rates <25% without training). Our system bridges these by leveraging edge-AI on Raspberry Pi for low-connectivity resilience, FAO-56-tuned RL for citrus-specific ETc, and modular ML—optimized for traditional open fields to promote national scalability.

The principal objective of this study is to evaluate and compare the potential for integrating Intelligent Irrigation Systems (IIS) in Morocco's diverse cultivation areas. Ultimately, aiming to identifying key actions for sustainable water management and agricultural transformation are. Specifically, this study seeks to:

(1) Assess the technical feasibility, economic viability, and environmental implications of IIS implementation across four distinct agricultural categories—protected agriculture, traditional open-field farming, urban agriculture, and natural ecosystems;

(2) Quantify the water-saving potential and scalability opportunities within each agricultural category through systematic comparative analysis using infrastructure readiness, technical compatibility, economic feasibility, environmental impact, and social acceptance criteria;

(3) Develop an evidence-based strategic framework for prioritizing IIS deployment that maximizes national water conservation impact while considering implementation complexity and resource constraints;

(4) Design and propose a scalable system architecture for intelligent drip irrigation specifically adapted to traditional open-field farming conditions, incorporating meteorological data integration, crop evapotranspiration modelling, machine learning-based soil moisture prediction, and automated decision-making capabilities.

Through this multi-dimensional evaluation approach, a specific focus of this research addresses on offering actionable, evidence-based intelligent drip irrigation system architecture in citrus open-field farming for Morocco's digital agriculture transformation strategy, essentially contributing to more efficient water resource usage, enhanced agricultural sustainability, and improved resilience to climate variability in arid and semi-arid environments.

This study's results will inspire policy creation, investment prioritization, and technology deployment strategies required for Morocco's transition through sustainable, digitally-enhanced agricultural water management systems.

2 Overview of Cultivated Spaces in Morocco

Morocco's agricultural environment is varied, containing several cultivated categories that vary in terms of size, infrastructure, and technology awareness for intelligent irrigation systems (IIS) integration. These spaces include protected agriculture (greenhouses), traditional open-field farming, urban agriculture, and natural ecosystems. Each category shows various features in terms of land usage, water dependence, and compatibility with modern irrigation technology.

2.1 Distribution of agricultural spaces in Morocco

The distribution of agricultural spaces in Morocco is diverse, encompassing various categories that differ significantly in terms of area, water usage, and potential for water reduction through intelligent irrigation systems. Table 1, provides a detailed comparison of each of those categories, including the proportion of agricultural land held by each cultivated area and their corresponding fraction of total water consumption. This imbalance underscores the dual strategy of prioritizing protected farmland for quick IIS implementation and conventional agriculture for high-impact water savings.

The analysis of Morocco's agricultural spaces highlights the dominant role of traditional agriculture, it covers 7.5 million hectares, accounting for 85% of total agricultural land, yet it consumes 70% of agricultural water resources. This stems from conventional farming practices, and despite its vast presence, its efficiency remains a challenge due to high water usage and vulnerability to climate variability, but it also presents the highest potential for water reduction, with a potential reduction of 70% through the integration of IIS [3]. In contrast, protected agriculture (Greenhouses) occupying only 0.4% of land, it includes practices such as greenhouses and other controlled environments. It uses 5% of total agriculture water use [4] and has a moderate potential for water reduction at 30%, suggesting an optimal balance between resource efficiency and productivity since it’s crucial for high value crops and year-round production [8].

Furthermore, Urban agricultural spaces and natural ecosystems play smaller but relevant roles in sustainability efforts covering 45 000 hectares and 1.25 million hectares (constitute 0.5% and 14.1% of the agricultural land), respectively, each presenting distinct advantages and limitations, with relatively modest water requirements and primarily through natural precipitation and traditional irrigation systems. Moreover, urban spaces use 3% of the water resources and have a potential water reduction of 45%, while natural ecosystems use 22% of the water resources and have a lower potential for water reduction at 15% [9]. Additionally, urban agriculture is increasingly important for local food production and sustainability in

Table 1. Distribution of Agricultural Spaces in Morocco.

