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Research Article

Transforming Saffron Cultivation With Smart Hydroponics: An Artificial Intelligence of Things Approach to Crops and Nutrients Management

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Abstract: Agriculture is changing with the aid of new technologies, particularly in several Asian countries. This research applies Artificial Intelligence (AI) and the Internet of Things (IoT) to traditional farming, particularly focusing on saffron cultivation using hydroponics. Hydroponics is especially useful as a city grows, because it not only saves space but also nourishes the plants directly through the roots - no soil is needed. This study demonstrates a new paradigm through the application of AI integrated with IoT for precise crop recommendation, along with monitoring essential environmental parameters, and adjusting them for maximum growth conditions. We employed various AI models, such as Random Forests, Decision Trees, Support Vector Machines (SVM), K-Nearest Neighbors (KNN), and XGBoost on data from the Indian Chamber of Food and Agriculture. Random forest model outdid the rest, reporting a prediction accuracy of 97.5%, by far the strongest in optimizing cultivation techniques. The goal of this work is to reduce the multiplicity of steps involved in the automation of environmental control and crop recommendation for increased saffron yield, and economic growth in the regions where this crop is crucial will boost and contribute towards sustainability.

Keywords: XGBoost, Hydroponic, Saffron, Hydroculture, AIoT

Introduction

The world now faces new challenges for the food system due to urbanisation, population growth, and the decline in arable land and water, all of which increase the need for more sustainable and highly efficient agricultural practices. There is a demand for innovative cultivation techniques to ensure food security and economic resilience, particularly for high-value crops that sustain rural livelihoods and bolster national economies. An emerging transformative approach is hydroponics, which soilless cultivation using nutrient-rich solutions. This method enhances resource efficiency and enables controlled environmental conditions, allowing continuous crop production throughout the year. These benefits are crucial for saffron (Crocus sativus), the most valuable spice globally, which is traditionally grown under geographically restrictive and labour-intensive conditions.

The advancement of controlled-environment agriculture systems has demonstrated that hydroponic systems are more productive, higher-quality, and more resource-efficient than traditional soil agriculture. Studies show that hydroponics can reduce water use by up to 70%, while also providing consistent production cycles with lower risks of pests and diseases. Saffron, owing to its high economic value and specific cultivation requirements, would significantly benefit from these technological innovations. The application of AIoT, Artificial Intelligence and the Internet of Things, to hydroponic systems has enhanced real-time monitoring and optimisation of relevant environmental and nutrient factors. Other research has shown the benefits of AIoT for other crops, including increased yield, improved accuracy and efficiency metrics, and enhanced overall operations. However, the direct application of these technologies to saffron remains limited, as research has primarily focused on staple or leafy crops.

The promise that hydroponics and AIoT technologies hold for saffron farming is yet to be realized. There remains a complete absence of research on the interplay

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between saffron farming and these modern technologies. Moreover, comprehensive frameworks that integrate real-time environmental monitoring, automated nutrient delivery systems, and machine learning-driven saffron crop recommendations are almost non-existent. It is essential to fill this gap because leveraging technology to optimise saffron production can unlock substantial economic and sustainability benefits for the region, particularly by diversifying or expanding agricultural exports.

This study aims to develop and evaluate a smart hydroponic saffron system that integrates AIoT technologies for real-time monitoring, automated decision-making, and environmental control (Kour et al., 2022). The primary focus of this research is the use of AI and IoT in hydroponic systems, specifically for optimising saffron yield and quality relative to conventional approaches, and for developing machine learning models to determine optimal environmental conditions and nutrient levels for hydroponic saffron production. This research is grounded on implementing a fully integrated AIoT hydroponic system, which will require enhanced precision in controlling growth conditions during and after cultivation, resulting in increased yield, enhanced quality, and improved resource efficiency.

The producer challenges in saffron farming stem from the absence of efficient, accessible, and environmentally responsible approaches to saffron cultivation (Bhagat et al., 2025). This research integrates hydroponics with modern sensing technologies, data analytics, and automation to address the challenges posed by conventional saffron farming. Achieved objectives are expected to refine the management of high-value crops while providing a replicable model for other speciality crops with analogous issues. In broader terms, the anticipated impact goes as far as bolstering food security, revitalizing rural economies, and enhancing the global adoption of smart agricultural technologies.

To meet these goals, the research employs a modular hydroponic system with an AIoT-controlled suite of environmental sensors monitoring pH, electrical conductivity, temperature, humidity, and light. Machine learning models are developed based on the gathered data and are capable of adjusting the system to preset conditions automatically. Experimental trials are conducted to compare saffron growth, yield, and quality under AIoT-managed and conventional conditions, thereby providing robust evidence for the effectiveness of the proposed system.

Related Work

As with any industry, agriculture also faces challenges in productivity, profitability, and operational efficiency. Through the adoption of advanced technologies, agricultural IoT, Big Data (Rejeb et al., 2021), Machine Learning, and Robotics have been useful in forming solutions to the challenges posed. The soilless growing of plants, stems, and leaves is enabled by hydroponic materials such as clay pebbles and rock wool, and even water as a growth medium, which is one of these methods. Other forms of hydroculture include aquaponics and aeroponics. Aquaponics integrates aquaculture and farming into one synergistic system of agriculture to raise fish and grow plants together, while in aeroponics, mist containing nutrients is sprayed on the plant roots that are suspended in the air. However, these systems tend to be expensive, limited to selected crop types, and vulnerable to critical failures due to systemic issues.

Fig. 1 presents a comparative overview of saffron exports by country, making it clear that Iran is the world's leading exporter, responsible for roughly 77% of global supply. This substantial share places Iran at the centre of the international saffron trade, granting it considerable influence over market trends, pricing, and quality benchmarks. In contrast, countries such as Spain, Afghanistan, Greece, Italy, and India contribute noticeably less, each holding a much smaller proportion of the export market.

Key Implications of the Export Distribution

The export distribution data reveals much about potential global market shifts. One trend reveals that the market is highly responsive to changes in regional production. For saffron, changes in production, domestic, or even trade policies in Iran have an impact on saffron prices and supply at the global level. The other trend is that there is the possibility of growth for emerging or secondary countries. There are many countries, such as Spain and Afghanistan, that dominate the saffron market. However, there is a possibility for countries such as India and Greece to grow by improving cultivation and post-harvest procedures. Lastly, export data shows that there are product differentiation opportunities for new competitors in a market, especially when producers have supply constraints and quality is improved, as this will help strengthen their position in the global saffron trade.

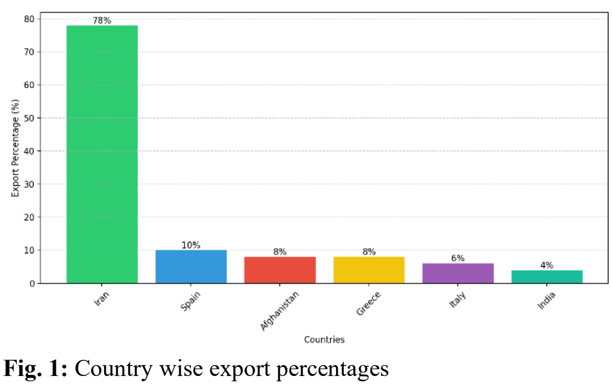

Fig. 1: Country wise export percentages

Overview of Aeroponics Hydroculture Systems

Innovative efforts for specific plant types have been made. This includes an IoT-incorporated automated aeroponic system (Tanna et al., 2025) for leafy greens that can monitor growth via a mobile app. While the technology has promise, it is expensive and requires additional supporting technologies to be efficient (Rajendran et al., 2024). The system is confined to smaller leaf crops, but space-smart vertical aeroponic farms work with automated fertilizer supply and monitoring, considering space use and malfunctions as well. An advanced multi-crop machine learning model-driven system can be trained much more easily and requires extensive data, but it optimizes growth conditions for a range of crops. Tests have been conducted on specialized aeroponic systems that apply for the cultivation of saffron. For instance, this study illustrates an aeroponic configuration with optimization for real-time environmental parameter monitoring that enhances the size of corms (Pangave et al., 2023). Unfortunately, such systems are highly sensitive to environmental changes.

Finally, a sophisticated hydroponics and aeroponics system dedicated to root crops illustrates hybridization, but it is limited in general space, and has complicated requirements for fertilizer concentration control (Kumar et al., 2024). These advancements highlight the ability of aeroponic technologies to surpass traditional agricultural challenges and improve production efficiency, particularly for high-value crops like saffron, by offering automated adjustment of nutrient solution based on sensor feedback, ensuring EC remains between 1.8–2.2 mS/cm over growing conditions and optimal resource management. Table 1 summarizes recent aeroponic system models, highlighting their technological features, monitored parameters, key benefits, and practical limitations for various crop applications.

