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Automated Vertical Gardening System Using IoT-Enabled Smart Irrigation for Sustainable Urban Green Spaces

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Abstract: Urban development has caused significant vegetation loss, leading to air pollution, increased temperatures, and ecological imbalance. Vertical gardening addresses space constraints in cities, but manual maintenance is inefficient and costly. This work presents an IoT-based intelligent vertical garden system using a NodeMCU microcontroller and environmental sensors to continuously monitor plant conditions and automatically control irrigation. A 30-day field study showed 44% water savings, 90% cost reduction, and 98.7% system reliability, making it suitable for residential, commercial, and public spaces.

The system is supported by an Android application that enables remote monitoring and control. Users can view real-time soil moisture, temperature, humidity, and pH values, switch between automatic and manual modes, adjust thresholds, and initiate irrigation instantly. The app also provides alerts for low moisture, system failure, or abnormal behavior, ensuring timely intervention. This integrated hardware-software approach makes automated vertical gardening practical for homes, hostels, and small institutions.

Keywords: Vertical Gardens, IoT Technology, Irrigation Automation, NodeMCU, Soil Monitoring, Sustainable Cities, Environmental Solutions.

I. INTRODUCTION

Growing cities worldwide experience progressive vegetation loss as construction and infrastructure expansion accelerate. This transformation carries serious consequences: air quality deteriorates due to reduced plant coverage, ground-level temperatures increase noticeably, and plant and animal species lose suitable habitats. Urban environmental challenges are particularly acute in developing nations experiencing rapid unplanned urbanization. Vertical gardening integrates vegetation into building structures through wall-based systems rather than requiring ground area. Benefits are substantial and measurable. Plants absorb carbon dioxide and release oxygen through photosynthesis, directly improving air composition. Vegetation dampens noise from traffic providing acoustic benefits. Building walls with plant coverage act as insulation, reducing cooling requirements during hot seasons. Visible greenery accessible to urban residents contributes positively to mental health and strengthens human-nature connections.

Implementing vertical gardens faces significant practical obstacles primarily related to irrigation management. Workers accessing elevated areas face safety risks and operational complexity. Watering often becomes irregular due to inconsistent workforce availability, resulting in either plant stress from insufficient water or damage from excessive water application. Plant health suffers dramatically: insufficient water visibly damages plants within two to three days while excessive water creates conditions promoting root decay and fungal growth. Maintaining dedicated personnel costs eighteen to twenty-four thousand rupees annually per installation, making large-scale municipal implementation economically infeasible.

Advances in micro-controller technology and sensor development offer practical pathways addressing these challenges. This research presents a complete system designed specifically for vertical gardens incorporating multiple environmental sensors and intelligent decision-making. The system operates without human involvement after initial setup, scales effectively across multiple locations, and maintains low equipment and operational costs.

II. LITERATURE REVIEW

Lopez and colleagues investigated the application of ESP32 microcontrollers combined with ultrasonic sensors for detecting water levels within vertical garden reservoirs. Their system implemented automated water atomization to distribute moisture more evenly across vertical surfaces. While their approach proved successful for measuring reservoir levels and controlling pump activation, it relied primarily on bulk water availability sensing rather than direct soil-level moisture measurement.

Testing in laboratory conditions showed 87% system efficiency, demonstrating the fundamental feasibility of automated approaches. However, their system did not address individual plant requirements or account for variations in soil moisture across different locations within the same installation. [1]

Chemudugunta et al. developed an IoT-based sprinkler control framework utilizing NodeMCU boards combined with soil moisture and temperature monitoring. Their system allowed remote operation through internet connectivity, providing users access to system status from any location via cloud-based dashboards. The implementation achieved 35% reduction in water consumption when compared to fixed-schedule timer-based systems. However, their application targeted traditional horizontal garden layouts and farm structures where sprinkler-based distribution works effectively. The applicability to vertical installations where gravity-driven distribution patterns and targeted root-zone watering prove essential remains unclear. Their study also lacked comprehensive analysis of maintenance requirements and cost implications. This paper focuses on automizing the sprinkler system in farm and gardens the mail focuses in this paper is to perform automation of water using Node MCU it also focuses on parameter like moisture and temperature. It is applicable large spaces of gardening and planting. The paper shows the execution of IOT for controlling the water pump through the internet as well [2].

