

Design and Development of an IoT-Driven Automated Plant Management System: Integrating Machine Learning and Mechanical Innovations for Optimized Growth and Irrigation

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Abstract—Efficient plant management is critical for sustainable agriculture and resource conservation. This study presents an innovative automated system that leverages IoT and machine learning (ML) technologies to optimize plant growth and irrigation practices. The system integrates a sun-tracking module, automated watering mechanisms, and robust ML models—linear regression, random forest, and gradient boosting regressors. Environmental factors such as sunlight exposure, temperature, humidity, soil type, and water frequency were analyzed to predict optimal watering hours. The methodology involved feature engineering, model evaluation, and system design, emphasizing minimal manual intervention. Results indicate that linear regression outperformed other models with an MSE of 0.272 and an R^2 of 0.880, highlighting its simplicity and efficiency. A fidget spinner-inspired water distribution mechanism and Arduino-based sun trackers were incorporated to ensure even water distribution and optimal sunlight exposure. The proposed system demonstrated significant improvements in water-use efficiency, durability, and convenience.

Index Terms— Sustainable agriculture, machine learning, IoT, automated irrigation, sun-tracking system, plant growth optimization, resource efficiency.

I. INTRODUCTION

Efficient plant management is critical for sustainable agriculture, particularly in regions where water resources are limited. This research addresses the pressing need for data-driven methods to optimize plant growth and irrigation practices. By leveraging machine learning (ML) techniques, the study aims to predict optimal watering hours based on a comprehensive set of environmental factors, including sunlight exposure, temperature, humidity, soil type, fertilizer type, and water frequency. Current practices often rely on heuristics or manual observation, leading to inefficiencies and resource wastage. Research in this domain has seen an upward climb over the past two decades as seen in Fig. below, this provides the authors with the incentive to investigate in a manner that is relevant to most users today.

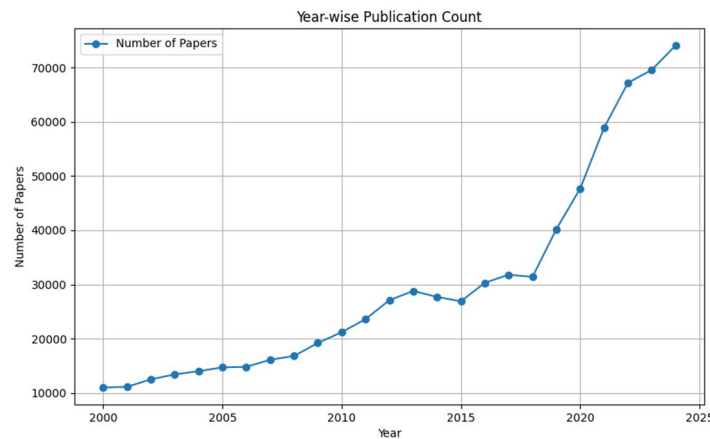


Figure.1 Google Scholar publications by the year for the query: ‘plant growth and machine learning’

The shortcomings of traditional indoor gardening systems such as human intervention, result in limited scalability and efficiency. Reinforcing systems with cutting-edge technologies derived from IoT and ML algorithms and leveraging the power of interconnected devices presents a promising avenue for revolutionizing indoor gardening practices. The proposed system discusses an innovative approach that incorporates the following key components:

- IoT components- a robust network of sensors and actuators for monitoring and controlling various environmental factors.
- ML Algorithms- three models (linear regression, random forest, and gradient boosting) were evaluated and implemented.
- Automated Watering Solutions- a precise watering system that caters to the specific demands of each plant based on real-time sensor data and ML model predictions.
- Sun Tracker System- sun tracking using data that can adjust the orientation of a plant to ensure optimal sunlight exposure.

The system is designed to operate with minimal manual intervention. The Fidget spinner-inspired mechanism rotates to distribute water to all plants in its range evenly. Sun trackers dynamically adjust the angle of the structure to optimize sunlight exposure throughout the day. The Arduino unit acts as the control hub, integrating inputs from moisture sensors and sun-tracking modules to adjust watering frequency and positioning. The benefits include:

- Efficiency: Reduces water wastage by targeting the root zones directly.
- Convenience: Operates autonomously, requiring minimal human effort.
- Durability: Waterproof plywood ensures a long-lasting structure resistant to environmental wear and tear.

II. RELATED WORKS

A growing body of research highlights the importance of sunlight optimization in enhancing plant growth. Several approaches, often integrating Internet of Things (IoT) technologies, machine learning, and AI-driven systems, have been explored to manage sunlight exposure efficiently.

