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AI-Driven Smart Fertigation: Integrating IoT and Machine Learning for Sustainable Precision Agriculture

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Abstract

Smart fertigation, integration of irrigation and fertilization through precision agriculture is revolutionizing modern farming with Internet of Things (IoT) and Machine Learning (ML) technologies. These innovations enhance water and nutrient management, minimize human intervention, and promote sustainability. This study reviews recent advancements in IoT-based fertigation systems, emphasizing ML models such as Support Vector Machines, Extreme Gradient Boosting and deep learning techniques for predictive analysis. Additionally, real-time sensor networks, cloud computing, and optimization methods like fuzzy logic are explored for their role in improving resource efficiency. A structured literature review identifies key challenges, including scalability, interoperability, and cost constraints. Comparative evaluations highlight the effectiveness of various ML models in precision fertigation. The findings demonstrate the potential of AI-driven fertigation for enhancing agricultural productivity and sustainability. Future research should focus on hybrid AI models, blockchain-based secure data management, and large-scale IoT deployment to further optimize smart fertigation systems.

Keywords: Smart fertigation, Internet of Things, Machine Learning, Support Vector Machines, Cloud computing.

1. Introduction

Agriculture plays the vital role in increasing an economy of the country; fulfilling food demand by increasing the production yield. In modern era different technologies are used to focus on crop production. These technologies save time and money of the farmers, also maintain the eco-balance of the environment. The role of IoT based smart farming is to modernise the agriculture with automation systems and minimise human intervention. An integration of IoT devices and Artificial Intelligence into decision support systems is transforming traditional farming into smart and sustainable farming. Sustainable fertigation combines fertilization with irrigation to deliver nutrients directly to the plant roots at optimal times and optimum quantities.

Smart fertigation became essential in modern agriculture, which addresses the critical need for optimizing resource utilization while enhancing crop productivity [1]. The growing demand for sustainable and efficient farming practices has accelerated the trends of advanced technologies such as Internet of Things (IoT), machine learning (ML), and data-driven decision-making need to be adapted for sustainable fertigation [2]. Traditional agricultural methods often struggle with inefficiencies in water and fertilizer management, leading to excessive resource consumption, environmental degradation, and higher production cost [3]. To mitigate these challenges, researchers have explored smart agricultural solutions, including IoT enabled monitoring systems, predictive ML models, and optimization techniques such as fuzzy logic, to develop more precise and automated fertigation strategies [4].

Recent studies highlight the effectiveness of integrating ML and IoT in improving irrigation efficiency and nutrient management. Advanced Machine Learning models such as Support Vector Machines (SVM), Extreme Gradient Boosting (XGB), and Multilayer Perception (MLP) [5] has demonstrated high accuracy in predicting fertilizer concentrations by using measurable parameters like electrical conductivity (EC), pH and soil temperature. Meanwhile, IoT based frameworks equipped with real-time sensors and cloud computing facilitate continuous monitoring of important factors such as soil moisture, pH, temperature, level of three key nutrients in the soil: Nitrogen (N), Phosphorus (P), and Potassium (K) (NPK) condition of soil, humidity and evapotranspiration [6]. Furthermore, optimization approaches such as fuzzy logic and evolutionary algorithms have been employed to dynamically regulate irrigation and fertilization based on real-time environmental and plant conditions [7]

This study explores the latest advancements in precision fertigation, with a particular focus on integrating IoT, ML, and data-driven optimization techniques to enhance agricultural productivity. By analysing recent research on smart fertigation systems, this work provides valuable insights into the effectiveness of various methodologies in achieving sustainable water and nutrient management, ultimately contributing to the development of more efficient and environment friendly farming practices.

2. Literature Review

A comprehensive literature review on smart irrigation and fertigation should highlight key advancements in IoT and machine learning (ML) for precision agriculture [8]. Integrated ML models with physical parameters like Electrical conductivity (EC), pH, and temperature for accurate fertilizer concentration prediction. demonstrating high R^2 values (0.989–0.997) [9]. E. A. Abioye et. al. implemented an IoT-based drip irrigation system for mustard leaf cultivation, optimizing soil moisture prediction with ARX models used IoT with ML models (RF, CNN, RNN, LSTM) for automated fertigation in controlled environments [10] introduced a solar-powered IoT fertigation system, optimizing irrigation scheduling using ETo models [11]. Menglong Wu et. al. developed a smart fertigation system with fuzzy logic and IoT for chilli production, improving resource efficiency [12]. These studies collectively emphasize IoT and ML's role in enhancing precision irrigation, sustainability, and resource management in agriculture.

The Agriculture automation played crucial role for revolutionized agriculture using IoT and artificial intelligence for real time monitoring and control of agriculture application with intelligence as compared to human effort [13]. The use of ESP32 microcontroller and IoT sensors are effective in managing the system parameter like temperature, EC and moisture content in soil to improve the fertigation system as per the nutrient level of the soil [14]. The significant improvement as compared to traditional method is possible by using Root mean square error [RMSE] and correlation coefficient, this research contributes the development reliable and efficient security system based on WSN and deep learning concept [15].

