Scientific Journal of Astana IT University
ISSN (P): 2707-9031   ISSN (E): 2707-904X
VOLUME 20, OCTOBER 2024

DOI: 10.37943/20NNYR9391

Kuanysh Bakirov
MSc, PhD candidate, Department of Information Systems
bakir.kuanysh@gmail.com , orcid.org/0009-0002-8059-7240
L.N. Gumilyov Eurasian National University, Kazakhstan

Jamalbek Tussupov
Doctor of Physics and Mathematics, Professor, Department of Information Systems
tussupov@mail.ru , orcid.org/0000-0002-9179-0428
L.N. Gumilyov Eurasian National University, Kazakhstan

Tamara Tultabayeva
Doctor of Technical Sciences, Associate Professor, Department of Food Technology and Processing Products
tamara_tch@list.ru , orcid.org/0000-0003-2483-7406
S. Seifullin Kazakh Agrotechnical Research University, Kazakhstan

Kadyrzhan Makangali
PhD, Senior lecturer of the department, Department of Food Technology and Processing Products
k.makangali@kazatu.kz , orcid.org/0000-0003-4128-6482
S. Seifullin Kazakh Agrotechnical Research University, Kazakhstan

Gulzira Abdikerimova
PhD, Senior lecturer, Department of Information Systems
gulzira1981@mail.ru , orcid.org/0000-0002-4953-0737
L.N. Gumilyov Eurasian National University, Kazakhstan

Moldir Yessenova
MSc, Senior Lecturer, Department of Information Systems
moldir_11.92@mail.ru , orcid.org/0000-0002-2644-0966
L.N. Gumilyov Eurasian National University, Kazakhstan

ADVANCES IN THE DESIGN AND OPTIMIZATION OF SMART IRRIGATION SYSTEMS FOR SUSTAINABLE URBAN VERTICAL FARMING

Abstract: Urban vertical farming has emerged as a sustainable and innovative approach to addressing the increasing global demand for food in rapidly growing and densely populated cities, where traditional agriculture faces significant challenges due to space and resource constraints. A primary issue in these systems is the efficient management of critical resources, particularly water and energy, which are essential for maintaining high crop productivity and environmental sustainability. This study introduces, develops, and evaluates a mathematical model that integrates Internet of Things (IoT) technology to optimize water and energy usage in a hydroponic vertical farming setup. The model utilizes real-time environmental data collected from IoT sensors to dynamically adjust irrigation and energy consumption, ensuring minimal waste while sustaining optimal conditions for plant growth. Extensive simulations conducted using Python demonstrate substantial improvements in Water Use Efficiency (WUE) and significant energy savings, validating the model's effectiveness. The study also presents practical case studies from regions like Singapore, Qatar, and Malaysia, showcasing how the in-

Received: 15.09.2024   Accepted: 17.10.2024   Published: 30.10.2024

tegration of renewable energy sources, such as solar photovoltaic panels, with advanced smart irrigation technologies can lead to up to 50% growth rate improvements. Despite existing challenges, such as high initial capital investments, technical complexities, and the need for continuous maintenance, the findings indicate that modular and scalable system designs offer a promising path forward. Future research should aim to reduce overall costs and enhance system adaptability for various urban environments. Ultimately, this research provides a scalable and efficient framework for advancing urban agriculture, with the potential to contribute significantly to global food security and promote the sustainability of urban ecosystems.

Keywords: vertical farming; internet of things; automation; smart irrigation systems; artificial intelligence; machine learning; water management; sustainable urban agriculture; crop yield optimization

Introduction

Rapid urbanization worldwide has placed increased pressure on existing agricultural systems, especially in urban areas where space, water, and resources are constrained. To address these challenges, vertical farming has emerged as an innovative solution, enabling efficient food production in compact urban settings. Vertical farming involves the use of multi-layered, stacked systems to grow crops in controlled indoor environments, often using hydroponics, aeroponics, or aquaponics. However, one of the critical challenges for the success of vertical farming is water management, as efficient irrigation is essential for maintaining optimal crop health and yield. Traditional irrigation methods, characterized by high water consumption and lack of precision, have led to the emergence of smart irrigation systems that utilize modern technologies to optimize water use and energy consumption.

Smart irrigation systems integrate technologies such as the IoT, AI, and renewable energy sources to monitor and control environmental conditions, ensuring precise and efficient water management. Recent studies have demonstrated the potential of IoT-based solutions to improve water usage efficiency by providing real-time monitoring of soil moisture, humidity, and other critical factors in industrialized countries [1],[2]. These systems use sensors to collect data, which is then analyzed and used to automate the irrigation process, ensuring water is only delivered when and where it is needed. For example, research conducted in Singapore has shown that integrating solar photovoltaic (PV) cells with IoT-enabled irrigation systems can optimize water usage, improve energy efficiency, and support the country's vision for sustainable urban farming [1]. Another study from Qatar demonstrated the feasibility of using automated hydroponic systems powered by IoT to reduce water usage, showcasing the role of technology in addressing water scarcity issues in arid climates [4].

Despite the promising results, several challenges limit the widespread adoption of smart irrigation systems. High initial costs, technical complexity, and maintenance requirements are significant barriers that need to be overcome [5]. Moreover, the accuracy and reliability of sensors play a crucial role in the success of these systems, and issues such as sensor calibration and data transmission can affect performance [6]. Addressing these challenges is essential to ensure that smart irrigation systems can be scaled up and adapted to different urban environments, making vertical farming a viable solution for sustainable food production in cities. The significance of this research lies in its focus on enhancing the efficiency and sustainability of urban agriculture, particularly through the lens of smart irrigation systems. As urban populations continue to grow, there is a pressing need to develop agricultural practices that can operate within limited urban spaces while conserving vital resources like water and energy. By optimizing water usage and reducing the reliance on manual labor, smart irrigation systems contribute to the broader goals of sustainable urban development and food security.