Category	Area (ha)	Percentage of Total Agricultural Land	Water Usage	Potential Reduction*
Traditional Agriculture	7.500.000	85%	70%	70%
Protected Agriculture	33.000	0.4%	5%	30%
Urban Spaces	45.000	0.5%	3%	45%
Natural Ecosystems	1.250.000	14.1%	22%	15%

**Potential Reduction: Modeled maximum water savings from IIS adoption (e.g., intelligent drip) relative to current practices, calculated as [(Baseline Efficiency - IIS Efficiency) / Baseline Efficiency] × 100, using FAO benchmarks for irrigation application efficiency (FAO Aquastat 2022 [10]). Baselines: Traditional (40%, surface; [3]); Protected (70%, baseline drip; [4]); Urban (60%, hydroponics; [15]); Natural (85%, rain-fed; [9]). IIS assumes 90-95% via precision tech ([11]). Figures represent upper-bound estimates from Moroccan pilots (e.g., 50-70% in open fields; World Bank 2024 [12])*.

urban areas, and natural ecosystems are vital for biodiversity and environmental balance but offer limited scope for water- saving interventions compared to other categories.
The water usage shares are based on national numbers from FAO Aquastat (2022), with agriculture accounting for over 87% of Morocco's total withdrawals, mostly from traditional open fields ([3]; [13]). Efficiency modeling shows that potential reductions can be made by comparing baseline application rates (for example, 40–50% for surface irrigation) to IIS-enhanced drip (90–95%). This gives category-specific maxima, such as up to 70% in traditional systems through less runoff and evaporation ([11]; World Bank 2024). This shows the strategic imbalance: focusing on protected locations for rapid wins (30%) and traditional areas for scale (70%).

2.2 Comparative overview of cultivated spaces categories

The Table 2 provides a comparative overview of these cultivated spaces, highlighting their definitions, prevalence, and key features to better understand their suitability for IIS implementation.

Protected Agriculture known as Controlled Environment Agriculture (CEA), has gained significant traction within Morocco, particularly for the cultivation of high-value crops including tomatoes and peppers, with notable concentration in regions such as Souss-Massa. Are characterised by their sophisticated environmental regulation capabilities, allowing precise management of critical growing parameters including temperature, humidity, and irrigation delivery. These controlled environments increasingly incorporate advanced technological solutions, integrating Internet of Things (IoT) devices, various sensor arrays, and precision irrigation systems to maximize production efficiency and resource utilization.

Also, Traditional Agriculture remain prevalent throughout rural Morocco, and continues to be the dominant farming methodology employed across the country, particularly evident in the cultivation of staple crops such as wheat and barley, as well as in the management of fruit orchards that contribute significantly to Morocco's agricultural output. Its operations predominantly rely on rudimentary surface irrigation techniques, including flooding and furrow methods that have been utilized for generations. Despite potential advantages offered by modern irrigation technologies, adoption rates remain notably limited within this sector.

Table 2. Comparative Overview of Cultivated Space Categories in Morocco..

Category	Definition	Prevalence	Key Features	Ref.
Protected Agriculture	Controlled environment agriculture (CEA)	Used for high-value crops in arid & semi-arid regions	Controlled temperature, humidity, and irrigation - High-tech solutions (IoT, sensors, and precision irrigation).	[14]
Traditional Agriculture	Conventional rainfed and irrigated agriculture in rural Morocco	Dominant farming method, especially in wheat, barley, and fruit orchards	Mostly dependent on surface irrigation (flooding, furrows), traditional practices and natural rainfall. - Limited technology adoption due to cost and lack of awareness	[2]
Urban Agriculture	Small-scale farming within cities, including rooftop gardens, hydroponics, and vertical farming	Growing in cities like Casablanca and Rabat	Uses space-efficient solutions like hydroponics and aquaponics.- Potential for automated irrigation in small areas.- Focus on local food production and sustainability	[15]
Natural Ecosystems	Agricultural practices integrated into natural landscapes (e.g., oasis agriculture, forest-based farming).	Common in semi-arid regions and mountain zones	Minimal infrastructure, relies on Natural irrigation cycles.- Focus on biodiversity conservation rather than high-tech irrigation.- Combines agriculture with natural ecosystem management	[16]

**Synthesis: Definitions and features derived from qualitative review of Morocco-specific literature (n=12 sources, 2018–2025), aggregated with national land-use data from Table 1. Prevalence calibrated against regional surveys for contextual fit.*

This technological gap persists primarily due to prohibitive implementation costs and insufficient awareness among farming communities regarding available innovations and their potential benefits.