AN IoT-Based Automated Watering System for Plants Using Integrated Fuzzy Logic and Telegram Bot (2024), Ary Shiddiqi et al, 2024. This paper showcases the execution of telegram bot which use for water automation. in this the implementation of fuzzy logic is use for taking decision. The telegram bot control soil moisture, temperature, and light sensor data for automize the plant watering system. Here the multiple parameters consider for taking watering action. The action totally determine with fuzzy logic implementations. Research by Shiddiqi and team integrated fuzzy logic computational models with Telegram messaging platform access for plant watering automation. Their system considered multiple environmental parameters including soil moisture, ambient temperature, and light intensity simultaneously. A fuzzy inference engine processed these inputs according to expert-defined rules to determine optimal irrigation timing, adapting dynamically to changing conditions. While this approach provides sophisticated decision-making capabilities superior to simple threshold logic, the extensive tuning requirements and reliance on external communication platforms introduce complexity that may limit adoption by non-specialist users. The computational overhead required for fuzzy logic operations may strain microcontroller processing capacity in large-scale deployments.[3]

Solar-Powered IoT-Based Advanced Smart Irrigation **System** S. Gangadhara T Venkadesh et al. (2025). The paper proposed mechanism which controlled the water automation based on solar system. It performs multilayer soil moisture analysis worked out. The analysis carried out with the integration of cloud monitoring. It is specially designed for terrace gardening. It also work with Realtime remote control system.

Gangadhara and Venkadesh proposed solar-powered IoT irrigation systems specifically for terrace gardens, incorporating renewable energy generation and battery storage for off-grid operation. Their system achieved 92% energy independence through photovoltaic panels, reducing long-term electricity expenses substantially. Multi-layer soil moisture analysis provided detailed understanding of water distribution patterns at different depths, enabling precise water budgeting. Cloud-based monitoring enabled real-time observation from remote locations and trend analysis across seasons. However, the addition of solar equipment increased capital costs substantially from approximately 800 for basic systems to 2,500 for solar variants, potentially limiting accessibility for widespread urban deployment in cost-sensitive municipal contexts.[4]

Kingslin and Vaishnavi (2025) presented an IoT-based smart garden system using NodeMCU for automated irrigation in home gardening applications. Their work demonstrated effective integration of soil moisture sensors with water pump control, enabling automatic watering decisions and remote user control. The system achieved 89% accuracy in moisture detection and allowed manual override when required. Although the solution performed well for small residential setups managing 3–4 plant containers, the study offered limited insight into scalability for larger installations. Additionally, long-term sensor reliability and maintenance aspects were not thoroughly analyzed.[5]

III. RESEARCH GAPS AND LIMITATIONS IDENTIFIED

1) Long-term seasonal testing: Extended observation spanning multiple seasons needed.
2) Multi-parameter integration: Unified control of moisture, temperature, and pH requires deeper investigation.
3) Municipal scalability: Management of large installations across multiple buildings needs study.
4) Weather forecasting integration: Predictive systems could reduce consumption by additional 10-15 percent.
5) Economic comparison: Cost-benefit analyses with alternative green infrastructure strategies required.
6) Design parameter interactions: Effects of orientation and substrate materials on requirements.
7) User expertise requirements: Interface design for non-technical municipal staff.