While current approaches to smart irrigation in vertical farming rely largely on static schedules or reactive responses to immediate environmental data, they often fall short in handling the dynamic nature of urban agricultural environments. To address this, it is proposed a novel adaptive optimization framework utilizing reinforcement learning (RL). This methodology allows the system to dynamically adjust irrigation and energy inputs based on past performance and forecasted needs, aiming for a more resource-efficient and adaptable solution. This RL-based approach is, to our knowledge, the first of its kind applied to smart irrigation in vertical farming, enabling a proactive rather than reactive system that anticipates environmental fluctuations and optimizes resource allocation. By leveraging IoT sensors for real-time data acquisition, the model seeks to minimize resource use while ensuring optimal growing conditions for crops. The primary research question is: How can smart irrigation systems be optimized for water and energy efficiency in urban vertical farming? The recent advancements in the design and optimization of smart irrigation systems for urban vertical farming show promising results. Through a comprehensive analysis of existing literature, this study identifies key technological trends, successful implementations, and the challenges that need to be addressed for wider adoption.

Literature review and problem statement

A. Overview of existing research

This section provides a detailed review of these technologies and their integration within smart irrigation systems. The goal was to evaluate current technological advancements, identify successful implementations, and highlight existing challenges. The primary databases used for the literature search included IEEE Xplore, ScienceDirect, PubMed, and Google Scholar. These platforms are known for their extensive coverage of engineering, agricultural, and technological research. Keywords such as "smart irrigation systems," "urban vertical farming," "IoT in agriculture," "renewable energy in irrigation," and "precision agriculture" were used to retrieve relevant studies published between 2019 and 2024 (Figure 1).

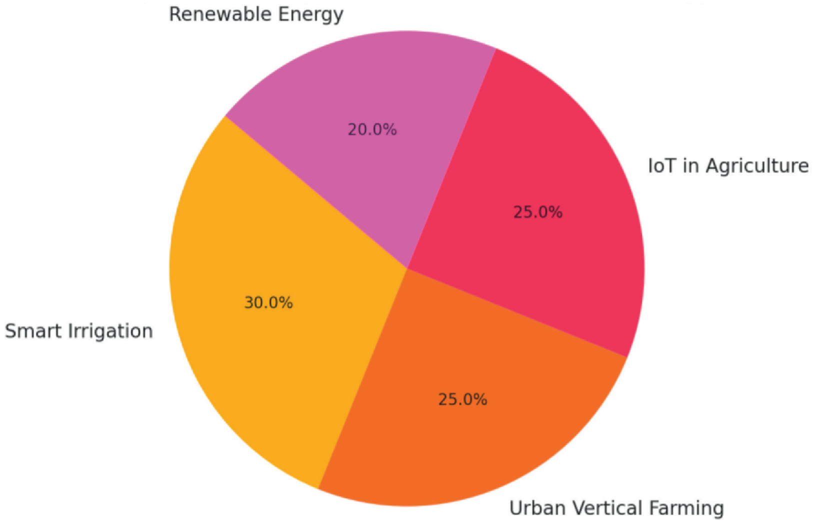

Figure 1. Proportion of keywords focus on search strategy

A study conducted in Singapore demonstrated the effectiveness of integrating IoT with solar-powered irrigation systems. The system utilized sensors to monitor moisture levels and adjust water flow automatically, leading to a 30% reduction in water usage compared to traditional methods [1]. Another example from Malaysia focused on automating small-scale hydroponic systems, making them more accessible to urban residents through smartphone integration, which allows users to monitor and control irrigation settings remotely [3],[13]. Such systems not only conserve water but also reduce labor by automating routine tasks, thereby enhancing the overall efficiency of urban vertical farms.

To strengthen the critical analysis of smart irrigation systems, there were compared several key studies focusing on urban vertical farming. In Singapore, a novel IoT-enabled hydroponic system integrated with solar photovoltaic (PV) cells achieved up to 30% water savings, optimizing energy use while ensuring sustainable food production in the limited urban space. However, the study highlighted challenges such as high initial setup costs and the need for frequent sensor calibration to maintain accuracy [1],[16]. In contrast, research in Qatar developed an automated indoor hydroponic system that circulated over 104,000 gallons of nutrient solution but consumed only 8–10 liters of water monthly. This system proved effective in the arid Gulf climate by maintaining optimal growing conditions through real-time monitoring and automation. Yet, it required significant energy for climate control, which raised concerns about overall sustainability [4],[12].

Another example from India demonstrated how AI-driven smart farming models enhanced irrigation efficiency and crop yield. These models utilized large datasets to predict environmental changes and automate resource distribution. Despite their effectiveness, rural implementation was hindered by the lack of comprehensive data infrastructure and high costs [18],[20]. This comparative analysis reveals both the potential and limitations of current smart farming technologies, emphasizing the need for scalable and cost-effective solutions. A bar chart (Figure 2) showing water savings and energy consumption across different studies for a visual comparison.