While Urban Agriculture model featuring innovative approaches such as rooftop gardens, hydroponic systems, and vertical farming structures, has experienced notable growth in Morocco's metropolitan centers, particularly in major urban areas including Casablanca and Rabat, where space constraints have necessitated creative cultivation solutions. They emphasis on space-efficient cultivation methodologies, with hydroponic and aquaponic systems representing particularly important technological adaptations to urban constraints, offering significant potential for the implementation of automated irrigation technologies, as their relatively compact dimensions make comprehensive technological integration more feasible and economically viable compared to larger traditional farming operations.

Finally, Natural Ecosystems that are thoughtfully integrated within existing natural landscapes, exemplified by traditional approaches such as oasis agriculture and forest-based farming systems, represent ecologically harmonious production techniques that work with rather than against natural processes. A defining characteristic of these systems is their minimal reliance on constructed infrastructure, instead depending primarily on natural irrigation cycles that follow seasonal patterns. Unlike more technologically intensive agricultural approaches, these systems typically prioritize biodiversity conservation and ecological balance over the implementation of sophisticated irrigation technologies, reflecting a fundamentally different philosophy toward agricultural development and sustainability.

2.3 Evaluation of Intelligent Irrigation Systems (IIS) Integration Potential

To create the decision matrix in Table 3, we used a mix of the Simplified Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). We changed both methods to work for qualitative expert judgments in assessments of agricultural sustainability. AHP enabled criterion weighting via pairwise comparisons conducted by a panel of six experts: three agronomists specializing in irrigation trials, two AI/IoT engineers, and one policy analyst. This was achieved using a two-round Delphi protocol for consensus, with anonymized surveys and an agreement threshold exceeding 80%. Morocco's National Initiative for Agricultural Development sets the weights based on national priorities. For example, the environmental priority is 0.30 because of the need to save water [3]. TOPSIS then used ordinal scoring to rank the categories (High=0.8–1.0, Medium=0.4–0.7, Low=0–0.3) and calculated the distances to the ideal and anti-ideal solutions. This data-driven method makes sure that IIS deployment is done in a clear order of importance.

2.3.1 Protected Agriculture

Greenhouses are regulated environments, therefore they are very fit for complete automation using sensors, actuators, and artificial intelligence-based irrigation management. Studies demonstrate the great value of automated irrigation in greenhouses, where parameters like temperature, humidity, and soil moisture may be carefully monitored and changed. Furthermore, in terms of control accuracy, hydroponics and drip irrigation provide for exact water and nutrient delivery, so greenhouses are perfect for very accurate irrigation [17].

Moreover, Greenhouses have high sensor densities (moisture, temperature, CO_2 sensors) per hectare due to controlled environments. Greenhouses typically have Wi-Fi or LoRaWAN connectivity, ensuring high data transmission rates. Smart irrigation controllers continuously monitor environmental conditions and adjust irrigation dynamically. Requires expertise in IoT, automation, climate control, and AI-based decision-making [14].

But, High capital investment is needed for greenhouse construction, automation (IoT sensors, climate control), and energy supply. Intensive production, water-use efficiency, and climate control maximize yields and profits, ensuring high return on investment.

Table 3. Decision Matrix of IIS Integration Potential.

Category	Infrastructure (w=0.15)	Technology (w=0.20)	Economic (w=0.25)	Environmental (w=0.30)	Social (w=0.10)	Composite Rank*
Protected Agriculture	High	High	High	High	Medium	1 (0.85)
Traditional Agriculture	Medium	Medium	Medium	High	High	2 (0.72)
Urban Agriculture	High	High	Medium	Medium	Medium	3 (0.68)
Natural Ecosystems	Low	Low	Low	Medium	High	4 (0.45)

**Composite Rank: TOPSIS closeness-to-ideal score (0-1 scale), aggregated from ordinal inputs (High/Medium/Low) weighted per AHP. Ranks stable under ±10% sensitivity. Derived from expert elicitation as detailed before Table 3.*

Greenhouses generate revenue quickly due to year-round production and higher-value crops (e.g., tomatoes, peppers) [18].

Protected agriculture significantly enhance food production efficiency by ensuring year-round crop growth, independent of climate variations. High-tech solutions in greenhouses, such as AI and IoT irrigation, promote technical skills development and agricultural innovation. Greenhouses promote modern farming techniques that may replace traditional knowledge and practices, reducing their cultural impact [14].