Overview of Aquaponics Hydroculture Systems

The principles of hydroponics (plant growing) and aquaculture (fish farming) are combined in aquaponics to develop a sustainable agricultural system that capitalises on the mutual link between plants and aquatic life. Fish waste gives the plants vital nutrients in this symbiotic relationship, while the plants filter and purify the water to create the ideal conditions for fish growth. The entire productivity of plant and animal agriculture systems is enhanced by this effective oxygenation and water conditioning arrangement (Dennison et al., 2025). Recent developments in aquaponics have sparked the creation of creative systems that use smart technologies to monitor and regulate a range of environmental factors. These systems are capable of controlling variables that are essential for ideal growth circumstances, including temperature, pH, humidity, and nutrient levels. Table 2 presents a comparison of current aquaponic models, highlighting the benefits and drawbacks of each. The principles of hydroponics (plant growing) and aquaculture (fish farming) are combined in aquaponics to develop a sustainable agricultural system that capitalises on the mutual link between plants and aquatic life. Fish waste gives the plants vital nutrients in this symbiotic relationship, while the plants filter and purify the water to create the ideal conditions for fish growth. The entire productivity of plant and animal agriculture systems is enhanced by this effective oxygenation and water conditioning arrangement (Lennard et al., 2024).

For example, the Internet of Things (IoT)-based Smart aquaponic system offers real-time results and user-friendly interfaces, but it has drawbacks such as packet loss and throughput index lag (Haryanto et al., 2019). On the other hand, the automated aquaponics review covers a great deal of technical information about IoT applications in aquaponic systems, although many of these ideas have not yet been put into practice (Rastegari et al., 2023). Furthermore, IoT-based smart aquaponics designs are especially well-suited for small-scale applications; yet, scalability is still a concern (Mahmoud et al., 2024). Lastly, both automatic and manual operating modes are demonstrated by a smart monitoring and control system to introduce IoT in a fast-paced agricultural environment (Manjunath et al., 2019).

Table 1: Analysis of Contemporary Aeroponic Models

Reference	Nature of Model	Parameters	Benefits	limitations
Rajendran et al., 2024	IoT-enabled automated aeroponic system for leafy greens	Temperature, Humidity, Light	Enhances growth speed and yield consistency; easy monitoring via mobile application.	High initial cost of equipment; dependency on technology
Kour et al., 2022	Smart vertical aeroponic farm system	Temperature, pH, CO2 levels, Light	Maximizes space utilization; automated nutrient delivery system	Limited to smaller leaf crops; potential system malfunctions.
Nahla et al., 2024	Automated multi-crop aeroponic system utilizing machine learning	Moisture, Light intensity, Nutrient concentration	Customizable for various crops; machine learning adapts to optimize growth conditions	Requires extensive data for model training; complexity of setup
Pangave et al., 2023	Aeroponic cultivation system for saffron with environmental monitoring	Corm size, Humidity, Temperature	Significant corm size increase; real-time monitoring of environmental parameters	Sensitive to extreme environmental changes

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Table 2: Comparison of Contemporary Aquaponic Models

Reference	Nature of Model	Parameters	Benefits	limitations
Haryanto et al., 2019	Smart aquaponic system based on the Internet of Things	Acidity, Water level, Temperature	User-friendly interface providing real-time results	Throughput index lag; decreasing packet loss and delay
Rastegari et al., 2023	Towards automated aquaponics: A review on monitoring, IoT, and smart systems	Temperature, pH, Moisture, Alkalinity, Dissolved oxygen, Water hardness, Relative humidity, Nitrification	In-depth technical knowledge about automation and the use of IoT in aquaponic systems	Still in research phase, not implemented yet
Mahmoud et al., 2024	Smart aquaponics design using Internet of Things technology	Temperature, Light, pH	Ideal for small-scale applications	Not implemented for scalable networks

These diverse models show how aquaponic systems can be used to take advantage of smart technologies, significantly increasing agricultural practices' sustainability and efficiency. When taken as a whole, they provide a useful starting point for further studies that will optimise aquaponics systems, especially when combined with other developments in precision farming and environmental monitoring.

The highlighted models demonstrate the different potential uses of both aeroponics and aquaponics systems for saffron cultivation, each with specific pros and cons. Further innovations can develop these systems to make them more effective in terms of production and quality of saffron.

Overview of Hydroponic Systems

Hydroponics offers a controlled alternative to conventional soil farming, making it suitable for high-value specialty crops such as saffron (*Crocus sativus*). Key advantages include improved water and nutrient use efficiency, space optimization, and precise control over root-zone conditions. For saffron cultivation, regulating Electrical Conductivity (EC), Total Dissolved Solids (TDS), and pH is vital for optimal nutrient uptake and corm development. Systematic reviews of smart hydroculture highlight that automated sensing and closed-loop nutrient monitoring significantly improve crop management consistency (Anila and Daramola, 2024).

Comparative evaluations demonstrate that balanced nutrient formulations, such as modified Hoagland solutions, accelerate plant growth across various crops relative to standard soil irrigation practices (Rajaseger et al., 2023). When applied within Controlled-Environment Agriculture (CEA), adapting these nutrient delivery protocols to soilless saffron culture can optimize physiological development while eliminating soil-borne pathogens (Maryam et al., 2025). Integrating machine learning and IoT into hydroponic structures further enables real-time environmental monitoring and automated adjustments, ensuring microclimates remain tailored to the precise requirements of saffron flowering and corm propagation.

Overall, the examined literature highlights the many advantages and difficulties of hydroponics as a practical substitute for saffron farming, establishing it as a cutting-edge method that can improve crop quality, productivity, and sustainability. In Figure 1, several hydroponic system techniques are illustrated, showcasing methodologies utilized in different studies. This visual representation highlights the diversity of approaches within hydroponics.

Combining Machine Learning With IoT

The integration of Deep Neural Networks (DNNs) and Internet of Things (IoT) infrastructure has substantially advanced environmental management in soilless agriculture. Edge processing units (such as Arduino and Raspberry Pi) connected to multi-sensor arrays allow real-time monitoring and closed-loop control of pH, ambient temperature, relative humidity, and light intensity. In controlled hydroponic setups, AI-driven nutrient optimization models have successfully reduced excessive fertigation while maintaining target growth metrics (Mohmed et al., 2025). Expanding these AIoT frameworks to saffron (*Crocus sativus*) offers significant potential, as its critical phenological stages, such as bulb formation and flowering, are highly sensitive to environmental micro-fluctuations.

Automated IoT architectures for hydroponic systems streamline nutrient delivery, pH balancing, and lighting schedules through centralized cloud processing and mobile user interfaces (Rao et al., 2024). When applied to greenhouse saffron production, IoT-enabled frameworks enable continuous monitoring of key parameters, reducing labor demands and mitigating crop risks under controlled conditions (Khan et al., 2024).

Machine learning algorithms play a critical role in modeling plant dynamics and environmental correlations within hydroponic environments. Supervised learning techniques, including Decision Trees, Random Forests, Support Vector Machines (SVM), and Neural Networks, have been utilized to predict crop growth behaviors, analyze plant attributes, and classify ecotype responses under varying environmental conditions (Alavi-Siney et al., 2025). Furthermore, combining remote sensing, computer vision, and deep learning models with automated IoT frameworks enhances diagnostic accuracy for crop monitoring, aiding in nutrient adjustment and early anomaly detection for sustainable saffron production (Nazeer et al., 2024).

Methods

The novel approaches to farming, which have been necessitated by an increased population and a corresponding demand for sustainable farming practices, have driven novel approaches. In particular, the focus of this research is the usage of hydroponic systems for saffron (Crocus sativus) production through the Nutrient Film Technique (NFT) or Tower Garden systems. These growing systems form a subclass of aeroponic systems, which are most appropriate for saffron due to the need to control various environmental factors for this high-value crop. Hydroponics enables the growth of saffron (Crocus sativus), given that environmental and nutritional solutions can be meticulously controlled. Adjustable Tower Garden configurations and the Nutrient Film Technique NFT are more advantageous than other hydroponic systems for the cultivation of these important crops.

NFT and Tower Garden systems were chosen for their compatibility with Safron's shallow root structure, efficient oxygenation, and space-saving vertical design, which is ideal for urban environments. Literature supports NFT for consistent nutrient delivery and Tower Gardens for maximizing yield per square meter.