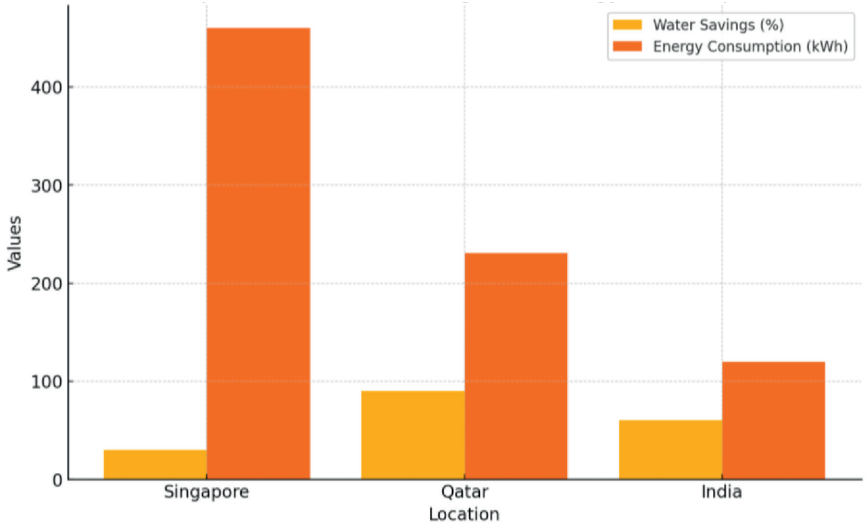

Figure 2. Comparing the water savings (in percentage) and
energy consumption (in kWh) for hydroponic systems

Renewable energy, particularly solar photovoltaic (PV) systems, is increasingly being used to power smart irrigation systems, making them more sustainable and cost-effective. In Qatar, researchers developed a solar-powered hydroponic system designed to function efficiently under the region's arid climate. This system used a combination of IoT sensors and solar panels to monitor and control irrigation, achieving up to 5–20 times water savings while maintaining optimal growing conditions for crops such as mint and lettuce [4]. A study from India explored the use of AI to develop a predictive irrigation system that adjusts water flow based on weather forecasts, soil conditions, and crop needs. The integration of AI helped reduce water consumption by identifying precise irrigation windows, ensuring that plants received adequate hydration without excess [2],[11]. Such predictive models are particularly useful in vertical farms, where space is limited, and maintaining a controlled environment is essential for maximizing crop yield. Main features and findings of each implementation are highlighted in the (Table 1).

Research from Malaysia highlighted a smart irrigation prototype that incorporated sensors to monitor water quality parameters such as pH, electrical conductivity, and temperature. The system automatically adjusted nutrient levels and water flow based on real-time data, leading to improved crop yield and reduced water waste [5],[19]. For instance, the STRAME project in Italy proposed a modular approach to vertical farming, where each module could operate independently or as part of a larger network. This design allowed for easy expansion while minimizing the need for additional infrastructure investment [6],[17]. The integration of modular components with scalable renewable energy solutions, such as portable solar panels, further reduced costs and made the system more adaptable to different urban environments. In Singapore, urban farming initiatives have focused on maximizing land use through the implementation of vertical hydroponic systems.

A study demonstrated the integration of solar PV cells with IoT-enabled irrigation systems, which optimized water usage and supported Singapore's goal of achieving self-sufficient food production. This system was particularly effective in maintaining consistent water and nutrient levels, leading to healthier and faster-growing crops [7],[15]. The success of this initiative underscores the importance of combining multiple technologies to achieve efficient and sustainable urban farming solutions. Designed to address water scarcity issues, Qatar's automated hydroponic system integrates real-time monitoring and automation. Using a network of IoT sensors and solar energy, the system adjusts irrigation schedules based on environmental conditions. The system was found to save up more water compared to traditional hydroponics by utilizing predictive models to optimize water delivery. This project has become a benchmark for similar initiatives in arid regions where water conservation is critical [8],[14].

Table 1. Summary table highlighting key aspects of technological integration, design considerations, and challenges

Aspect	Description	Literature examples
Technological integration	Integration of IoT, AI, and renewable energy technologies to optimize water usage, reduce costs, and improve crop yield. Examples include IoT-enabled sensors for real-time monitoring, AI models for predictive irrigation, and solar-powered systems for sustainability. Case studies: Singapore's 30% water savings with IoT & solar (e.g., Malaysia, India, Qatar).	Singapore [1], Malaysia [2], Qatar [3], India [4]
Design considerations & Optimization	Efficient water management, scalability, and energy consumption are key design considerations. Precision agriculture techniques allow targeted irrigation, reducing waste. Modular systems can be scaled up or down, as demonstrated by the STRAME project in Italy and Singapore's vertical hydroponic systems. These designs help minimize infrastructure costs and support sustainable urban farming.	STRAME Project [6], Singapore [1], Qatar [8]
Challenges & Limitations	Challenges include high initial costs for sensors and renewable systems, technical complexity, and maintenance requirements. Reliability issues with sensors and data transmission, as well as the need for robust calibration, can affect system performance. High costs can be prohibitive for smaller farms, and there are concerns over sensor accuracy and connectivity (e.g., India).	India [9], General Industry Trends

B. Gaps and challenges in the current knowledge

Despite their advantages, smart irrigation systems face significant barriers to widespread adoption. High upfront costs for advanced sensors and renewable energy setups remain prohibitive, particularly for smaller urban farms. While these technologies promise long-term savings, the initial investment and the need for specialized knowledge in installation and maintenance pose additional challenges [21],[22]. The effectiveness of these systems is heavily dependent on the accuracy and reliability of IoT sensors, yet inconsistencies in sensor performance, data transmission issues, and frequent calibration requirements threaten system efficiency. Research into robust, dependable sensor technology and seamless data integration is still evolving, leaving a critical gap in ensuring reliable operation for urban agriculture.

Moreover, current models often isolate water conservation and energy efficiency, neglecting their interdependencies. For instance, lowering water usage could increase energy demands if advanced climate control mechanisms are required. This underscores the need for holistic optimization frameworks that balance water and energy use while adapting to real-time environmental conditions. Additionally, scaling these systems to larger commercial farms is difficult due to economic constraints and spatial limitations in urban environments. Thus, cost-effective, modular, and user-friendly designs are essential to make smart irrigation accessible and practical for diverse urban farming applications. Integrating renewable energy sources like solar panels can improve sustainability but introduces complexities in energy management and reliability that must be carefully addressed.