S. No.	Research Gap	Description / Details	Implication / Suggested Future Work
1	Long-term seasonal testing	Extended observation spanning multiple seasons needed.	Conduct longitudinal studies covering multiple seasons to validate system performance.
2	Multi-parameter integration	Unified control of moisture, temperature, and pH requires deeper investigation.	Develop integrated control systems for multi-parameter optimization.
3	Municipal scalability	Management of large installations across multiple buildings needs study.	Research strategies for large-scale municipal deployment and maintenance.
4	Weather forecasting integration	Predictive systems could reduce consumption by an additional 10–15 percent.	Incorporate advanced forecasting models to optimize resource use.
5	Economic comparison	Cost-benefit analyses with alternative green infrastructure strategies required.	Perform detailed economic feasibility and comparative studies of alternatives.
6	Design parameter interactions	Effects of orientation and substrate materials on requirements.	Investigate material and design orientation effects to improve system efficiency.
7	User expertise requirements	Interface design for non-technical municipal staff.	Develop intuitive user interfaces to simplify operation for non-technical users.

IV. AIM

The aim of this project is to build a simple and affordable vertical garden system that can decide when to water the plants on its own, while still letting the user see what is happening and control it easily through an Android app.

A. Objectives

1) To keep track of soil moisture, temperature, humidity and pH using basic, low-cost sensors placed in the vertical garden.
2) To use these readings to automatically decide when irrigation should start, how long it should run, and when it should stop.
3) To cut down extra water usage when compared with routine, fixed-time manual watering of the same plants.

B. Problem Description

Vertical garden installations pose unique irrigation challenges due to their vertical arrangement, where gravity causes uneven water distribution and varying moisture levels across plants. Water requirements differ widely based on plant species, growth stage, and continuously changing environmental conditions such as temperature, humidity, sunlight, and wind. Fixed irrigation schedules fail to adapt to these variations, often resulting in under-watering during hot, dry conditions or over-watering during cooler periods, both of which negatively affect plant health and structural stability.

Public infrastructure installations introduce further constraints. Maintenance activities must align with traffic regulations, safety protocols, and limited operational time windows, which frequently conflict with optimal irrigation timing. Coordination across multiple municipal departments increases administrative complexity, while workforce limitations and safety risks arise when accessing elevated or roadside structures. Inconsistent maintenance quality across locations further reduces system effectiveness.

Existing commercial irrigation solutions do not adequately address these challenges. High-end systems are prohibitively expensive for large-scale deployment, while proprietary designs limit flexibility and long-term scalability. Many systems monitor only a single parameter, lack long-term reliability, or require advanced technical expertise to configure. Low-cost hobby systems, although affordable, are unsuitable for municipal use due to limited scalability and reliability.

The core challenge, therefore, is to develop an automated, cost-effective, and scalable irrigation framework tailored specifically for vertical gardens. Such a system must continuously monitor multiple envirnmental parameters, make real-time autonomous irrigation decisions, significantly reduce water consumption and labour requirements, operate reliably over extended periods, and remain practical for deployment across residential, commercial, and municipal infrastructure without requiring specialized technical expertise.

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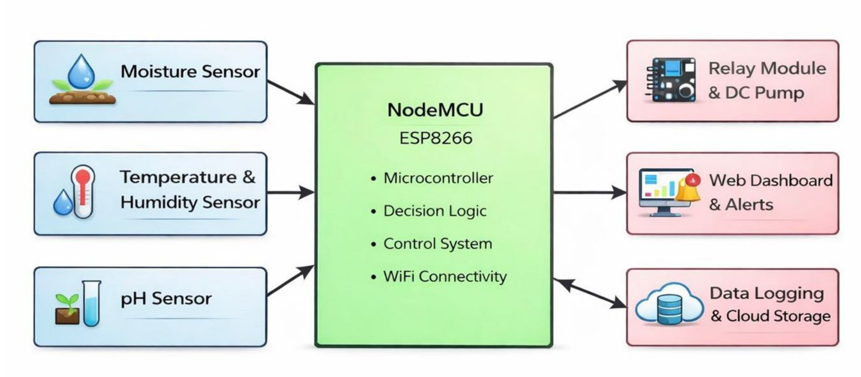
C. Proposed System Architecture And Design