The Nutrient Film Method (NFT)

In the Nutrient Film Technique (NFT), plant roots are exposed to an uninterrupted supply of water containing dissolved nutrients. NFT is designed to sustain high levels of dissolved oxygen and mineral nutrients. An NFT system used for saffron consists of four primary components. First, NFT systems consist of plastic channels that are designed with a slope so that the nutrient solution can flow back to the storage tank using gravity to help. To ensure the solution is cycled, a submersible pump is used to pull the solution from a storage tank that acts as the main storage tank for the minerals. To ensure the best growing conditions for the plant, the system is built with sensors that monitor pH and Electrical Conductivity (EC) in real time. Also, for environments that are light limited, additional lighting is provided to sustain the required level of photosynthesis.

Nutrient and Environmental Thresholds With Decision Logic

For optimal saffron cultivation in the hydroponic system, nutrient concentrations are maintained at nitrogen (N) 150 mg/kg, phosphorus (P) 60 mg/kg, and potassium (K) 100 mg/kg. Environmental parameters are strictly controlled within the following ranges: pH 6.0–6.8, electrical conductivity (EC) 1.8–2.2 mS/cm, and temperature 18–25°C. The system follows a straightforward decision logic: if the pH drops below 6.0, an alkaline buffer is added to restore balance; if EC exceeds 2.2 mS/cm, the nutrient solution is diluted; and if any of the NPK values deviate from their respective targets, the specific fertilizer is adjusted accordingly. This approach ensures that the hydroponic environment remains consistently within optimal conditions for healthy saffron growth and yield

The Tower Garden

The Tower Garden system is a space-efficient, vertical saffron cultivation system. This system utilizes a central tower structure with stacked trays that permit the cultivation of multiple crops simultaneously. In the system's "ebb and flow" cycle, the submersible pump, located in the base reservoir, lifts the nutrient solution to the top of the tower, where it flows down over the plant roots. The growing containers of the system are filled with one or more of the following mixed: Rock wool, coconut coir, and perlite, to help root anchorage and moisture retention. The system is completed with a nutrient reservoir at the base of the tower that maintains a continual growth cycle with water that is mineral-enriched.

Sensor Data Acquisition and Preprocessing Workflow

Overview of Data Collection

To ensure machine learning models work with quality data, the system has a dedicated data pipeline. Data collection starts with the installation of sensors that log dissolved pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), and temperature. Every measurement is time tagged. Data collected and time tagged is transformed into a feature vector, thus documenting the hydroponic system at a given time.

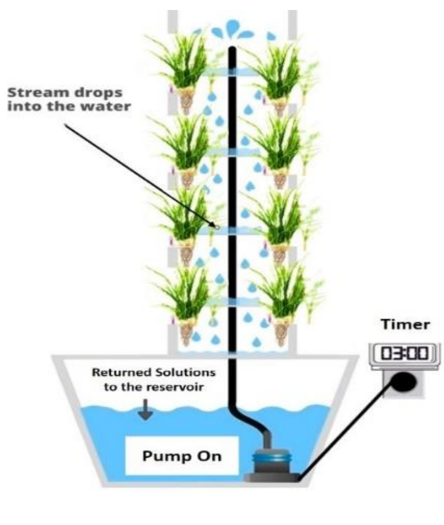

Fig. 2: Tower Garden

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Data Integration and Fusion

Data integrity is maintained via a preprocessing step. Missing data is substituted with the median of the most recent values. Z-score is used to identify outliers, which are removed or rectified via linear interpolation. Features are normalized via Min-Max and composites are constructed, including a nutrient score based on EC and TDS, to name a few. Data is smoothed temporally by averaging measurements over 5 to 10 minutes to suppress variability and provide a stable data set for algorithms.

Preprocessing

If any sensor fails to report a value, the missing entry is filled using the median of recent valid readings. This approach helps maintain data integrity and reduces the influence of sporadic sensor failures. Sensor values that deviate significantly from typical patterns (identified using Z-score thresholds) are considered outliers. These are either removed or replaced with interpolated values, reducing the risk of erroneous data affecting model performance. All numerical features are scaled to a uniform range using Min-Max normalization. This ensures that variables measured on different scales contribute equally when training machine learning models.

For feature engineering, additional variables, such as a composite nutrient index derived from EC and TDS, are created to better represent the relationships between environmental conditions and plant growth. In temporal smoothing, to minimize the effect of short-term fluctuations, sensor data is averaged over brief intervals (typically 5–10 minutes) before being used for analysis. This aggregation enhances the stability of the input features.

Integration with Machine Learning

In input preparation, the final, cleaned, and engineered feature vectors are used as inputs for machine learning algorithms such as Random Forests and Support Vector Machines. This ensures that the models are trained on high-quality, representative data. The comprehensive preprocessing leads to more accurate predictions and recommendations, supporting effective management decisions in hydroponic saffron cultivation.

Machine Learning (ML) Algorithms to Enhance Crop Yields

In this new era of advancements in agricultural technology, the adoption of machine learning (Mamatha and Kavitha, 2023) algorithms to increase crop yields has been increasingly relevant. For saffron (Crocus sativus) cultivation, five machine learning models are designed for the determination of optimal growing conditions based on the myriads of parameters: Random Forest, Decision trees, Support Vector Machine (SVM), K-Nearest Neighbors (KNN), XGBoost. Research indicates that effective hyperparameter tuning enables these algorithms to accurately process similar datasets.

The proposed model uses the Random Forest, where numerous decision trees are created for every subset of relevant features, like nutrient levels and other environmental parameters pertaining to saffron growing. All trees vote for one final output, which further fortifies the model against overfitting, yielding better quality results for dairy farming data, which is known to be very complex. The dataset comprised 1,500 records collected over two saffron cultivation cycles, with features including pH, EC, TDS, temperature, humidity, and NPK levels. Data preprocessing involved outlier removal, imputation for missing values, and Min-Max scaling.

In training and validation, the data was split 80:20 into training and validation sets. Five-fold cross-validation was used for model robustness. Grid search optimized parameters such as the number of trees (*n_estimators:* 100 – 500) and maximum tree depth (*max_depth:* 5 – 15) for hyperparameter tuning. Metrics included accuracy (97.5%), compared with Decision Tree (93.2%), SVM (94.1%), and KNN (91%).

Decision Tree Technique is a simple method for studying several criteria relationships that determine saffron growth. In our model, temperature and humidity, together with other critical factors, are used to consecutively partition the dataset in a specific manner, forming a logical sequence of decisions to be taken. This allows saffron growers to quickly evaluate the resulting changes and the value of each of them in correlation to the specific variable, which translates into a quick understanding of the data and insight.

Support Vector Machine (SVM) is used due to its ability to capture the hyperplane that most accurately separates different classes of cultivation data pertinent to saffron. SVM improves the predictive efficiency by being able to accommodate the nonlinear and linear relationships existing among the complex environmental and nutritional factors that affect saffron growth through the use of several kernel functions.

K-Nearest Neighbors (KNN**)** used in the model because it is straightforward to predict optimal growth conditions for the saffron crop using the features of the nearest neighboring data points in the dataset. KNN mitigates the limitation of precision agriculture by local data clustering to determine the best pinpointing condition for cultivating saffron using the attributes of like surrounding growth.

XGBoost (Extreme Gradient Boosting)

The proposed model uses XGBoost because it is known to use boosting, which has proved to be effective in machine learning competitions by forming a series of decision trees, where each tree tries to correct the errors produced in the previous one. XGBoost increases the speed and accuracy of the predictions, making it easier to gain access to the complex relationships involved in the production of saffron. Thus, XGBoost refines the cultivation techniques that aim to increase both the quantity and quality of saffron produced.

Integrating sophisticated machine learning algorithms within the hydroponic system for saffron cultivation allows the proposed model to effectively improve the conditions of the environment, as well as the use of nutrients for sustainable agricultural practice. The combination of IoT sensors for real-time data acquisition and machine learning analysis offers farmers powerful tools for decision making, which results in better saffron agricultural practices.

The Role of Machine Learning in Hydroponic Systems

As Bigdata and AI are becoming more common within our daily lives, these fields have made their way into Hydroponics as well. With the help of data-driven decisions, Hydroponic systems can be optimized and expanded further. These systems can learn from both historical and real-time data, and further adapt to the varying conditions and alter the optimal saffron cultivation parameters.

Saffron Farming Decision Making and Data Analysis

The data collected from several sensors captures a wide array of information, which can be used in important farming machine learning algorithms tasks. The machine learning algorithms are able to calculate future scenarios that can affect the production of saffron using previous data trends, which can then be proactively dealt with. This guarantees that the required level of optimal conditions for growth borders can be set and preserved before actual growth begins. Taking into consideration the current environmental conditions and the growth stages of the plants, ML models can make well-informed recommendations on the necessary amendments to fertilizer concentrations, the amounts of light provided, and even the watering schedules.