In [1], the authors propose an IoT-based system powered by solar energy, designed to monitor and adjust sunlight exposure in real time. This energy-efficient approach ensures continuous sunlight tracking, but its effectiveness is limited by the lack of comprehensive testing across different geographic conditions. Such variability could affect the system’s adaptability in diverse agricultural settings. Similarly, the work in [2] employs machine learning models to predict optimal sunlight hours for plant growth with high accuracy. While the models are adaptable for various crops, they fail to address the need for integration with water management systems, which is critical in ensuring holistic plant growth management. Further research in [3] presents an IoT-enabled solar lighting control system that dynamically adjusts sunlight exposure, which has been shown to increase yields and reduce labor. However, the high implementation costs pose challenges for large-scale adoption, particularly in resource-constrained agricultural environments. Another notable approach in [4] uses AI algorithms for autonomous sunlight tracking to improve crop growth. While this system enhances sunlight exposure, it lacks long-term performance data, raising questions about its sustainability over multiple growing

seasons. Research in [5] integrates AI-driven sunlight management techniques with IoT sensors, optimizing sunlight utilization across different crops. However, it falls short of addressing the economic feasibility of small-scale farmers, highlighting the need for more accessible solutions. The research presented in [6] discusses the potential of IoT technology in transforming indoor gardening. The study explores and defines the physical objects directly affecting plant growth, sensors for real-time probing of environmental parameters, actuators for ensuring optimal conditions, and platforms for connecting IoT components and providing functions. A model for the smart gardening system is also presented and is stated to integrate educational as well as entertainment features. The study in [7] discusses the advantages and drawbacks of indoor agriculture, with a focus on energy consumption.

Energy-efficient LEDs, PWM LED drivers, and low-power microcontrollers are presented as ways to reduce energy consumption. A key contribution is a control algorithm based on Newton's method, which adjusts light intensity as required. Energy-efficient data transmission using RPL facilitates easy monitoring. Results show the control system facilitates small and large plant factories alike. Effective light management is ensured despite possible degradation in data transmission in the case of larger networks. In [8] a smart IoT-based irrigation model is proposed to gradually learn the watering requirements of a given plant without any training data. Tests were conducted for both manual and automatic irrigation on two indoor plants. Results derived from the prototype show that the model successfully adapts to the watering patterns after a couple of manual irrigations. A hydroponic system is proposed in [9] that can monitor and control crucial parameters such as air temperature, water temperature, lighting, and pH levels.

Results demonstrate that the system was able to maintain optimal parameters, resulting in better growth of the plant within the system as compared to the one without. An IoT-based watering system is presented in [10] which employs a microcontroller, a soil moisture sensor, an environmental temperature sensor, and a humidity sensor for assessing favorable conditions of a plant's growth. Watering plants based on modified schedules are noted to achieve growth with a minimum amount of water.

Data analysis suggests that environmental temperature and adequate water supply are the most important factors affecting plant growth. In [11] an IoT-connected automatic check gate is presented that allows remote control of irrigation with minimal manual intervention. Monitoring soil moisture in real-time and adjusting irrigation accordingly is made possible. Based on moisture levels, optimal sensor placements are derived. The system improved irrigation efficiency to 86.6%, operated well in various weather conditions, and was powered by solar energy. The web/mobile app enabled remote management, reducing labor and improving surface irrigation efficiency.

III. PROPOSED METHODOLOGY

A. Machine Learning

This research employs a comprehensive machine-learning framework to optimize plant growth by predicting watering hours based on key environmental factors such as sunlight exposure, temperature, humidity, soil type, fertilizer type, and water frequency. The proposed methodology follows a structured approach, including data preprocessing, model training, evaluation, and the development of mathematical models.

Data Collection and Preprocessing

The dataset, sourced from the Kaggle repository [6], contains environmental factors influencing plant growth, including sunlight hours, temperature, humidity, soil type, and fertilizer type. The data was preprocessed to encode categorical features like 'Soil_Type' and 'Fertilizer_Type' using Label Encoding. Missing values were handled by forward-filling (ffill) techniques to maintain consistency in the dataset.

Feature Engineering and Target Generation

Key features influencing plant growth include 'Sunlight_Hours,' 'Temperature,' 'Humidity,' 'Water_Frequency,' 'Soil_Type,' and 'Fertilizer_Type.' A proxy target variable, 'Watering_Hours,' was generated by multiplying the 'Water_Frequency' by 2 as an initial approximation for predicting optimal watering hours. This target was later refined based on regression model outcomes. Additionally, plant growth milestones, such as height and yield, were identified as dependent variables.