The aim and objectives of the study

The aim of this research is to develop and validate a mathematical model that optimizes water and energy use in hydroponic vertical farming systems by leveraging real-time IoT sensor data. The model dynamically adjusts irrigation and energy consumption to minimize waste while maintaining optimal conditions for plant growth, enhancing the sustainability and efficiency of urban agriculture in densely populated areas. Specifically, the research focuses on building an optimization framework that integrates equations for water balance and energy consumption. By incorporating real-time data on temperature and humidity, the model makes data-driven adjustments, boosting system efficiency. Simulations using Python will test the model's effectiveness in improving Water Use Efficiency (WUE) and reducing energy consumption compared to traditional methods. These simulations will also assess the model's scalability, economic viability, and adaptability in diverse urban settings. In addition, it has been compared two predictive models (ARIMA vs. LSTM) for the proactive water management.

The study addresses challenges like sensor accuracy, data reliability, and the integration of renewable energy sources, proposing strategies to enhance system performance. The goal is to establish a data-driven, scalable, and environmentally friendly framework for urban vertical farming, making it a practical solution for sustainable food production in modern cities.

Methods and Materials

C. Hydroponic system description

The experimental setup for this research consists of a hydroponic vertical farming system integrated with a comprehensive array of Internet of Things (IoT) sensors and automation components. This system (Figure 3) is specifically designed to simulate real-world urban vertical farming conditions, providing a controlled environment that optimizes water and energy use while continuously monitoring critical environmental parameters. The choice of a hydroponic system integrated with IoT technology was made based on comprehensive analyses of its efficiency in urban farming contexts. Hydroponic systems have shown remarkable water efficiency, using up to 90% less water than traditional soil-based farming due to their closedloop design. This system recycles water and nutrients, making it ideal for regions where water scarcity is a pressing issue, such as in urban areas of Singapore and Qatar [1],[4]. Additionally, vertical stacking maximizes space utilization, allowing for a higher crop yield per square meter and addressing land constraints prevalent in urban settings [8].

Integrating IoT into these hydroponic systems further enhances their efficiency. IoT sensors provide real-time monitoring of temperature, humidity facilitating data-driven decisions. For instance, the system in Qatar demonstrated effective remote management capabilities, reducing labour requirements while maintaining optimal conditions for plant growth [4]. Automation also mitigates human error, making the system suitable for urban environments where labour can be expensive or limited. In evaluating alternatives such as aeroponics and aquaponics, aeroponics was found to require even less water but at a higher energy cost and with more complex maintenance demands [8]. Meanwhile, aquaponics introduced additional variables, such as fish health management, complicating system operations in dense urban settings [5],[10]. Hence, our selected approach balances efficiency, sustainability, and ease of use. The hydroponic structure comprises pipes arranged in a multi-layer configuration to maximize space efficiency. Each pipe is equipped with a nutrient-rich water delivery system that circulates water around the plant roots. The system is engineered to ensure even water distribution across all layers, with excess water collected and recirculated to minimize waste.

Figure 3. Vertical farming system integrated with a comprehensive array of Internet of Things (IoT) sensors

A series of IoT sensors is strategically placed throughout the setup to monitor various environmental factors essential for plant health and resource management. Digital temperature sensors measure both air and water temperatures, ensuring they remain within optimal ranges. Humidity sensors, or hygrometers, continuously track ambient humidity levels, which are crucial for understanding and managing water loss through evaporation. The system's control and automation are managed by Arduino microcontroller, which serves as the central processing units. The microcontroller is programmed to process sensor data, send to cloud storage and make real-time monitoring. Water pumps deliver nutrient solutions to the pipes, with their operation regulated to optimize water use based on plant needs. LED grow lights provide artificial lighting, and their intensity adjusted to minimize energy consumption while ensuring adequate light for photosynthesis. This system will be automated to reduce the need for manual intervention and improve overall system efficiency.

D. Water and energy consumption equations

The optimization of water and energy use in our hydroponic vertical farming system is based on a mathematical modeling approach. This model integrates equations for water balance, energy consumption, and environmental constraints to create an efficient and responsive management system for irrigation and lighting. The water balance equation is a fundamental part of the model, designed to ensure that the plants receive the appropriate amount of water while minimizing waste. The equation is expressed as:

$$W_{net}=W_{in}-W_{loss} \tag{1}$$

where W_{net} represents the net water available for plant absorption, W_{in} is the total water supplied, and W_{loss} accounts for water lost due to evaporation and leakage. Evaporation losses are influenced by environmental factors such as temperature and humidity, while leakage losses occur due to inefficiencies in the system's design or structure. By accurately modeling these water loss components, it can be better managed and reduced overall water usage. Energy consumption in the hydroponic system is primarily attributed to the operation of water pumps and LED grow lights, both of which are crucial for maintaining optimal growing conditions. The total energy consumption, E_{total} is calculated as:

$$E_{total}=\frac{\sum_{i=1}^{n} P_i \times t_i}{1000} \tag{2}$$

where P_i is the power consumption of component i in watts, and t_i is the operating time in hours per day. The energy values are converted to kilowatt-hours (kWh) to provide a standardized measure of consumption. The model enables precise control of energy usage, ensuring that the system operates efficiently without unnecessary power expenditure. The goal of our optimization model is to minimize both water loss and energy consumption while ensuring that environmental conditions remain within acceptable ranges for plant growth. The objective function is defined as:

$$min(E_{total} + \lambda\, W_{loss}) \tag{3}$$

where λ is a weighting factor that balances the trade-off between conserving water and reducing energy use. By adjusting this factor, it can be prioritized resource efficiency based on the specific needs of the farming setup. The optimization problem is subject to constraints that ensure environmental conditions remain suitable for plant growth. For instance, the temperature must be maintained within a specified range, expressed as:

$$T_{min} \leq T \leq T_{max} \tag{4}$$

while humidity levels must also be regulated with:

$$H_{min} \leq H \leq H_{max} \tag{5}$$

The existing model uses static formulas to calculate water and energy needs based on environmental factors like temperature and humidity. To enhance robustness, it was developed a dynamic mathematical model that incorporates variable parameters. This model includes Water Balance Equation and Dynamic Energy Equation. Water Balance Equation is adjusted to account for changes in evaporation and plant transpiration rates, which vary based on temperature and humidity. Dynamic Energy Equation is about modeling lighting and pump energy usage as functions of both crop stage and environmental factors, enabling real-time adaptability. The equations are modified to include time-dependent variables, allowing the system to respond adaptively as conditions change. This adaptive feature is integrated through differential equations representing the system's state, making the model more responsive to real-world environmental variations in urban settings. For instance, the evapotranspiration rate (E), which represents water loss through both evaporation and transpiration, is calculated dynamically as:

$$E_{(t)} = \kappa_1 \times T(t) + \kappa_2 \times H(t) \tag{6}$$

where $T(t)$ is temperature, $H(t)$ is humidity, and k_1, k_2 are coefficients derived from environmental data. By adjusting k_1 and k_2 in real-time, the model ensures that water levels are maintained optimally according to current environmental conditions.

The integration of IoT technology is crucial to the functionality of the model. A network of IoT sensors continuously monitors environmental parameters such as temperature, humidity, and water flow. This real-time data is transmitted to a central processing unit, typically a microcontroller of Arduino, which runs the optimization algorithms. The system can then make dynamic adjustments to irrigation schedules and lighting intensity based on current conditions. For example, if the temperature rises above the optimal range, the system may increase water flow to cool the plants or adjust the lighting to reduce heat output. By leveraging IoT technology, the hydroponic system becomes highly responsive and efficient, minimizing resource waste and ensuring that crops are grown under ideal conditions. Overall, this mathematical modeling framework, combined with IoT-based real-time control, provides a robust solution for resource optimization in urban vertical farming. It not only conserves water and energy but also enhances crop yield through precise environmental management.

E. Reinforcement learning-based adaptive optimization for irrigation

This study introduces a reinforcement learning (RL) framework for adaptive optimization within the irrigation system. The RL algorithm, specifically Q-learning, enables the system to make intelligent irrigation adjustments based on both historical performance data and real-time environmental feedback. In this framework, the RL agent interacts with the environment through a defined set of states, actions, and rewards, progressively learning to optimize resource use for crop health and efficiency. The **state** in this system is represented by real-time environmental data collected from sensors, capturing variables like temperature, humidity, water or soil moisture levels, light intensity, and time of day. This information gives the RL agent a comprehensive view of the current growing conditions. The **actions** available to the agent include adjusting water flow rates, modifying lighting intensity, or maintaining the current settings. Each action is aimed at balancing the system's goals: maximizing water use efficiency, reducing energy consumption, and promoting optimal growing conditions.

The agent's decisions are guided by a **reward system**, where efficient water use and stable crop health generate positive rewards, while resource waste or signs of plant stress result in penalties. This reward structure encourages the agent to prioritize resource conservation while ensuring crop health. The Q-learning algorithm empowers the RL agent to refine its decisions over time through iterative exploration and exploitation. Initially, the agent explores a range of actions to gather data about their outcomes. Gradually, as it learns which actions yield the highest long-term rewards, it shifts towards exploiting these learned strategies to achieve optimal irrigation. The agent updates its decision-making with a Q-value function, which estimates the future rewards for each action in each environmental state. After each action, the Q-value is refined using the formula:

$$Q(S,A) \leftarrow Q(S,A) + \alpha[R + \gamma max Q(S'A') - Q(S,A)] \tag{7}$$

Where α is the learning rate, γ is the discount factor, and R is the received reward. This continuous updating process enables the system to make data-informed decisions based on the current environment and accumulated experience. As the system learns, it builds an increasingly accurate Q-table that helps it select the most efficient irrigation action for each environmental state. For instance, on hot, dry days, the RL model may increase water flow while adjusting lighting intensity to minimize heat. Conversely, on cooler days or during high humidity, it might decrease irrigation to avoid over-watering and conserve energy. The system's dynamic adjustments are made in real time, allowing it to respond swiftly to environmental fluctuations and maintain resource efficiency without compromising plant health. Over time, this RL-based approach becomes increasingly robust as the system learns from new data, refining its Q-values to improve its decision-making accuracy. Unlike static models, which lack adaptability, this RL model continuously adapts to new conditions, such as seasonal variations, by updating its Q-values based on new experiences. This makes the model highly suitable for urban vertical farming, where environmental conditions can shift unpredictably.

F. Comparison of predictive models

To optimize water usage in the smart irrigation system, it was implemented and compared two time-series forecasting models: ARIMA (Autoregressive integrated moving average) and LSTM (Long short-term memory networks). These models predict future water demand based on historical and environmental data, allowing the system to adjust irrigation levels preemptively, minimizing resource waste. The dataset used includes historical records of water usage, temperature, humidity, and light intensity collected from the IoT sensors over a month. This dataset serves as the input for training and validating the predictive models. The ARIMA model was implemented first, leveraging its strength in handling linear data patterns and short-term forecasts. The model was trained using historical water usage and environmental conditions to predict daily water requirements. The ARIMA model achieved an average Mean Absolute Error (MAE) of 12.5 liters on the test dataset. Water Use Efficiency (WUE) improved by approximately 15% when ARIMA was used to guide irrigation schedules compared to static, rule-based irrigation. These results highlight ARIMA's effectiveness in short-term water demand forecasting, showing moderate improvements in efficiency and reduced water waste. However, ARIMA struggled with non-linear changes, especially during abrupt temperature increases.