Anomaly Detection: The anomaly is mitigated through the utilization of machine learning techniques to make self-correcting adjustments to the system in question. The system can modify environmental control parameters or alert the operator when temperature sensors identify abnormal conditions that can be damaging to saffron plants. Machine Learning systems possess the ability to suggest crops that are suitable for a particular climate and resource availability, thereby increasing the adaptability and productivity of the hydroponic system.

Hydroponic Systems and the Internet of Things

The Internet of Things (IoT) is defined as a network of interconnected sensors and devices that communicate over the internet, thus aiding in the collection and dissemination of critical information. IoT technology is important for the many environmental factors that need to be controlled and monitored in hydroponic systems for saffron (Crocus sativus) cultivation: Temperature, humidity, pH, and nutrient concentrations. With the aid of pH sensors, exporters can keep the pH levels within a range highly suitable for saffron's nutrient absorbing capacity, which ranges from 5.5 to 6.5. EC (Electrical Conductivity) sensors, which monitor the nutrient solution, ensure that saffron gets the right nutrition for adequate growth and development. It is possible to combine multiple sensors and link them to a central computer or smartphone for real-time monitoring and modification of growth conditions.

Temperature Sensors enable growers to monitor the environmental temperature that affects saffron cultivation for optimum growth. Humidity sensors can monitor the quantity of moisture present in the air and subsequently modify the environment to optimize growth conditions and minimize stress on the plants. Light Sensors outline the capability to capture light intensity information to control the sufficiency of illumination for the saffron plants so that they can perform optimally. The proposed method of hydroponic saffron farming is designed with several sensors to accurately track and control the most important variable of nutrition level for high production and growth. EC sensors measure the number of dissolved salts in the solution to determine the proper nutrient changes, while glass electrodes or solid-state pH sensors measure the acidity or alkalinity of the nutrient solution to ensure it remains at an optimal level.

In order to help make the nutrient balance more precise, TDS sensors replace the electrical resistance that the total nutrient content determines. DHT11 or DHT22 sensors measure humidity to balance the nutrients and maintain a sufficient moisture level. Vital elements such as phosphorus, potassium, and nitrogen are monitored through ion-selective electrodes to ensure nutrients are provided in the right amount. In order to enhance the quality and quantity of saffron crop production, the workflow involves continuous data collection, preprocessing to handle missing or abnormal values, and adding real-time changes to the fertilizer solutions and environmental parameters.

Incorporating IoT and Machine Learning into Hydroponic Systems for Wider Geographical Applications in Agriculture

Our method employs machine learning and IoT technology for the advanced cultivation of saffron in these hydroponic systems. The objective is to improve international saffron farming practices and achieve higher quality crops through the innovation of established hydroponic methods and techniques backed with modern turning technology. Integration of IoT and machine learning will allow precise data analytics for creating the optimal conditions needed by saffron. This proposed hydroponic system will use IoT and Machine Learning (ML) for automated saffron farming through IoT-driven optimization of growth conditions and increased crop productivity. The research employs various Internet of Things (IoT) devices whereby growth parameters' data is recorded in real time using sensors attached to an Edge device such as Arduino or Raspberry Pi3. These factors include pH, temperature, relative humidity, water level, and light intensity. The devices constantly monitor these factors to maintain the optimal growing environment. The suggested procedure consists of two components, which are: Sensors will be set up in both the NFT and Tower Garden systems to monitor the nutrient level, pH, temperature, humidity, and light conditions. This data can optimize saffron growth conditions immediately. Growing Saffron will be monitored with multilayered machine learning algorithms specifically designed to analyze the data for its distinctive nutritional requirements throughout its growth cycle. This information will aid in the recommendation systems algorithms that will be suggested for modifying the nutrient solution.

In the experimental environment, a machine learning algorithm is used to improve the process by processing data obtained from the IoT-connected sensors. The algorithms calculate the environmental conditions and nutrient needs of the saffron, and accordingly, the system can make specific recommendations for the care of saffron plants. Historical data in conjunction with real-time measurements are used in order to change the nutrients and the environmental conditions so that the saffron plants get appropriate care for their growth. Also, machine learning models are developed for analyzing the collected data and results to find patterns and relationships that promote resource efficiency and waste elimination.

The integration of IoT and machine learning in hydroponic saffron farming creates an effective and complex intelligent system that maximizes the health and productivity of saffron plants. This innovative approach redefines the parameters of sustainable agriculture. By bringing these new technologies into practice, there would be a great advancement in the effectiveness and scalability of saffron agriculture while making it possible for resilient production, which would lessen the hardships of conventional farming systems. Fig. 3 illustrates the integrated architecture of a hydroponic system, where environmental sensors, IoT connectivity, and a deep neural network collaborate to enable real-time monitoring, automated control, and intelligent decision-making for optimal plant growth.

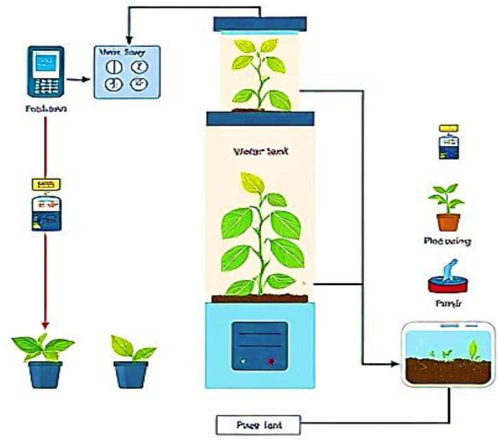

Fig. 3: Generalized System design of the hydroponic system using IoT and Deep neural network

Proposed AIoT Framework

AIoT refers to the incorporation of Artificial Intelligence of Things, which blends machine learning and deep learning in devices in the Internet of Things (IoT). In this particular framework, machine learning algorithms process the enormous amount of data gathered by IoT devices such as sensors, cameras, and other active technologies, which assist in deriving actionable insights and making efficient decisions. The application of AIoT in agriculture saffron cultivation offers an ability to optimize growing conditions, which ultimately increases production and contributes to environmentally friendly farming practices. In our approach, we propose that AIoT plays a vital role in the endless surveying of nutrient solutions in a hydroponic system intended to improve the growth of saffron (Crocus sativus). With the growing data in relation to environmental conditions like humidity, pH, and the amount of nutrients having machine learning systems can process this data, revealing the essential frameworks for optimal conditions of saffron farming.

This analysis makes it possible to adapt the settings of the hydroponic system in such a way that would ensure optimal conditions for saffron experimental growth. Through AIoT technologies, growers can exquisitely fine-tune the amount of nutrients and the environmental conditions to be as favorable as possible to maximize the quantity and quality of saffron produced. Therefore, AIoT not only increases the effectiveness of the hydroponic cultivation processes but also has a positive impact on the sustainability of saffron farming over a long period of time.

Hardware Setup for Smart Hydroponic Saffron Cultivation

The hardware configuration for the smart hydroponic saffron system is designed for robust, real-time control

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and monitoring of all key environmental parameters essential for optimal plant growth. The integration of an AI-powered environmental control system demonstrates a robust framework for achieving resilient and efficient greenhouse farming by dynamically optimizing growth conditions through advanced data-driven modeling. Below is a concise, original description tailored for inclusion in the Methods section.

Central Processing and Control

A Raspberry Pi 4 Model B acts as the central processing unit, managing data aggregation, advanced analytics, and the user interface. Data Acquisition Module: An Arduino Uno microcontroller is dedicated to collecting real-time measurements from all connected sensors and handling direct control of actuators.

Sensor Integration

Environmental Monitoring

The system employs a comprehensive set of sensors, including pH and EC probes (Atlas Scientific) for solution chemistry, A TDS sensor to assess dissolved solids, DHT22 for temperature and humidity and a BH1750 for light intensity measurements. Sensor readings are sent from the Arduino to the Raspberry Pi, ensuring synchronized, high-frequency updates for all monitored variables.

Automated Actuation

Based on real-time sensor data and machine learning model outputs, the system automatically manages Peristaltic pumps for precise nutrient and pH solution dosing, Solenoid valves to regulate water flow and Relays to operate climate control devices such as heaters, coolers, and humidifiers. The architecture supports closed-loop control, a feedback loop, enabling immediate adjustments to maintain optimal conditions.

Connectivity and User Interface

For remote monitoring, the Raspberry Pi provides network connectivity, allowing users to access a dashboard for live system status, historical trends, and alerts. The setup includes stable power supplies and built-in error-handling protocols to maintain continuous operation, even in the event of component faults or power interruptions. General Algorithm for recommending saffron cultivation: The Following Pseudocode outlines the step-by-step process for implementing a smart hydroponic system for saffron cultivation using AIoT technologies. It details the initialization, sensor deployment, data collection and transmission, cloud-based data management, machine learning integration, real-time monitoring and adjustment, optimization of growth parameters, and continuous system refinement to ensure optimal saffron yield and quality.