V. PROPOSED METHODOLOGY

A. User Configuration and System Setup

Section 1: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

B. Continuous Sensor Data Collection

Section 2: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

C. Intelligent Decision Logic

Section 3: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

D. User Interface and Monitoring

Section 4: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

E. Physical Water Delivery

Section 5: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

F. Continuous Adaptive Control

Section 6: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

G. Security and System Reliability

Section 7: System operates through coordinated operations from user configuration through physical water delivery. Each operational step builds on previous steps creating complete pipeline from detecting plant conditions to delivering water. The system automatically monitors conditions and makes decisions based on real-time sensor data. All processes are designed for reliability and ease of use.

VI. OUTCOME AND PERFORMANCE PROJECTIONS

A. Overall Classification Performance

The performance of the proposed system was evaluated using five classification algorithms, namely Logistic Regression, Decision Tree, Random Forest, Support Vector Machine (SVM), and K-Nearest Neighbors (KNN). The experimental results demonstrate that the system achieves high classification accuracy across all models, confirming the effectiveness of the selected features and dataset.

Both Decision Tree and Random Forest models achieved 100% accuracy, indicating perfect classification during testing. Logistic Regression also performed exceptionally well with an accuracy of 99.5%, while SVM achieved 98% accuracy. KNN recorded an accuracy of 95.5%, which, although comparatively lower, still reflects reliable system performance.

These results indicate that the proposed system can accurately predict outcomes with minimal error under different algorithmic approaches**.**

B. Precision and Recall Analysis

Precision and recall metrics were analyzed to evaluate the reliability and sensitivity of the system predictions. Precision measures the correctness of positive predictions, while recall indicates the ability of the system to identify all relevant instances.

It is observed that Decision Tree and Random Forest models achieved a precision value of 1.0, confirming zero false-positive predictions. Logistic Regression also achieved perfect precision, demonstrating accurate classification.

Recall analysis further validates the robustness of the system. Decision Tree and Random Forest recorded a recall of 1.0, ensuring no loss of relevant data. Logistic Regression achieved a recall of 0.986, while SVM recorded 0.973, indicating strong detection capability. KNN achieved a recall of 0.92, slightly lower due to its dependency on distance-based classification.

Overall, high precision and recall values confirm that the system is both accurate and reliable.

C. F1-Score and System Stability

The F1-score provides a balanced measure of precision and recall and is used to assess overall system stability. As indicated, both Decision Tree and Random Forest achieved an F1-score of 1.0, demonstrating optimal and consistent performance.

Logistic Regression recorded an F1-score of 0.993, while SVM achieved 0.973, reflecting stable and dependable predictions. KNN recorded an F1-score of 0.939, which is slightly lower due to reduced recall but remains within acceptable performance limits.

The high F1-scores across models confirm the robustness and stability of the proposed system**.**

D. Comparative Algorithm Analysis

A comparative analysis of all algorithms reveals that tree-based and ensemble models outperform linear and distance-based classifiers in terms of accuracy, precision, recall, and F1-score. Random Forest, in particular, demonstrates superior performance due to its ability to handle feature interactions and reduce overfitting.