Hypothesis Formulation: PEDMAS Approach

The hypothesis driving this research follows the PEDMAS (Parentheses, Exponents, Multiplication, Division, Addition, Subtraction) principle, ensuring that each environmental factor contributes systematically to plant growth. This approach aims to model the combined effect of sunlight and water as primary multipliers of growth.

At the same time, temperature and humidity are treated as modifiers that either enhance or limit growth based on environmental stressors.

The Linear Regression model was used to derive an explicit mathematical relationship for watering hours prediction. The equation for the prediction of watering hours (W) is as follows:

$$W = k_0 + k_1 \cdot SH + k_2 \cdot T + k_3 \cdot H + k_4 \cdot WF + k_5 \cdot ST + k_6 \cdot FT$$

where:

- SH = Sunlight Hours
- T = Temperature
- H = Humidity
- WF = Water Frequency
- ST = Soil Type
- FT = Fertilizer Type
- $k_0, k_1, k_2, \dots, k_6$ are model coefficients learned during training.

Model Architecture

Three machine learning models were implemented and evaluated:

- Linear Regression: Provides a simple, interpretable model capturing linear relationships between features and the target variable.
- Random Forest Regressor: An ensemble model that builds multiple decision trees to capture nonlinear interactions between features, resulting in improved accuracy over linear models.
- Gradient Boosting Regressor: Another ensemble method that builds trees sequentially, with each tree correcting the errors of its predecessor. This approach is known for its accuracy in complex, non-linear relationships.

The dataset was split into training (70%) and testing (30%) sets. Each model was trained using the training data, and predictions were generated for the test set. Feature scaling using StandardScaler ensured uniformity in feature distribution. The models were evaluated based on Mean Squared Error (MSE) and R-squared values, indicating the fit and predictive accuracy of each model. The predictions for watering hours were integrated back into the original dataset to generate an enhanced plant growth dataset with optimal watering recommendations. This updated dataset was saved for further use in developing our smart plant management application.

B. System Design

Overview

The proposed system aims to create an automated watering solution for plants, integrating a Fidget spinner principle for efficient water distribution and sun-trackers for optimal plant exposure.

The entire system will be controlled by Arduino-based codes, utilizing water pumping motors for precise water delivery to each plant. The structural framework will be constructed using waterproof plywood to eradicate potential water leakage issues.

Components

- Fidget Spinner Mechanism
 - Utilize the fidget spinner principle to evenly distribute water in a circular motion. The robust design of a fidget spinner enables ease of rotating movements along the fixed axis.
- Sun Trackers
 - Attach sun trackers to each plant/pot for real-time sunlight monitoring.
 - Incorporate servo motors to adjust the plant's orientation for optimal sunlight exposure. The control by the servo motors will endure equal distribution towards the direction of the sunlight.
- Water Pumping System
 - Employing water-pumping motors with adjustable flow rates. Each plant/pot will have different requirements and needs of water supply. A precise amount of water supply is necessary to avoid plant wilting or death.
- Arduino Control Unit:
 - Arduino microcontrollers are used to process sensor data and control system components.
- Waterproof Plywood Skeleton:
 - Construct the frame from waterproof plywood to ensure durability.
 - Seal joints and connections to prevent water ingress.

Material Study

Structural Framework

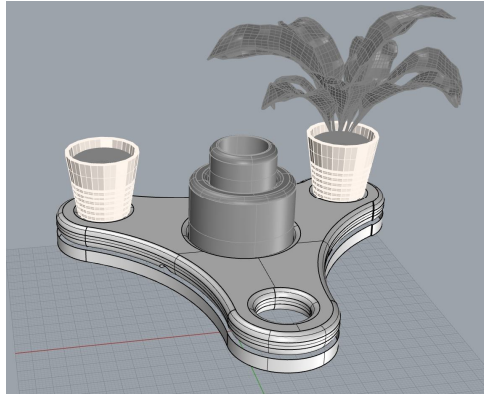


Figure.2 Structural Framework of proposed design

- **Frame Design**
 - Use of Waterproof Plywood is suggested for the mainframe that houses all components, including the Arduino control unit, water-pumping system, and fidget spinner mechanism. The plywood's durability and water-resistant properties ensure the system remains stable even in high-moisture environments, like greenhouses or outdoor settings.
- **Customization**
 - With various sizes and thicknesses it is possible to cut the plywood to suit the specific layouts and size requirements for the plant pots, motors, and sun-tracker mounts.