2.3.2 Traditional Agriculture

While automation is possible through smart irrigation systems, it is limited by large field sizes and variability in environmental conditions. Wireless sensor networks (WSNs) and IoT can enhance automation but require significant investment and adaptation. Precision is limited due to external environmental influences such as wind and soil heterogeneity. Technologies like Variable Rate Irrigation (VRI) improve precision but are not widely adopted in Morocco yet. Open fields require extensive infrastructure (e.g., soil moisture sensors, weather stations) to ensure effective precision irrigation, which increases complexity [2].

Furthermore, Traditional agriculture -Open fields- use IoT sensors, but density is lower compared to greenhouses due to cost and deployment challenges. Some rural areas lack strong cellular or LoRaWAN network coverage, limiting large-scale IoT deployment. Real-time monitoring is possible but depends on available communication infrastructure (e.g., LoRa, NB-IoT). Farmers need knowledge of drip irrigation automation, soil sensors, and remote monitoring tools but less than in greenhouses [12].

Likewise, moderate investment in irrigation infrastructure (drip systems, smart controllers, soil sensors). Increased water efficiency and optimized fertilization improve productivity, but benefits depend on farm size and crop type. Farmers typically recover costs within 3–7 years due to incremental yield improvements [11].

In other hand, open-field farming remains the backbone of food production in Morocco, directly impacting national food security. While traditional farmers adopt some technological advancements, the pace of knowledge transfer is slower due to conservative agricultural practices. Open-field farming preserves traditional farming methods, indigenous knowledge, and rural community structures [20].

2.3.3 Urban Agriculture

Moreover, Small-scale, structured spaces make automation feasible, with IoT-based irrigation widely used in urban farming. Urban agriculture often uses hydroponics or controlled soil-based systems with high precision irrigation. Space constraints and water access in urban areas present challenges but are not as complex as large-scale open-field farming [15].

Also, urban agriculture setups have high sensor density due to limited space and the need for precise automation. Urban environments have excellent network infrastructure (Wi-Fi, 5G, NB-IoT, LoRa), ensuring seamless IoT operation. Smart irrigation in urban farms often uses AI and cloud-based platforms for real-time monitoring and decision-making. Less technical complexity than greenhouses, but still requires knowledge of IoT irrigation controllers and urban farming techniques [15].

While for urban spaces costs include hydroponic/aeroponic setups, vertical farming systems, and automated irrigation. Rooftop farming and community gardens create economic opportunities but are often limited in scale. Short investment recovery due to high demand for fresh, local produce in urban markets [21].

While urban agriculture contributes to local food production, its scale is limited compared to traditional and greenhouse farming. Urban agriculture serves as a knowledge hub, educating citizens on sustainable practices and engaging youth in innovative farming. While urban farming reconnects city dwellers with agricultural practices, it does not fully preserve traditional farming knowledge and rural lifestyles [22].

2.3.4 Urban Ecosystems

Additionally, Natural ecosystems rely on ecological balance, and artificial irrigation is rarely used except for restoration projects. Irrigation is impractical due to the complexity of natural ecosystems and the presence of multiple species with different water needs. Implementing irrigation in natural ecosystems could disrupt biodiversity, making integration highly complex [16].

In contrast, IoT-based monitoring is rare due to the vast, unmanaged nature of ecosystems. Many natural ecosystems lack network infrastructure, making remote sensor deployment challenging. Monitoring is usually done through periodic field assessments rather than real-time automation. Minimal expertise is needed, as irrigation systems are rarely deployed here [23].

But, for natural ecosystems, minimal investment is required since irrigation is rarely applied to natural ecosystems. No direct commercial return, as these spaces focus on conservation rather than agricultural production. Benefits are long-term (decades) and mainly environmental rather than financial.

Additionally, natural ecosystems are not primarily used for food production, making their contribution to food security minimal. Since natural ecosystems require minimal human intervention, knowledge transfer related to irrigation and food production is limited. Natural ecosystems play a crucial role in preserving indigenous and cultural heritage, as many traditional communities rely on them for spiritual and ecological balance [24; 25].