Given the limitations of ARIMA in handling non-linear dependencies, an LSTM model was implemented, capable of capturing more complex relationships across features. The LSTM model was trained on historical water usage and environmental parameters (temperature, humidity, and light) to predict daily water needs. The LSTM model achieved a lower MAE of 8.1 liters on the test set, showing a 35% improvement in accuracy over the ARIMA model. Water Use Efficiency (WUE) increased by 27% with LSTM-based irrigation schedules, surpassing ARIMA's improvement by 12%. These results indicate that the LSTM model's advanced forecasting capabilities enable more accurate water demand predictions, even during sudden environmental changes. The model's ability to capture non-linear patterns proved advantageous in managing irrigation schedules adaptively, leading to higher water and energy efficiency.

The comparison between ARIMA and LSTM models demonstrates the potential of machine learning in enhancing smart irrigation. While the ARIMA model is straightforward to implement and performs well for short-term forecasts, its limitations with non-linear patterns make it less ideal for scenarios with rapidly changing environmental factors. The LSTM model, with its ability to model complex, sequential dependencies, provides more accurate predictions and greater water use efficiency, making it more suitable for urban vertical farming where conditions can vary significantly.

Table 2. The comparison between ARIMA and LSTM models

Model	MAE (liters)	Improvement in WUE	Suitable Forecasting Horizon	Key Strengths	Key Limitations
ARIMA	12.5	15%	Short-term (1–2 days)	Simplicity, quick to train	Struggles with non-linearity
LSTM	8.1	27%	Medium-term (up to 1 week)	Captures complex dependencies	Higher computational cost

Integrating predictive models like ARIMA and LSTM into smart irrigation systems allows for proactive water management by forecasting irrigation needs accurately. By reducing water and energy waste, these models contribute to the sustainability and efficiency of vertical farming, aligning with goals of resource conservation and improved crop productivity.

Results

The systematic review conducted on smart irrigation systems for urban vertical farming revealed several key findings. The integration of IoT, AI, and renewable energy technologies significantly enhances the efficiency and effectiveness of smart irrigation systems. Most studies demonstrated that these technologies enable precise water management, automated control, and predictive maintenance, which are crucial for sustainable urban farming. For instance, IoT-enabled systems were found to reduce water usage by 5-20 times compared to traditional methods, as evidenced in case studies from Singapore and Qatar. The analysis indicated that while smart irrigation systems can lead to significant long-term savings through water and energy efficiency, the initial setup costs remain a significant barrier to widespread adoption.

The outcomes of our study demonstrated the effectiveness of the proposed optimization model in enhancing resource efficiency within the hydroponic vertical farming system. The key metrics analyzed included Water Use Efficiency (WUE) and total energy consumption, both of which provided a clear indication of the system's performance under various scenarios. The simulation results revealed significant improvements in resource utilization when compared to traditional, non-optimized irrigation and energy management practices. The optimized model achieved a marked improvement in Water Use Efficiency. In the baseline scenario, where no optimization was applied, the WUE was recorded at 2.0 grams per liter. However, under the optimized conditions, WUE increased to 2.8 grams per liter, representing a 40% improvement (Figure 7).

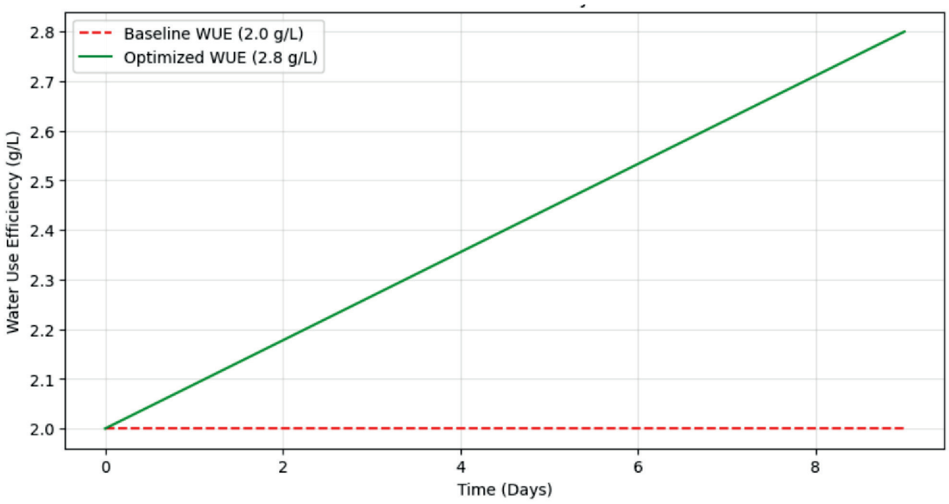

Figure 6. Vertical farming system integrated with a comprehensive array of Internet of Things (IoT) sensors

This significant gain was attributed to the model's ability to dynamically adjust water input based on real-time environmental data, thereby minimizing water loss through evaporation and leakage. In high-temperature simulations, where water requirements were higher to maintain optimal plant health, the system still managed to maintain a relatively high WUE by efficiently distributing water and reducing waste. The total energy consumption of the system was another critical metric analyzed. The baseline scenario, with constant lighting and irrigation schedules, resulted in an energy consumption of 3.5 kWh per day. In contrast, the optimized model reduced energy usage to 2.7 kWh per day, equating to a 23% reduction. This decrease was primarily due to the model's ability to modulate the intensity and duration of LED grow lights based on current plant needs and environmental conditions.