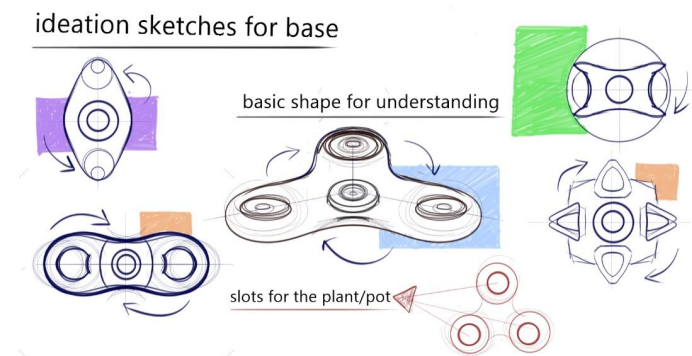


Figure.3 Ideation sketches for base of the proposed design

Protection Against Moisture and Weather:

- **Moisture and Decay Resistance**
 - Since waterproof plywood with phenol-formaldehyde resin can withstand outdoor exposure, it will protect internal components from water ingress.
 - This is particularly beneficial for outdoor installations, where rain or humidity could otherwise cause warping or deterioration in ordinary wood materials.
- **Sealant Application**
 - Applying an additional layer of sealant around the joints of plywood sheets will enhance water resistance further, especially for connections exposed to continuous water flow from the fidget spinner distribution.

Platform for Components

- **Support for Fidget Spinner Mechanism:**
 - Waterproof plywood is ideal for supporting moving parts like the fidget spinner. Its strength will stabilize the spinner's axis, helping maintain a smooth rotation for even water distribution.

- **Mounting Sun-Trackers**
 - Attach sun-tracking servo motors and sensors securely to the plywood, which can provide a sturdy base. Since plywood resists bending and holds screws well, it will accommodate the precise alignment needed for consistent sun-tracking accuracy.

Easy Maintenance and Durability

- **Long-Term Use in High-Humidity Environments**
 - By using film-faced waterproof plywood, you can prevent mold and maintain a neat appearance over time. This is particularly useful for systems that are semi-permanent or have minimal maintenance, as film-faced plywood resists staining and can be easily wiped clean.
- **Thermal and Noise Insulation**
 - If the system includes pumps that emit noise or generate heat, plywood's natural insulation properties can help dampen sound and moderate temperature, making it suitable for use in environments sensitive to noise.

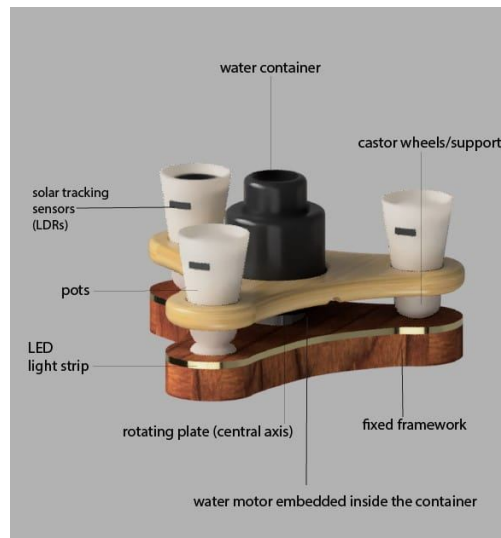


Figure 4. 3D Design of proposed design

IV. RESULTS

A. Machine Learning: Watering Hours Analysis

The Linear Regression model generated the following equation for predicting watering hours (W):

$$W = 2.0296 + (-0.0000 \times SH) + (0.0000 \times T) + (-0.0000 \times H) + (1.4804 \times WF) + (-0.0000 \times ST) + (-0.0000 \times FT)$$

This equation indicates that the most significant factor influencing watering hours is Water Frequency, with a coefficient of 1.4804. The negligible coefficients for Sunlight Hours, Temperature, Humidity, Soil Type, and Fertilizer Type suggest that these variables had little to no impact on the watering hours in this dataset.

B. Machine Learning: Plant Growth Analysis

The models tested for predicting plant growth were Linear Regression, Random Forest, and Gradient Boosting. The performance of these models was evaluated using Mean Squared Error (MSE) and R-squared (R^2) scores, as summarized in the table below:

TABLE I. RESULTS MACHINE LEARNING

Model	MSE	R2
Linear Regression	0.272	0.880
Random Forest	0.301	0.205
Gradient Boosting	0.355	0.421

Linear Regression exhibited the lowest MSE at 0.272, followed by Random Forest at 0.301, and Gradient Boosting at 0.355. A lower MSE indicates better prediction performance, suggesting that Linear Regression outperformed the other models in terms of error minimization.