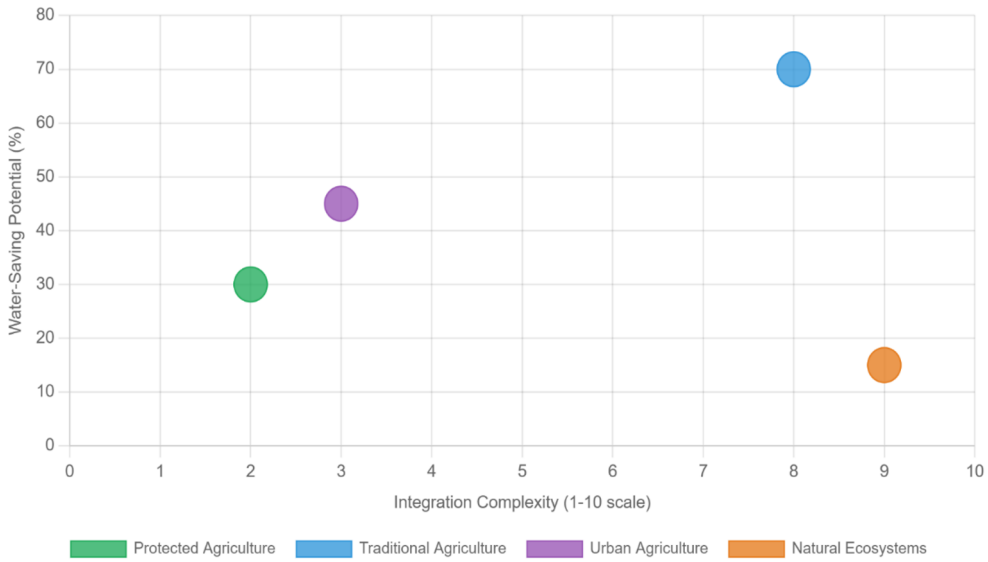

Fig. 1. Water-Saving Potential vs Integration Complexity.

3 The Impactful potential of traditional agriculture

The analysis made on different cultivated spaces highlight the varying potential for integrating IIS across different cultivated spaces in Morocco. Each agricultural category presents unique advantages and constraints, influencing the feasibility of IIS implementation.

Table 1 shows that traditional open-field farming dominates Morocco's agriculture, it spans 7.5 million hectares, or 85% of farm land, and it also consumes over 70% of the country's agricultural water resources. This intensity makes it as the priority national reform of irrigation or water conservation. Substantial savings can occur here, unlike in protected agriculture (0.4% of land).

3.1 Highest Water-Saving Potential

Figure 1 illustrates a strategic quadrant-based scatter plot situating each farmed region according to its IIS integration difficulty and possible water-saving effect, traditional agriculture is positioned in the 'High Complexity–High Impact' quadrant, underlining its role as the important long-term priority for sustainable water management.

But, while our objective and main concern is overcoming water scarcity and conserving freshwater, our focus will be addressed to traditional agriculture despite infrastructural constraints considering its high water saving potential with estimations projecting up to 70% reductions under precision irrigation (like drip irrigation systems) [3; 11].

3.2 Strategic Target for Digital Agriculture Scalability

The implementation efficacy of Intelligent Irrigation Systems (IIS) is fundamentally contingent upon the availability and reliability of critical infrastructure components, including consistent water supply mechanisms, automation capabilities, and comprehensive monitoring technologies. Infrastructure represents the foundational architecture upon which technological innovation in agricultural water management can be sustainably constructed and maintained, and traditional agricultural environments face significant infrastructural challenges including irregular field topography, limited electrical connectivity in remote locations, and substantial spatial heterogeneity that complicates uniform sensor deployment and data collection.

But, unlike protected agriculture, which is high-tech but restricted in size, traditional farms may scale upgrades across thousands of hectares, using government investment subsidies. Presenting a scalable, blank-slate potential for installing low-cost sensors, solar-powered IoT nodes, and LoRaWAN/GSM telemetry, which makes traditional farms suitable for establishing Morocco's digital agricultural backbone.

3.3 Economic Considerations

While infrastructure expenses are challenging, For instance, installing basic IoT-enabled drip irrigation in 1,000 hectares of traditional farming land in Souss-Massa, at an approximate cost of 60 to 120 MAD per hectare, would involve an initial investment of 60 000 to 120 000 MAD, which is low compared to protected agriculture (approximately 250 000-450 000 MAD per hectare for protected agriculture). The return on investment (ROI) arrives in 3-7 years, driven by water savings and crop yield improvement, but the long-term economic benefits significantly outweigh these initial expenditures when multiple variables are comprehensively assessed [20].