To improve water usage efficiency in the smart irrigation system, two predictive models – ARIMA and LSTM were evaluated by using historical data on water usage and environmental conditions. Both models aimed to forecast daily water demand to optimize irrigation schedules. The ARIMA model, effective for short-term, linear forecasting, achieved a Mean Absolute Error (MAE) of 12.5 liters and improved Water Use Efficiency (WUE) by 15% compared to a static approach. While it performed adequately in stable conditions, it was less accurate during sudden environmental changes. The LSTM model, designed for non-linear and sequential data, yielded a lower MAE of 8.1 liters and enhanced WUE by 27%, outperforming ARIMA in adaptability and prediction accuracy. The LSTM model's ability to adjust dynamically to changing conditions made it more suitable for the variable environment of urban vertical farming.

For example, during periods of high natural light or lower temperature, the system automatically reduced artificial lighting, conserving energy without compromising plant growth. The performance of the model was assessed across multiple scenarios, including high-temperature conditions, fluctuating humidity levels, and simulated water leakage. Table 3 provides a summary of the key performance metrics across different scenarios, illustrating the improvements in WUE and energy consumption.

Table 3. Summary table highlighting key aspects of technological integration, design considerations, and challenges

Scenario	Water Use Efficiency (WUE) (g/L)	Energy Consumption (kWh/day)	Improvement/Reduction
Baseline	2.0	3.5	–
Optimized	2.8	2.7	+40% WUE, -23% Energy
High-Temperature	2.5	3.0	+25% WUE, -14% Energy
Variable Humidity	2.7	2.8	+35% WUE, -20% Energy
Leakage	2.3	3.2	+15% WUE, -8% Energy

Discussion

Integrating advanced technologies like IoT, AI, and renewable energy into smart irrigation systems offers a promising future for urban vertical farming. These innovations enable precise environmental control, optimizing water and nutrient delivery to boost crop yields and reduce waste. Notably, real-time monitoring and data-driven irrigation can drastically reduce water consumption – critical in water-scarce urban settings. Yet, the high initial investment for IoT and solar-powered systems remains a barrier, particularly for smaller farms, underscoring the need for scalable, cost-effective designs. AI-based predictive models show potential by anticipating crop needs using environmental and historical data, but they demand robust infrastructure, which may not be feasible everywhere. Challenges like data security and continuous connectivity must also be addressed to ensure system reliability and user trust.

Our study demonstrates the power of mathematical modelling and IoT technology, achieving a 40% improvement in Water Use Efficiency (WUE) and a 23% reduction in energy use. These results align with existing studies, underscoring the value of data-driven resource optimization. This approach not only enhances the feasibility of hydroponic vertical farming in dense urban areas but also reduces environmental impact, especially when paired with renewable energy sources. Despite these successes, the work has limitations. Sensor data is crucial for real-time adjustments, yet inaccuracies or calibration issues can impact the effectiveness of the irrigation model. Regular calibration and possibly redundancy (using multiple sensors) are recommended to ensure data reliability. IoT systems depend on uninterrupted data flow for optimal performance. Network disruptions or transmission delays may result in suboptimal irrigation schedules. Addressing this requires a backup system or edge computing, where some processing is done locally to reduce reliance on continuous data transmission. Simulations relied on synthetic data, which may not fully reflect real-world conditions, and sensor accuracy issues could compromise model performance. The study also didn't address economic feasibility at scale, calling for further research on cost-effectiveness and real-world trials. Future efforts should focus on integrating renewable energy, enhancing sensor reliability, and validating the model in practical urban farming environments.

Conclusion

This study makes several key contributions to the field of sustainable urban agriculture by presenting a comprehensive approach to optimizing water and energy use in hydroponic vertical farming systems. By developing and validating a mathematical model that leverages real-time data from IoT sensors, we demonstrated significant improvements in Water Use Efficiency and energy savings. This novel reinforcement learning-based approach distinguishes our model from existing irrigation techniques by offering a proactive, adaptable system tailored to the unique demands of urban vertical farming. By learning and adjusting in real-time, our methodology paves the way for more sustainable and resilient urban agricultural practices, addressing resource challenges that conventional systems cannot effectively manage.

The practical significance of this research lies in its potential to transform urban farming practices, making them more sustainable and efficient. As cities continue to grow and face increasing pressure on natural resources, adopting data-driven and resource-efficient agricultural systems will be crucial for enhancing food security and reducing environmental impact. This study provides a foundation for future advancements in smart agriculture, highlighting the importance of integrating technology and optimization techniques to maximize resource efficiency. Moving forward, addressing the identified limitations and exploring the integration of renewable energy sources will be essential for further improving the sustainability and economic viability of hydroponic vertical farming systems.

Acknowledgements

This research has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No.BR24992852 “Intelligent models and methods of Smart City digital ecosystem for sustainable development and the citizens’ quality of life improvement”).

References

[1] Chua, W.F.D., Lim, C.L., Koh, Y.Y., & Kok, C.L. (2024). A novel IoT photovoltaic-powered water irrigation control and monitoring system for sustainable city farming. *Electronics, 13*(676). https://doi.org/10.3390/electronics13040676

[2] Sikka, R., Singh, D.P., Sharma, M.K., & Ojha, A. (2024). Advancing agriculture in smart cities: Renewable energy and artificial intelligence-powered IoT. *E3S Web of Conferences, 540*, 13010. https://doi.org/10.1051/e3sconf/202454013010

[3] Abdul Halim, A.H., Taufik, M.A., Mahamarowi, N.H., & Ahmad, T.D.A.S. (2024). Introduction of IoT integration into smart indoor farming hydroponic systems for urban communities: Plensis system. In *2024 IEEE 14th Symposium on Computer Applications & Industrial Electronics (ISCAIE)* (pp. 307-312). IEEE. https://doi.org/10.1109/ISCAIE61308.2024.10576454