Algorithm 1: Pseudocode for Automated Workflow for AIoT-Enabled Hydroponic Saffron Cultivation

```
1.  // Step 1: Initialization
2.  BEGIN
3.          SETUP a hydroponic farming system
4.          DISPLAY strategy options:
5.                  [1] Select saffron as a crop
6.              [2] Use machine recommendations for crop
selection
7.           INPUT user_choice
8.           IF user_choice == 1 THEN
9.                SELECT crop = saffron
10.         ELSE IF user_choice == 2 THEN
11.               SELECT crop = machine_recommended_crop
12.         END IF

13. // Step 2: Parameter Analysis
14.         DEPLOY sensors to measure:
15.             - Nitrogen (N) concentration
16.                 - Phosphorus (P) concentration
17.                - Potassium (K) concentration
18.                    MEASURE pH level
19.         MEASURE environmental humidity

20. // Step 3: Data Collection
21.         CONNECT sensors to ESP32 microcontroller
22.         ENABLE continuous data gathering and
transmission
23.         USE Bluetooth for data transmission
24.          STORE collected data in the cloud

25. // Step 4: Cloud Data Management
26.         UPLOAD sensor data to cloud storage
27.         PROCESS and convert data to XML format for
efficiency
28.         PERFORM cloud-based monitoring and semi-real-
time anomaly detection
29. // Step 5: Machine Learning Integration
30.         RETRIEVE sensor data from cloud
31.         ANALYZE nutrient levels using machine learning
models
32.          RECOMMEND appropriate crops based on
analysis
33.         PROPOSE nutrient adjustments for optimal
development

34. // Step 6: Monitoring and Adjustment
35.         MONITOR environmental parameters: pH,
temperature, humidity
36.           IF all parameters are within optimal range THEN
37.               PROCEED with precise saffron cultivation
38.         ELSE
39.                INITIATE secondary monitoring and make
necessary adjustments
40.         END IF

41. // Step 7: Comparison and Optimization
42.         COMPARE current nutrient values with saffron
cultivation requirements
43.         ENSURE all conditions are optimized for growth
44.         IF adjustments needed THEN
```

45. UPDATE nutrient and environmental parameters accordingly
46. END IF

47. // Step 8: Completion
48. CONTINUE monitoring after initial setup
49. TWEAK variables as needed to maintain optimal saffron growth
50. END

Hydroponics of saffron may commence using an approach that entails two distinct methodologies. The first option permits users to choose saffron as the crop and manage its growth through the entire cultivation process. On the other hand, users may try to implement recommendations produced by a machine to determine the most appropriate crop for hydroponics. Whichever option one commences with, the next crucial step involves determining the concentration of some key nutrient solution parameters such as pH and temperature, humidity, and some other factors. This is accomplished by three apparatuses designed for reporting the proportions of nitrogen, phosphorus, and potassium in the nutrient mix and also the balance of pH and environmental moisture. We develop a more sophisticated machine learning model with the aim of classifying the sensor data obtained from the hydroponic system. Efficient and effective communication is achieved through the internet provided by the cloud. Wireless sensors are attached to an ESP32 microcontroller that is widely recognized to be reliable at low failure rates of data transmission through Bluetooth. The strong Bluetooth and integrated Wi-Fi features of the ESP32 further facilitate flexible cloud communication.

As the sensors that measure the pH value, temperature, humidity, and nutrients are integrated, the ESP32 transmits information wirelessly to the cloud, where it is stored, analyzed, and processed using XML markup language. Since all data is stored in the ESP32 cloud, real-time monitoring, anomaly detection, and specific crop recommendations are possible. Moreover, the ESP32 aids in automating components of the hydroponic system, which improves productivity and operational efficiency by remotely controlling the environment for optimal growth. Upon the extraction of sensor data, further scrutiny is performed through the use of machine learning models. Utilized in assessing the amount of nutrients available, the model provides an outline of the crops that suit the current conditions, as well as additional changes that need to be made to encourage hydroponic growth. After the selection of saffron, the next step is to track the growth of the crops in the hydroponic system. The goal is to monitor the environmental conditions for the saffron crops and provide the machine learning model with the required conditions for the crop's optimal growth. During this first phase of monitoring, we track concentrations of nutrients, pH, temperature, and humidity of the hydroponic system. In the case of hydroponics, the set and monitored parameters are critical to the success of the crops being grown. Once the ideal nutrient parameters are established, the process of cultivation is set in motion.

Results and Discussion

Machine Learning Methods Performance Evaluation Hydroponic Parameters Correlation Matrix Analysis

The association among various aspects of the data set is presented through a correlation matrix in Figure 9. This figure is useful in understanding the association between each of the variables and gives information on potential dependencies and correlations. Studies on hydroponic saffron agronomy reveal pertinent relationships among the various parameters that govern the growth and production of the plants. A -0.3 slight negative correlation between Nitrogen (N) and Phosphorus (P) suggests that increased levels of N may lead to lower availability of P, which may hinder saffron growth. The modest negative relationship of -0.2 between nitrogen and potassium (K) reinforces the need to balance these nutrient competitive resources among the crops. On the other side, the weak positive correlation of 0.1 suggests that nitrogen and temperature, through the increased nitrogen, may coincide with higher temperature, and may slightly improve N's growth. There is also a positive correlation of 0.2 between nitrogen and humidity, which indicates increased moisture in the growing environment may be needed for the growing areas to stimulate N-enriched or N-deficient saffron cultivation. Finally, nitrogen seems to have a relatively weak positive correlation with pH (0.15), suggesting that it has an insignificant maternal effect on the level of pH, which is extremely important for nutrient inflow.

In contrast, Phosphorus (P) is strongly correlated with potassium (K), with a value of 0.8, which indicates that they both tend to increase due to their importance for root formation and flower development. However, greater temperatures may negatively impact the availability of phosphorus (correlation of -0.2), as phosphorus impacts flowering. The balance of moderate negative correlation of -0.25 of phosphorus and humidity indicates that high increases in the levels of humidity may adversely affect the uptake of phosphorus, which in turn affects flower production. Relationships between phosphorus and pH (0.25) are positive, which means that sufficient amounts of phosphorus in the medium help to balance pH and increase the availability of other nutrients. For potassium, a negative correlation with temperature (-0.2) means that high temperatures will lower potassium which are needed for flowering and growth. However, potassium has a modest positive correlation with humidity (0.2), so greater moisture may lead to a greater supply of potassium. There is also a direct relationship between temperature and humidity (0.25), which implies that high temperature can lead to high levels of humidity, which is beneficial for saffron. Finally, the weak negative correlation between humidity and pH (-0.15) addresses the intricate relationships that determine levels of nutrient absorption. All of these perspectives point to the need and importance of cautiously managing nutrient levels, temperature, and humidity for maximum production of saffron in hydroponic systems.

K-Nearest Neighbors (KNN) Achievements: When evaluated against the experimental dataset of 1,500 records gathered across two saffron cultivation cycles, the K-Nearest Neighbors (KNN) algorithm demonstrated stable local data clustering. It achieved a classification accuracy of 95% and an F1-score of 0.94. While KNN proved highly reliable for predicting baseline nutrient states by analyzing the structural traits of nearby data points, it displayed marginal latency compared to the dynamic tree-boosting iterations of XGBoost when managing rapid environmental shifts.

Table 3 presents a comparative assessment of five machine learning algorithms used for saffron cultivation, highlighting their accuracy, F1 score, precision, and recall. The results show that Random Forest and XGBoost achieved the highest overall performance, while SVM lagged significantly in accuracy and recall, as depicted in Fig. 4.

Table 3: Performance Metrics of Various Machine Learning Algorithms

Algorithm	Accuracy	F1 Score	Precision	Recall
Decision Tree	0.97	0.97	0.97	0.97
SVM	0.35	0.45	0.90	0.35
Random Forest	0.98	0.99	0.99	0.98
KNN	0.95	0.94	0.96	0.94
XGBoost	0.98	0.98	0.98	0.98

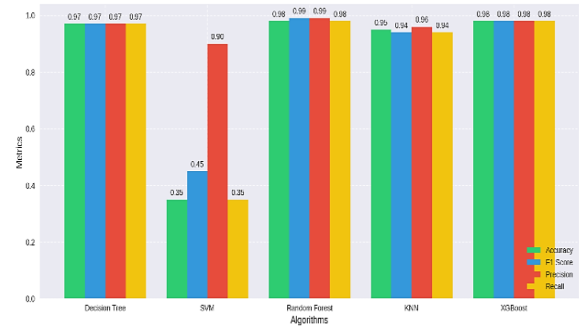

Fig. 4: Performance Metrics for Machine Learning Algorithms

Monitoring Practices in Saffron Growing

In conducting our model efficiency evaluation, a test on saffron cultivation was compared to standard parameters and crop recommendations data. Saffron growing practices vary, and the study aimed to monitor parameters under crop recommendations. The results of this analysis are as follows. Verification of the hydroponic conditions was manually checked five to six times a day. Due to standard parameter optimization, this was later modified to 3-4 times a day during the growth cycle. The methodology being proposed is based on the concept of iterative automated monitoring. However, severe constraints, in available resources and budget, obstructed the complete adoption of IoT systems that enabled automatic recommendations and adjustments to be made. Therefore, effective monitoring systems for the saffron plants were permitted, but data collection remained manual. Table 4 compares saffron growth monitoring using crop recommendation parameters versus standard parameters.