Based on past consumption patterns of traditional agriculture, this would save around 700,000 m³ of water per year, which is 55–70% of the water that would normally be used, these numbers show how important it is to put money into this area first [11].

3.4 Environmental Impact

Traditional open-field agriculture has a reduced ecological impact compared to high-input protected agricultural systems such as greenhouses. While greenhouses allow intense production, they frequently depend on excessive fertilizer and pesticide usage, plastic mulch, and artificial heating, which contribute to soil deterioration, microplastic pollution, and agrochemical runoff. Moreover, the concentration of these inputs in controlled conditions promotes the leaching of nitrates and phosphates into water bodies when not appropriately regulated.

In contrast, traditional agriculture (particularly when modernized via drip irrigation and intelligent scheduling) has the ability to minimize environmental impact by decreasing surface runoff and nutrient leaking through localized water utilization, while lowering energy consumption (especially with solar-powered irrigation controllers), and it helps maintaining soil integrity and natural microbial life by avoiding excessive water saturation.

3.5 Social Perspective

From a social perspective, the transition toward advanced irrigation technologies necessitates comprehensive farmer training programs and knowledge transfer initiatives. Our analysis reveals significant gaps in technical knowledge regarding IIS operation and maintenance among agricultural practitioners, particularly those transitioning from traditional to technological farming approaches. Addressing these educational deficiencies requires structured training protocols focusing on technical competency development in sensor calibration, data interpretation, and system troubleshooting;

Plus, digital literacy enhancement to facilitate interaction with software interfaces and analytical tools; Also, decision-support system utilization training to maximize the value of data-driven insights for irrigation management. The implementation of comprehensive farmer education programs could potentially accelerate IIS adoption rates by 30-45% based on comparative analysis with similar technological transitions in agricultural contexts.

4 A Scalable System Architecture for Intelligent Drip Irrigation in Traditional Open-Field Farming

4.1 System architecture overview

In response to the urgent need for sustainable water management in Morocco's water-intensive open-field agriculture, this section presents a scalable system architecture for integrating intelligent drip irrigation into traditional agriculture farming. The suggested architecture utilizes low-power IoT sensors, meteorological data, and automated decision-making modules to provide accurate irrigation scheduling based on crop water demands and real-time environmental conditions. The method is structured around the utilization of meteorological inputs—including reference evapotranspiration (ET_0) provided by AgroTech Association datasets—and crop coefficient (Kc) models that will be calculated based on growth stage of the crop and the wind speed to predict daily crop evapotranspiration (ETc) based on FAO technical paper 56 [26]. This data is then utilized to simulate soil moisture dynamics with machine learning algorithms to finally compare it with implemented soil

moisture sensors implemented in site in objective to avoid sensors implementation in other farms in the region, since a huge amount of sensors is needed especially in open-fields farm known by the large scale surface. This will allow predictive irrigation scheduling using a well-trained deep Q-learning algorithm. While full implementation is scheduled for research to come, this architectural structure provides the necessary components for transitioning from traditional surface irrigation to digitally improved, energy-efficient drip systems, building the core of Morocco's digital agriculture strategy in arid zones.

4.2 Functional Workflow

The suggested system follows a modular workflow that links meteorological inputs with real-time sensor data to allow intelligent drip irrigation scheduling. The basic logic is broken into five essential operating stages:

4.2.1 Input Meteorological Data

The AgroTech association provide the historical daily data from station close to the study site, that include Temperature (Min, Average, Max), Relative Humidity (Min, Average, Max), reference evapotranspiration ET_0, Rainfall precipitations, Wind Speed, Global solar Radiation, stored locally. But, before utilizing this data, it needs processed, to handle missing or erroneous items using linear interpolation and domain-based filtering, plus the conversion of units when required and the normalization for deep learning models, finally the derivation of additional characteristics such as vapor pressure deficit and mean daily temperature.

4.2.2 ETc Calculation Module

The crop evapotranspiration ET_C quantifies how much water a specific crop, in a specific growth phase, actually needs under current weather conditions. And it's was determined using the FAO Penman–Monteith equation, following the criteria in FAO-56 [26], by the equation (1):

$$ET_c = K_c * ET_0 \quad (1)$$

, where K_C changes by development stage as mentioned above.