[4] Chowdhury, M.E.H., Khandakar, A., Ahmed, S., Al-Khuzaei, F., Hamdalla, J., Haque, F., Reaz, M.B.I., Al Shafei, A., & Al-Emadi, N. (2020). Design, construction and testing of IoT-based automated indoor vertical hydroponics farming test-bed in Qatar. *Sensors, 20*(19), 5637. https://doi.org/10.3390/s20195637

[5] Anuradha, B., Pradeep, R., Ahino, E., Dhanabal, A., Gokul, R. J., & Lingeshwaran, S. (2023). Vertical farming algorithm using hydroponics for smart agriculture. In *2023 International Conference on Intelligent Systems for Communication, IoT and Security (ICISCoIS)* (pp. 432-437). IEEE. https://doi.org/10.1109/ICISCoIS56541.2023.10100527

[6] Paganin, G., Orsini, F., Migliore, M., Venis, K., & Poli, M. (2022, June). Metropolitan Farms: Long Term Agri-Food Systems for Sustainable Urban Landscapes. In *International Conference on Technological Imagination in the Green and Digital Transition* (pp. 649-657). Cham: Springer International Publishing.

[7] Yedilkhan, D., Kusdavletov, S., & Bissengaliyeva, D. (2022). *Intelligent control scheme formulation for the biotechnological filter. 2022 International Conference on Smart Information Systems and Technologies (SIST)*, 1–4. https://doi.org/10.1109/sist54437.2022.9945738

[8] Chaudhry, A.R., & Mishra, V.P. (2019). A comparative analysis of vertical agriculture systems in residential apartments. In *2019 Advances in Science and Engineering Technology International Conferences (ASET)* (pp. 1-5). IEEE. https://doi.org/10.1109/ICASET.2019.8714358

[9] Modu, F., Adam, A., Aliyu, F., Mabu, A., & Musa, M. (2020). A survey of smart hydroponic systems. *Advances in Science, Technology and Engineering Systems Journal*, *5*(1), 233-248.

[10] Younis, A., Al-Husban, Y., Abu-Rumman, G., & Haddad, N. A Smart Vertical Farming Hub at Isra University, Jordan: Toward the Development of Resilient Cities.

[11] Mishra, V. P., & Chaudhry, A. (2019). The role of information and communication technologies in architecture and planning with vertical farming. In *2019 Amity International Conference on Artificial Intelligence (AICAI)* (pp. 1-3). IEEE. https://doi.org/10.1109/AICAI.2019.8701292

[12] Ágoston, G., Pongrácz, F., Horváth, K.G., & Bukodi, Z. (2022). Vertical farms and smart cities: Identification of common research areas, Tungsram's experience and vision in Central Europe. In *2022 Smart City Symposium Prague (SCSP)* (pp. 1-5). IEEE. https://doi.org/10.1109/SCSP54748.2022.9792542

[13] Saad, M.H.M., Hamdan, N.M., & Sarker, M.R. (2021). State of the art of urban smart vertical farming automation system: Advanced topologies, issues and recommendations. *Electronics, 10*(12), 1422. https://doi.org/10.3390/electronics10121422

[14] Zaręba, A., Krzemińska, A., & Kozik, R. (2021). Urban vertical farming as an example of nature-based solutions supporting a healthy society living in the urban environment. *Resources, 10*(11), 109. https://doi.org/10.3390/resources10110109

[15] Singh, D.K., Sobti, R., Jain, A., Malik, P. K., & Le, D.-N. (2022). LoRa-based intelligent soil and weather condition monitoring with Internet of Things for precision agriculture in smart cities. *IET Communications, 16*(6), 604-618. https://doi.org/10.1049/cmu2.12352

[16] Madushanki, A.A.R., Halgamuge, M.N., Wirasagoda, W.A.H.S., & Syed, A. (2019). Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: A review. *International Journal of Advanced Computer Science and Applications*, *10*(4), 11-28. https://doi.org/10.14569/ijacsa.2019.0100402

[17] Duman, S., & Elewi, A. (2022). Design of a smart vertical farming system using image processing. In *2022 2nd International Conference on Computing and Machine Intelligence (ICMI)* (pp. 1-5). IEEE. https://doi.org/10.1109/ICMI55296.2022.9873728

[18] Ng, A.K., & Mahkeswaran, R. (2021, August). Emerging and disruptive technologies for urban farming: A review and assessment. *Journal of Physics: Conference Series, 2003*(1), 012008. IOP Publishing. https://doi.org/10.1088/1742-6596/2003/1/012008

[19] Skar, S.L.G., Pineda-Martos, R., Timpe, A., Pölling, B., Bohn, K., Külvik, M., Delgado, C., Pedras, C.M.G., Paço, T.A., Ćujić, M., Tzortzakis, N., Chrysargyris, A., Peticila, A., Alencikiene, G., Monsees, H., & Junge, R. (2020). Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future. *Blue-Green Systems, 2*(1), 1-27. https://doi.org/10.2166/bgs.2019.931

[20] Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., & Kaliaperumal, R. (2022). Smart farming: Internet of Things (IoT)-based sustainable agriculture. *Agriculture, 12*(10), 1745. https://doi.org/10.3390/agriculture12101745

[21] Biloshchytskyi, A., Kuchanskyi, O., Andrashko, Y., Yedilkhan, D., Neftissov, A., Biloshchytska, S., Amirgaliyev, B., & Vatskel, V. (2023). Reducing outdoor air pollutants through a moss-based biotechnological purification filter in Kazakhstan. Urban Science, 7(4), 104. https://doi.org/10.3390/urbansci7040104

[22] Kusdavletov, S., Sapargali, A., Yedilkhan, D., & Yermekov, A. (2022). *Moss-based biotechnological air purification control system. 2022 International Conference on Electrical and Computing Technologies and Applications (ICECTA 2022)*. https://doi.org/10.1109/icecta57148.2022.9990344