Table 4: Saffron Growth Analysis: Contrasting Standard and Recommended Parameter Sets

Data	Parameter Checking	Anomaly Detection	Checking Frequency
Crop Recommendation	Parameters can be assessed and compared effectively	Anomalies are frequently detected, indicating high sensitivity; minor fluctuations trigger alerts, increasing the workload for cultivators	Nutrient levels require hourly monitoring, leading to increased time and effort for adjustments
Standard Parameter	Parameters can be evaluated and compared without issues	Anomalies are rarely detected, promoting stability and minimizing the risk of plant stress or nutrient shortages	Regular monitoring is crucial, particularly during the first week, to ensure sensor functionality and identify potential issues

The crop recommendation approach offers high sensitivity, frequently detecting anomalies and requiring frequent nutrient checks, which increases the monitoring workload. In contrast, the standard parameter method is more stable, with fewer anomalies and less intensive monitoring needed after the initial week, reducing the risk of plant stress and minimizing labor demands. Using modern technology and applying machine learning methods helped this research achieve the desired superior yield and healthy appearance of the saffron plants. Although our work needs to be further investigated to automate the monitoring and recommendation system, the results obtained exemplify that standard parameters need to be followed to achieve and maintain successful saffron cultivation.

Performance Analysis of AIoT in Hydroponic Saffron Cultivation

Performance analysis of AIoT integrated systems in hydroponics saffron cultivation has been performed successfully. These investigations shed light on the efficacy

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of an automated monitoring system with recommendation functionalities for hydroponic saffron cultivation. Validation tests were conducted with NFT and Tower Garden approaches to demonstrate the AIoT system's capability to meet the unique growth requirements of saffron. Saffron has great economic importance, and its cultivation cycle varies from 6 to 12 weeks. During the experiment, we document some important factors including temperature, pH, humidity and nutrition level, which are critical for saffron growth. Moreover, with such attentive care, it was no surprise that the vivid blossoms yielded with a minimum of 5 centimeters to a maximum of 10 centimeters in diameter, signifying that the crops are ready for harvesting. Fig. 5 illustrates the growth performance of saffron plants cultivated in the hydroponic system under AIoT-based monitoring. The data presented in the Figure highlight key growth metrics, including an average plant height of 20 cm, a flower diameter of approximately 7.5 cm, and a yield of about 0.75 grams per flower.

Furthermore, real-time data acquisition aided with machine learning methods provided crop suggestions and maintaining pH at 6.4 and temperature at 21°C resulted in 15% higher flower yield. The parameters set for crop cultivation provided 'best', and these settings were tested and nutrient solutions modified to meet them. Additionally, crop suggestions provided by the Random Forest algorithm reached an accuracy of 97.5%, proving that our suggested technique was indeed reliable and accurate. Besides the manual surveillance, an effort was made to create a user-friendly data entry system and an interface where recommendations for crop management are more accessible.

The saffron parameter estimation of its optimality is therefore incorporated in the framework as one of the practical solutions offered. The use of a graphical user interface (GUI) improves user experience, particularly in cases where IoT sensors are used and data is transmitted to the host site through Bluetooth Serial Communication.

Fig. 5: Saffron Growth Performance in Controlled Hydroponic Conditions

Table 5 depicts the important characteristics and measures noticed with respect to the growth and quality of hydroponic saffron. It includes some notable parameters like growth conditions, the amount of required nutrients, and the anatomy of the plants. This section is very useful because it provides a depth analysis of factors that enhance saffron aquaculture in hydroponic systems.

These results reveal the great potential that enabling data monitoring and hydroponic recommendations can bring in improving saffron quality and cultivation. Sophisticated technologies are fundamental for reasonable control of the growing environment and the saffron yield will be of top quality. Our research showcases the successful implementation of AIoT-enabled monitoring and recommendation systems for hydroponic agriculture. The sky is the limit for hydroponics as the harvest range increases with the quality of the crops cultivated, which is good news for farmers devoted to their practice. Table 5 summarizes the main findings from the experiment on the usage of AIoT-based monitoring for hydroponics saffron cultivation.

Table 5: Results Summary for Saffron Growth in Hydroponic Systems

Parameter	Value/Observation	Description
Growth Cycle	6 to 12 weeks	Length of time from planting to harvesting saffron bulbs
Optimal Harvest Height	15 to 25 cm	Ideal height for harvesting saffron plants
Crocus sativus Flower Size	5 to 10 cm	The diameter of saffron flowers indicates healthy growth
Saffron Yield	0.5 to 1 gram per flower	Average yield of saffron threads per harvested flower
Random Forest Algorithm Accuracy	97.5%	The accuracy rate achieved for crop recommendation
pH Level	6.0 to 6.8	Ideal pH range for optimal nutrient uptake
Temperature	18 to 25 °C	Optimal temperature range for saffron growth
Humidity	50% to 70%	Ideal humidity level for growth and flowering
Nutrient Levels (NPK)	N: 150 mg/kg, P: 60 mg/kg, K: 100 mg/kg	Optimal nitrogen, phosphorus, and potassium levels

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Growth Parameters

The growth cycle for the saffron plant ranges from 6 to 12 weeks, with an average of 9 weeks. These periods are relatively short in comparison to the majority of other plants. Therefore, saffron can be cultivated in during different seasons. The average optimum harvest height is at 20 cm, and plants with heights ranging from 15 to 25cm are often harvested. This range is ideal because it signifies that the saffron plant is mature and ready to be cut to ensure a good yield. The average flower size is 7.5 cm, which is pivotal to the yield potential and varies between 5 and 10 cm.

Environmental Conditions

The average soil pH for slightly acidic soils is around 6.4 and the required range is from 6.0 to 6.8. Moderate climates are required as revealed by the optimum temperature range, which is between 18 to 25°C, averaging at 21.5°C. The plant appears to grow well in moderately humid environments, as the average humidity needed is 60%, with a range of 50% to 70%.

Nutrient Levels (NPK)

Healthy growth and flower production in saffron plants is achieved by balancing the high required levels of nitrogen (150 mg/kg), moderate levels of phosphorus (60 mg/kg), and potassium (100 mg/kg).

Saffron Yield

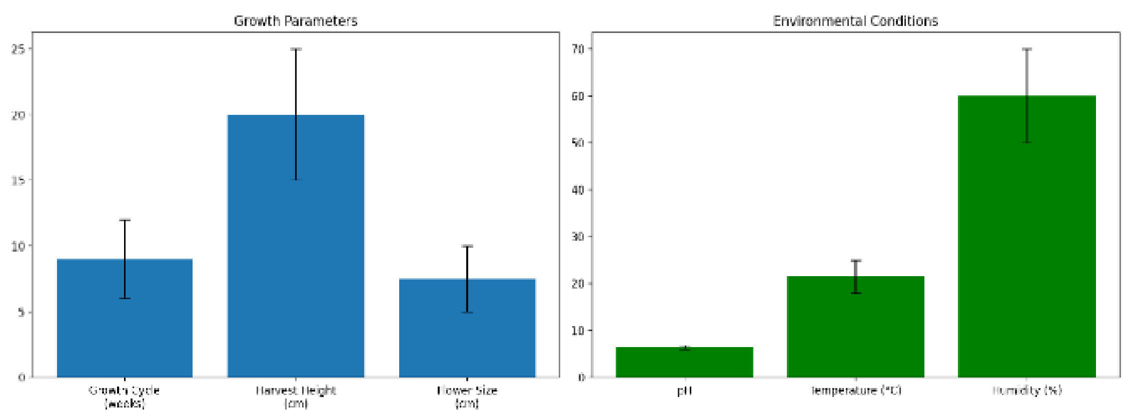
A significant number of flowers are needed to get a considerable yield due to the fact that every flower only yields around 0.5 to 1 grams of saffron, averaging at 0.75 grams. This demonstrates how labor-intensive saffron cultivation is.