Considering the crop cultivated in the study site (Citrus trees, specifically Orange), cultivated under open-field circumstances. The agricultural growth cycle was separated into four key stages [27]:

- Initial stage: Bud break to leaf emergence (30 days)
- Development stage: Vegetative development and blooming (40 days)
- Mid-season stage: Fruit development (70 days)
- Late season stage: Ripening to harvest (40 days)

Finally, this ET_C measurements were utilized both to determine crop water needs and as inputs for soil moisture modeling.

4.2.3 Soil Moisture Prediction Module

Once the daily crop evapotranspiration (ETc) is determined, the system continues to model soil moisture dynamics by incorporating climatic water demand, precipitation, and previous irrigation data. This stage permits a forward-looking prediction of how soil moisture levels will vary over the following days [28]. The forecast model takes into consideration

daily ETc values, effective rainfall data, and earlier irrigation events captured by the system. In its current form, the architecture integrates modular machine learning algorithms—including Random Forest (RF) [29], Gradient Boosting (XGBoost) [30], Long Short-Term Memory (LSTM) [31], and Gated Recurrent Unit (GRU) [32]—which will be evaluated and compared in future study rounds. These models capture temporal dependencies and non-linear interactions among climate and irrigation factors, the system's output is a short-term soil moisture prediction (1–3 days), represented as volumetric water content (VWC) and feeds the irrigation decision module, by shifting from static threshold systems to predictive modeling, this design allows irrigation scheduling to become more proactive, lowering the danger of moisture stress or over-irrigation and increasing overall water usage efficiency.

4.2.4 Irrigation Scheduling Module

Based on the projected soil moisture levels, the irrigation decision-making module calculates if and how much water should be administered via the drip system. In its first version, the module runs on a simple rule-based logic: for instance, if the estimated volumetric soil moisture content drops below a critical threshold (e.g., 50%), the system schedules a predefined irrigation dose, such as 3.5 mm/day, delivered via solenoid-controlled drip lines. This reasoning is customizable dependent on crop type and seasonal context. In future versions, the rule-based scheduler will be replaced with a reinforcement learning model—specifically, Deep Q-Learning—that will learn to optimize irrigation levels dynamically by interacting with the environment [33, 34]. This AI-driven strategy will examine numerous state factors, including expected ETc, previous soil moisture patterns, and short-term weather predictions, to select the most efficient irrigation action (ranging from 0 to 3.5 mm/day). The purpose of this module is to balance agricultural water demand with water conservation, allowing adaptive irrigation that adapts not just to current field circumstances but also to emerging climate trends and crop phenology.

4.2.5 Irrigation Execution & Feedback

The last step of the system comprises the execution of irrigation directives and the incorporation of a feedback loop to promote system transparency, flexibility, and learning. A Raspberry Pi 4 acts as the core processor unit, holding the decision-making logic and future AI models responsible for developing irrigation schedules. Upon establishing the necessary irrigation amount, the Raspberry Pi transfers control signals to solenoid valves, initiating the drip irrigation system to give accurate water dosages. (0 to 3.5 mm per day drip adjustment). Simultaneously, all sensor readings, ETc values, expected soil moisture levels, and irrigation choices are documented in real time. These data points are transmitted to a cloud-connected dashboard accessible by web or mobile interface, giving farmers and operators with live visualizations, alarms, and irrigation suggestions. This user interface bridges the gap between automated control and human supervision, enabling manual overrides if required and functioning as an instructional tool for developing digital literacy in traditional agricultural communities. Over time, this feedback loop will also facilitate continual training and improvement of AI models, boosting the accuracy and responsiveness of irrigation choices in varied climatic and agronomic conditions.