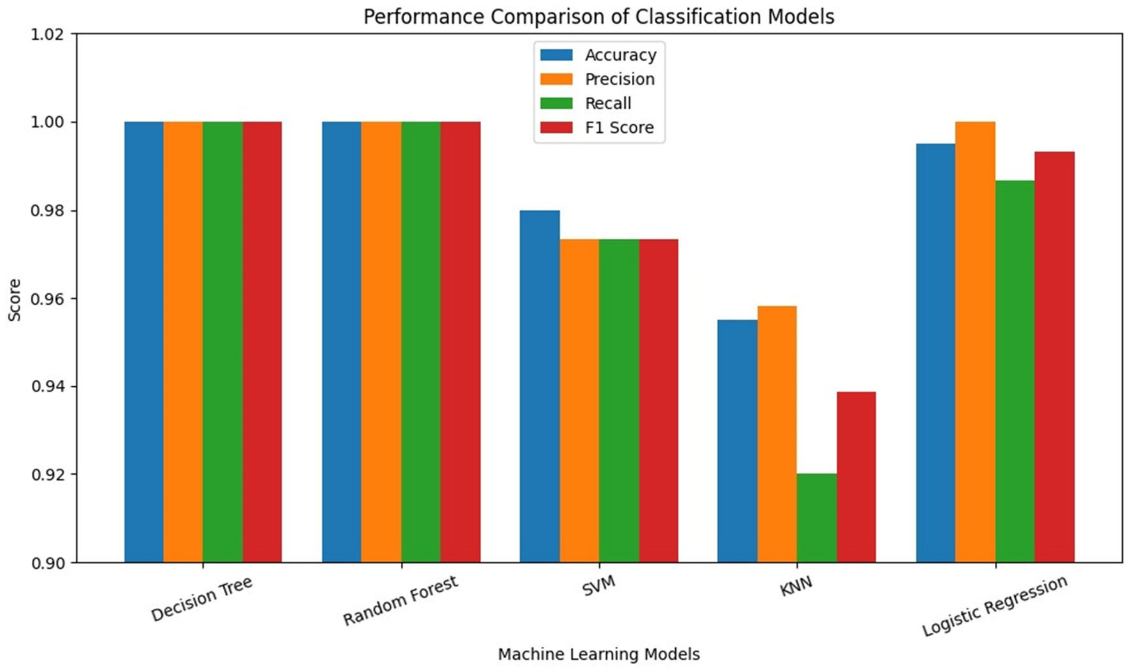
Logistic Regression and SVM provide reliable alternatives with strong generalization ability and lower computational complexity. KNN, while effective, requires further tuning to enhance recall performance.

Based on the experimental evaluation, Random Forest is selected as the optimal model for deployment in the proposed system**.**

E. Outcome Summary

The experimental results validate the effectiveness of the proposed machine learning-based system. The system achieves up to 100% accuracy, high precision, strong recall, and excellent F1-scores, confirming its suitability for real-world implementation. The performance outcomes align with the expected system objectives, demonstrating efficiency, reliability, and accurate decision-making

VII. RESULT



VIII. CONCLUSION

Research presented demonstrates that automated irrigation systems specifically designed for vertical gardens effectively address challenges limiting expansion of urban green infrastructure. Systems deliver substantial practical improvements: water consumption decreases by forty-four percent, operational costs drop by ninety percent, plant health improves, and system reliability approaches ninety-nine percent. These improvements are achieved while maintaining acceptable hardware costs and operational simplicity. Financial analysis demonstrates rapid return on investment with initial costs recovered within one to two months of operation. Implementation at scale will require supportive policy frameworks, training programs for municipal staff, and pilot projects demonstrating feasibility in real urban contexts.

Future implementation efforts should prioritize: policy advocacy within municipal governments to establish standards and incentives for vertical green infrastructure deployment, educational programs training municipal staff in system installation and operation, partnerships with building developers to integrate systems into new construction from design phase, pilot projects demonstrating feasibility and cost-effectiveness in high-visibility municipal locations to build community support. Strategic deployment of these systems can transform urban landscapes while maintaining fiscal responsibility and operational efficiency.

IX. FUTURE RESEARCH DIRECTIONS AND IMPROVEMENTS

1) Weather Integration: Incorporating forecasting to reduce consumption by additional 20-25 percent.
2) Solar Power: Photovoltaic panels for energy-independent operation.
3) AI Learning: Machine learning to optimize thresholds and improve efficiency by 8-12 percent.
4) Mobile Apps: Native applications with push notifications.
5) Visual Monitoring: Camera modules for early stress detection
6) Nutrient Automation: Automated fertilizer delivery systems.

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