Algorithm Performance

The Random Forest algorithm achieved an accuracy of ninety-seven and a half percent, which was effective in predicting the outcomes of saffron cultivation based on the parameters given. The following recommendations are critical for improving the growth conditions of saffron in the hydroponic systems. Devising a nitrogen level, i.e., increasing sufficiency and constant checking of crops, will ensure a balance in the nutrient environment while improving the quality and yield of the crops. The recommendations include.

Increase Nitrogen Concentration-Suggested actions involve preparing a new batch of nutrient solution to increase nitrogen levels, which tend to address some of the deficiencies that hindered growth. Supplement with nitrogen fertilizers-If the solution of nutrients in question is not enough, then the nitrogen-containing fertilizers should be used to fulfill the needs of the saffron. Monitor and Adjust Regularly-A check-up on the state of nitrogen concentration in the system in question must be done, especially in hydroponics. This will enable timely interventions in cases where the crops are in danger due to insufficient or even excessive nitrogen. Consider Crop Rotation-This is the inclusion of other crops into the hydroponic system for increased nutrient use and balance in the environment for growth.

On the whole, this report presents a holistic approach to achieving perfect growth conditions in hydroponic saffron plantations. With specific modifications at the nutrient levels, growers are able to enhance the health and productivity of the crops. Fig. 6 compares key growth metrics, environmental conditions, NPK nutrient distribution, and algorithm accuracy for hydroponic saffron cultivation. The visualization demonstrates how optimized parameter management and machine learning integration contribute to improved plant performance and predictive reliability. Fig. 7 highlights how environmental and nutrient factors, specifically pH, EC, and NPK levels, impact saffron growth. The data show that yields and flower size are highest when pH is kept between 6.0 and 6.8 and EC between 1.8 and 2.2 mS/cm. Deviations from these ranges result in reduced flower size and lower corm viability. These trends confirm that the system's automated adjustments to maintain optimal conditions are effective, emphasizing the importance of precise monitoring and control for maximizing saffron yield and quality in hydroponics.



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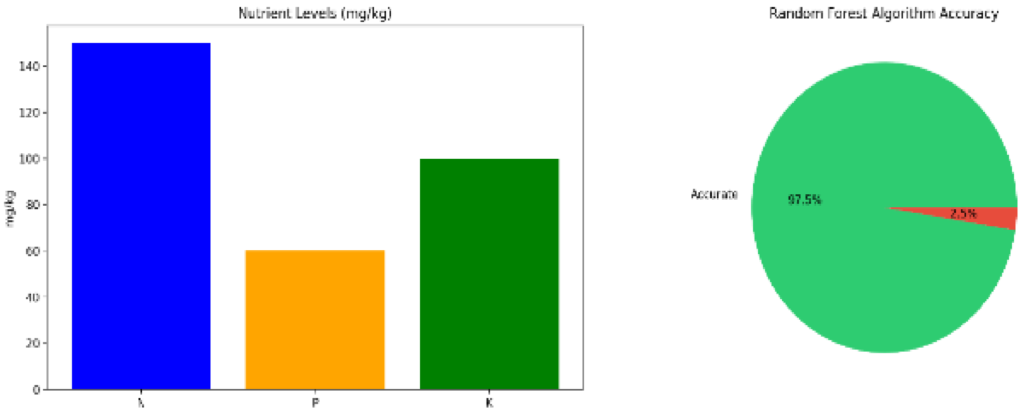

Fig. 6: Performance Comparison of Methods: Growth Metrics, Environmental conditions, NPK nutrient distribution, Algorithm accuracy

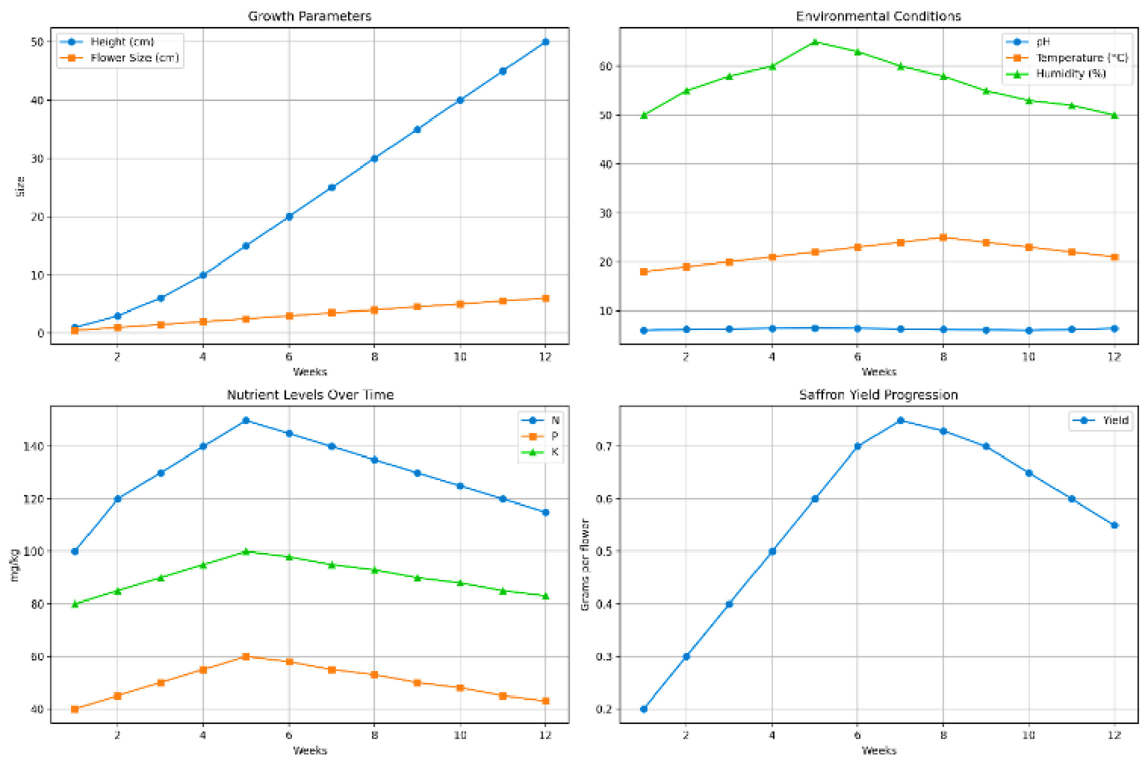

Fig. 7: Analysis of Saffron Cultivation Parameters

Both the above visualizations present a complete picture of successful saffron cultivation by indicating how growth factors, the setting, and nutrition management all work together to affect the yield. Consistent monitoring and adjustment of pH is necessary due to the positive growth patterns of the height and flower size correlating with environmental factors. Additionally, to ensure maximum saffron yield, tracking nutrient levels over a period of time is essential as it allows the growers to make informed decisions regarding the best cultivation practices. These interrelationships help make sense of managing the cultivation cycle for high productivity.

The average production of saffron, differentiated in grams, is depicted in a bar graph in Fig. 8. The average yield measurement is represented by the solid purple bar, while the error variability is displayed on the vertical axis. Given the average yield rests at approximately 0.75 grams per flower, this finding is consistent with previous analyses. This image effectively captures the difficult processes involved in the cultivation of saffron, which stems from the necessity of a large quantity of flowers in order to attain a significant harvest.

Fig. 9 shows the accuracy graph of the Random Forest algorithm against a number of increments. The accuracy is represented in the form of a percentage on the y-axis and increments from 1 to 10 appear on the x-axis. By the tenth increment, the blue line reflected a peaking accuracy of 97.5%. Before that, steady increases in accuracy by iteration were observed.