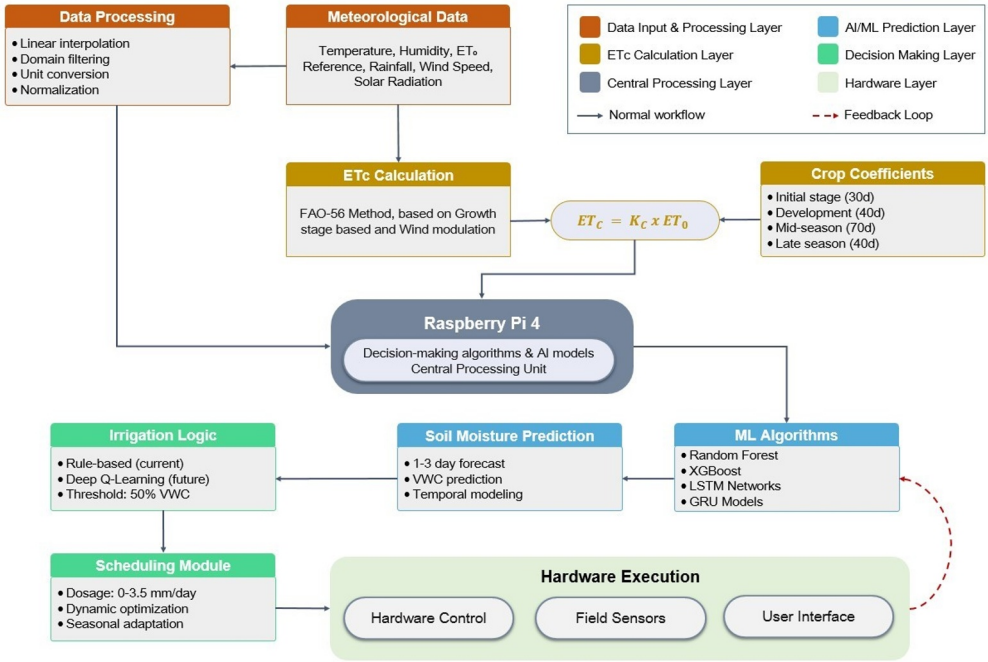

Fig. 2. Intelligent Drip Irrigation System Architecture

4.3 System Architecture Diagram

Figure 2 illustrates the proposed system architecture for an intelligent drip irrigation solution aimed to traditional open-field agriculture. The system is developed around a modular and scalable architecture that combines meteorological data, real-time sensor inputs, predictive modelling, and automated actuation. At the ground of this system comes a Raspberry Pi 4, which acts as the local processing unit responsible for executing all decision-making algorithms and controlling data flows between components.

The procedure starts with the use of meteorological data, involving daily reference evapotranspiration (ET_0), temperature, humidity, solar radiation, rainfall, and wind speed. These data are used to determine crop evapotranspiration (ETc) based on citrus crop-specific coefficients (Kc) equivalent to each growth stage. The ETc measurements are then input into the soil moisture prediction module, which predicts short-term volumetric water content using AI models such as Random Forest, LSTM, and XGBoost.

The expected soil moisture levels feed the irrigation scheduling module, which calculates the proper water dosage to deliver via drip irrigation. The Raspberry Pi directly controls the irrigation module, which contains solenoid valves, relays, and flow sensors to deliver and verify irrigation events.

In parallel, a collection of field-deployed sensors continually checks as soil moisture to give real-time data that improve model accuracy and allow continuous system feedback [28]. The system also contains a user interface module that gives real-time visualizations, irrigation suggestions, and alarms to farmers via a dashboard. This interface encouraging transparency and allows for manual overrides when required.

This architecture provides phased deployment in distant agricultural zones, is compatible with solar power, and enables edge-AI computing for resilience in low-connectivity conditions. It also establishes a fundamental layer upon which reinforcement learning algorithms may be eventually added to improve irrigation efforts over time.

5 Conclusion

This study gives key insights into integrating Intelligent Irrigation Systems (IIS) across Morocco's agricultural spaces, guiding sustainable water management practices. While protected agriculture exhibits superior technology readiness, traditional open-field farming emerges as the strategic priority. It dominates 85% of farmed land and 70% of irrigation water, delivering up to 70% savings through precision techniques.

Our multi-dimensional evaluation—involving infrastructure, technical, economic, environmental, and social criteria—demonstrates trade-offs between implementation obstacles and benefits. Traditional agriculture has the best water saving potential, with strong returns on investment through scaling reductions and yield benefits. Environmentally, it decreases runoff, promotes soil health, and reduces energy via solar automation. Socially, adoption requires farmer training to bridge digital literacy gaps, while its scale supports Morocco's digital agricultural backbone.

Ultimately, data confirms traditional farming as the cornerstone for sustainable irrigation transitions, maximizing national benefit. The proposed scalable architecture for intelligent drip irrigation solves infrastructure-digital gaps. By merging meteorological data, FAO-56 evapotranspiration modelling, and machine learning for soil moisture prediction, it enables data-driven adjustments in arid zones—advancing modernization and climate resilience. Future pilots in Souss-Massa could validate these projections.

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