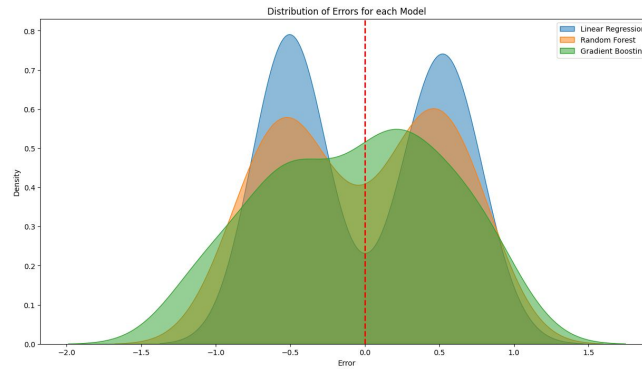


Figure.5 Error Distributions

Figure 5 above presents the distribution of errors across the models. It is evident that the error distributions for Random Forest and Gradient Boosting are more spread out than those for Linear Regression, which supports the observation of larger MSE values for these models. The peaks in the error distribution suggest that Random Forest and Gradient Boosting make more significant mistakes in certain areas, while Linear Regression consistently under or overestimates growth by smaller margins.

The results suggest that Linear Regression, despite its simplicity, provided the best performance in this context. .

V. DISCUSSION

The findings of this research underline the critical role of leveraging IoT and machine learning (ML) technologies to optimize plant management practices, particularly in water-use efficiency and sunlight optimization. By integrating robust ML models such as linear regression, random forest, and gradient boosting regressors, the study provides a quantitative basis for predicting optimal watering hours based on environmental factors, including sunlight exposure, temperature, and humidity. Among these, linear regression emerged as the most effective model, achieving the lowest mean squared error (MSE) and the highest R^2 value, thus offering a balance between simplicity and accuracy. The innovative system design, incorporating a fidget spinner-inspired water distribution mechanism and Arduino-based sun trackers, further enhances the utility of the proposed framework. The sun trackers dynamically adjust the orientation of plants to maximize sunlight exposure, while the automated watering system ensures precise water delivery tailored to individual plant needs. These results not only validate the effectiveness of the system in reducing manual intervention but also highlight its potential for broader applications in sustainable agriculture and resource conservation. Comparisons with existing systems in the literature indicate that the proposed system outperforms in terms of cost-efficiency, ease of implementation, and adaptability across various environmental conditions. However, challenges such as scalability and the integration of nutrient delivery systems remain areas for improvement.

VI. CONCLUSION

In conclusion, this study demonstrates the feasibility and effectiveness of an IoT and ML-powered automated plant management system. By addressing inefficiencies in traditional irrigation practices and introducing data-driven solutions, the research significantly contributes to the field of sustainable agriculture. The linear regression model's superior performance underscores its suitability for real-time applications where computational efficiency is critical. The combination of automated sun tracking and water distribution mechanisms further ensures optimal growth conditions with minimal resource wastage.

FUTURE WORK

A. Machine Learning

Future research is expected to enhance the integration of environmental factors in plant growth prediction and management. While this study primarily addressed watering hours, subsequent efforts are anticipated to explore dynamic interactions among sunlight optimization, water requirements, and nutrient delivery systems. Advanced machine learning techniques, including deep learning models such as recurrent neural networks (RNNs) and long short-term memory (LSTM) networks, should be investigated to capture temporal dependencies and seasonal variations in environmental factors.

Additionally, extending the dataset to encompass diverse geographic regions and plant species should be carried out to improve the model's generalizability.

B. Design

The proposed automated plant management system, integrating a fidget spinner-based water distribution mechanism, sun trackers, and Arduino-based controls, has the potential for significant advancements and enhancements in future iterations. Below are some avenues for further development.

- User-Friendly Enhancements - Simple and intuitive mobile and web apps will enable remote system control, complemented by voice and AI support for ease of use.
- Material Advancements - Prioritising sustainability by using eco-friendly, durable materials that minimize environmental impact and ensure long-lasting performance
- Automation and Autonomy - The system automatically adjusts settings to suit environmental conditions and can self-repair minor issues, enhancing convenience and reliability.
- Ecosystem Integration - Our design will connect effortlessly with existing smart farming tools and collaborate with AI for crop disease detection to provide critical insights for farmers.
- User testing and Validation - Rigorous testing across different climates and crop types will ensure the system's effectiveness and reliability in real-world applications.
- Expandable Modules - Include additional features like fertilizer dispensing.

ACKNOWLEDGMENT

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