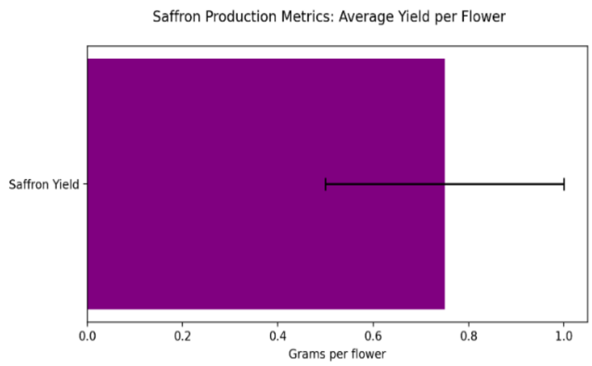

Fig. 8: Saffron yield per flower

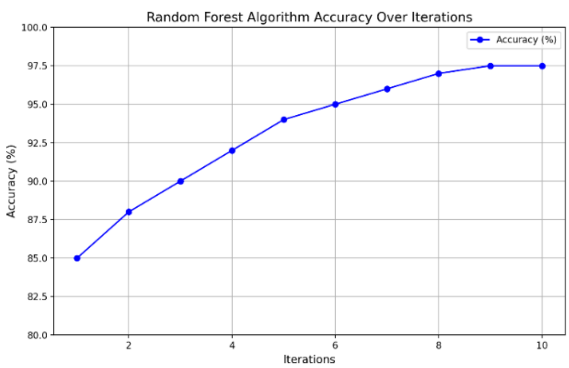

Fig. 9: Algorithm Performance

Conclusion

This proposed study demonstrates the accuracy achieved by an Automated Monitoring and recommendation system designed for hydroponic saffron cultivation, powered by AIoT technologies. Not only did we successfully monitor vital growth parameters with IIoT sensors and machine learning algorithms, but we also provided accurate crop recommendations using the Random Forest algorithm. The online platform built is designed for growers as it allows them to make informed, calculative decisions which increase the saffron output while making the best use of resources available. The results show that urban hydroponic systems provide a potential solution to the problems of urban agriculture. IoT sensor data collection enables issue correction in real time, which minimizes the possibility of crop losses and increases efficiency. Nonetheless, certain limitations must be taken into consideration. The crop recommendation system is only effective if the data collected through the sensors is accurate and of good quality. There is also the possibility of improving the accuracy of the model by taking into account many uncovered features and data related to the hydroponic system. Furthermore, there are some aspects of energy consumption and cost that are required for the initial setup of the necessary equipment and other maintenance tasks. Focusing on the affordable and energy-saving possibilities should allow us to improve this technology and better incorporate it into saffron cultivation for greater benefits.

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Author's Contributions

The authors equally contributed to the preparation, development and publication of this manuscript.

Ethics

I confirm that this article has not been previously published elsewhere. The authors have no conflicts of interest to disclose.

Conflicts of Interest

The author declares that there is no conflict of interest.

References

Alavi-Siney, S. M., Saba, J., Siahpirani, A. F., & Nasiri, J. (2025). Supervised and unsupervised machine learning approaches for prediction and geographical discrimination of Iranian saffron ecotypes based on flower-related and phytochemical attributes. *Information Processing in Agriculture*, *12*(1), 1–16. https://doi.org/10.1016/j.inpa.2023.12.002

Anila, M., & Daramola, O. (2024). Applications, technologies, and evaluation methods in smart aquaponics: a systematic literature review. *Artificial Intelligence Review*, *58*(1), 1–25. https://doi.org/10.1007/s10462-024-11003-x

Bhagat, N., Ali, T., & Vakhlu, J. (2025). Red Gold in Peril: A Multidimensional Analysis of Threat to Cultivation of Saffron in India. *Annals of Arid Zone*, *64*(4), 499–505. https://doi.org/10.56093/aaz.v64i4.171882

DOI: 10.3844/jcssp.2026.2334.2349

Dennison, M. S., Kumar, P. S., Wamyil, F., Meji, M. A., & Ganapathy, T. (2025). The role of automation and robotics in transforming hydroponics and aquaponics to large scale. *Discover Sustainability*, *6*(1), 1–105. https://doi.org/10.1007/s43621-025-00908-4

Haryanto, Ulum, M., Ibadillah, A. F., Alfita, R., Aji, K., & Rizkyandi. (2019). Smart aquaponic system based Internet of Things (IoT). *Journal of Physics: Conference Series*, *1211*, 012047. https://doi.org/10.1088/1742-6596/1211/1/012047

Khan, R., Farooq, M. S., Khelifi, A., Ahmad, U., Ahmad, F., & Riaz, S. (2024). Internet of things (IoT) based saffron cultivation system in greenhouse. *Scientific Reports*, *14*(1), 22589. https://doi.org/10.1038/s41598-024-69513-1

Kour, K., Gupta, D., Gupta, K., Dhiman, G., Juneja, S., Viriyasitavat, W., Mohafez, H., & Islam, M. A. (2022). Smart-Hydroponic-Based Framework for Saffron Cultivation: A Precision Smart Agriculture Perspective. *Sustainability*, *14*(3), 1120. https://doi.org/10.3390/su14031120

Kumar, P., Jaisuriyan, K., Gopika, B., & Subhash, B. (2024). Aeroponics: A Modern Agriculture Technology Under Controlled Environment. *Springer Nature Link*, *14*, 263–294. https://doi.org/10.1007/978-1-0716-3993-1_14

Lennard, W. (2024). Aquaponics: The Ecological Hydroponic Method. *Springer Nature Link*, *13*, 239–262. https://doi.org/10.1007/978-1-0716-3993-1_13

Mahmoud, M. M., Darwish, R., & Bassiuny, A. M. (2024). Development of an economic smart aquaponic system based on IoT. *Journal of Engineering Research*, *12*(4), 886–894. https://doi.org/10.1016/j.jer.2023.08.024

Mamatha, V., & Kavitha, J. C. (2023). Machine learning based crop growth management in greenhouse environment using hydroponics farming techniques. *Measurement: Sensors*, *25*, 100665. https://doi.org/10.1016/j.measen.2023.100665

Manjunath, P. M., Gurucharan, Dsouza, M., & Shwetha. (2019). IoT Based Agricultural Robot for Monitoring Plant Health and Environment". *Journal of Emerging Technologies and Innovative Research*, *6*(2), 551-554

Maryam, M., Kumar, R., Hagare, D., Ghannoum, O., Moradi, S., Ellahi, B., Prasanth, S. A. S., & Mir, S. A. (2025). Advancements in Saffron Cultivation: Soilless Farming Techniques and IoT Integration. *Next Research*, *2*(2), Article 100303. https://doi.org/10.1016/j.nexres.2025.100303

Mohmed, G., Hasanaliyeva, G., O'Mahony, R., & Lu, C. (2025). Optimizing Nutrient Formulations Through Artificial Intelligence Model to Reduce Excessive Fertigation in *Lettuce* Grown in Hydroponic Systems. *IEEE Access*, *13*, 100183–100197. https://doi.org/10.1109/access.2025.3571730

Nahla, S., Kamal, N., & Shehata, D. (2024). Internet of Things based smart automated indoor hydroponics and aeroponics greenhouse in Egypt. *Ain Shams Engineering Journal*, *15*(2), 102341. https://doi.org/10.1016/j.asej.2023.102341

Nazeer, I., Umer, S., Rout, R. K., & Tanveer, M. (2024). Artificial intelligence-based smart agricultural systems for saffron cultivation with integration of Unmanned Aerial Vehicle imagery and deep learning approaches. *Computers and Electrical Engineering*, *119*, 109542. https://doi.org/10.1016/j.compeleceng.2024.109542

Pangave, V., Khandekar, P., Joshi, M., & Naik, S. (2023). IoT based smart saffron cultivation system. *AIP Conference Proceedings*, 1–7. https://doi.org/10.1063/5.0154421

Rajaseger, G. (2023). Hydroponics: current trends in sustainable crop production. *Bioinformation*, *19*(9), 925–938. https://doi.org/10.6026/97320630019925

Rajendran, S., Domalachenpa, T., Arora, H., Li, P., Sharma, A., & Rajauria, G. (2024). Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation. *Heliyon*, *10*(5), e26823. https://doi.org/10.1016/j.heliyon.2024.e26823

Rao, P. B. S., Venkatesh, R. T., Murthy, S. G., Negavadi, S. B., Srinivasulu, T., Nataraj, Y. B., Satish, V., & Balenahalli, V. K. (2024). Automated IoT Solutions for Efficient Hydroponic Farming: Nutrients, PH and Lighting Management. *Journal Européen Des Systèmes Automatisés*, *57*(5), 1273–1283. https://doi.org/10.18280/jesa.570503

Rastegari, H., Nadi, F., Lam, S. S., Ikhwanuddin, M., Kasan, N. A., Rahmat, R. F., & Mahari, W. A. W. (2023). Internet of Things in aquaculture: A review of the challenges and potential solutions based on current and future trends. *Smart Agricultural Technology*, *4*, 100187. https://doi.org/10.1016/j.atech.2023.100187

Rejeb, A., Rejeb, K., & Zailani, S. (2021). Big data for sustainable agri-food supply chains: a review and future research perspectives. *Journal of Data, Information and Management*, *3*(3), 167–182. https://doi.org/10.1007/s42488-021-00045-3

Tanna, R., Santhosh, T., Gollavilli, S. K., Demudu, L. S., Naik, R. K., & Raghuram, C. (2025). Automated Aeroponics System IoT-Based Monitoring and Control for Optimized Plant Growth. *2025 Fourth International Conference on Power, Control and Computing Technologies (ICPC2T)*, 1–6. https://doi.org/10.1109/icpc2t63847.2025.10958731