Thematic Analysis

The research work in the area of sustainable precision agriculture is based on key technological advancements, including:

i) Machine Learning Models: SVM, CNN, RNN, LSTM, XGBoost, ARX, etc

ii) IoT-based Frameworks: Sensors like EC, pH, soil moisture, temperature, Cloud computing, Edge AI.

iii) Sustainability and Resource Efficiency: Water conservation, fertilizer optimization, solar-powered irrigation

iv) Compare different methodologies, frameworks, and performance metrics (R^2, RMSE, accuracy, water savings)

Comparative Evaluation and Synthesis

i) Identify the strengths, limitations, and gaps in existing studies.

ii) Compare studies based on experimental validation, dataset size, real-time implementation, and integration with decision-support systems.

iii) Highlight trends in ML algorithms and IoT-based automation, emphasizing their impact on crop yield, water use efficiency, and sustainable agriculture.

3. Research Gaps and Future Direction

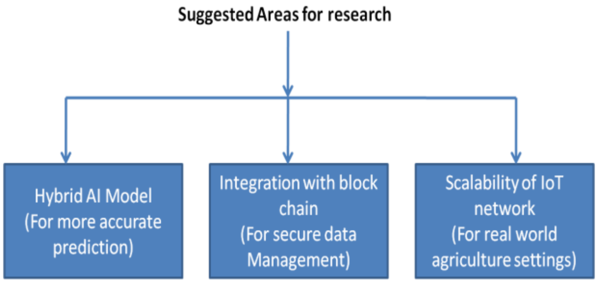

Figure 1. Suggested areas of research

Limitations in existing systems for sustainable precision agriculture are lack of large-scale field trials, interoperability issues, energy consumption, or cost constraints. Suggested areas for further research are shown in fig. 01

4. Problem Statement

In uncertain weather conditions, management of water and fertilizer resources in agriculture remains a challenge, especially in the mixed variable-rate fertigation systems. Technological constraints and cost constraints hinder precise monitoring and optimization of fertilizer concentrations, irrigation components, and crop growth. This proposed system aims to integrate ML and IoT technologies to enhance the efficiency of fertigation systems by accurately predicting fertilizer components, optimizing irrigation, and improving resource utilization, while also addressing environmental sustainability

5. Proposed Architecture of Fertigation System

The proposed architecture of fertigation system shown in figure 2. Fertigation system consist of different types of sensors are used to take the soil information from agriculture land and provide such information to arduino based system for further processing.

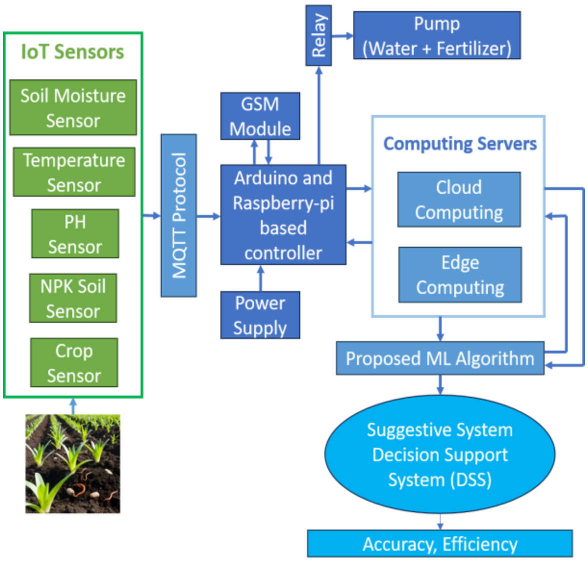

Figure 2. Proposed architecture of Fertigation System

The field data transmission is enabled by Message Queue Telemetry Transport (MQTT) messages. Agriculture field information and the data sensed by the IoT sensor are to be given to machine learning algorithm (core of the Decision Support system - DSS system) for further processing to provide fertilizer and irrigation recommendations and predictions. The Field data is stored in cloud for future use and proposed ML algorithm is used to analyse and optimized the data and recommended the require fertilizer and water supply to increase the crop production and maintain the efficiency and sustainability

6. Technologies Used in Smart Fertigation

Smart fertigation is the combination of irrigation and fertilizers with precision agriculture. Different advance technologies are used to find the solution on smart farming to improve the performance of crop and also increase the efficiency and accuracy. In this survey and review it is found that, different researcher has done their research by using different techniques to get the accuracy and efficiency in fertigation. The following table compares the different techniques, their descriptions and key benefits for sustainable fertigation to increase the production yield

Table 1: Error rates for four different trials.

Technology Category	**Description**	**Key Benefits**
Advanced Sensor and IoT Networks	Deployment of useful sensors for soil, plant, and environment and wireless connectivity for data aggregation.	Real-time monitoring, precision data, and enhanced decision-making
AI, Machine Learning & Digital Twins	Utilization of predictive analytics, simulation modelling, and digital twin representations	Optimized fertigation scheduling, proactive adjustments, and risk mitigation
Robotics and Automation	Integration of autonomous machinery, drones, and remote sensing for precise field operations.	Reduced labour, high spatial precision, optimal resource allocation
Renewable Energy & Fertilizer Innovations	Solar-powered systems coupled with advanced slow-release and controlled-release fertilizers.	Sustainability, energy efficiency, and minimized environmental footprint.
Blockchain & Data Management	Traceability systems for fertilizer usage and transparent documentation through	Enhanced regulatory compliance, sustainability reporting, and

Technology Category	Description	Key Benefits
	blockchain technology.	consumer trust.

7. Communication Technologies for IoT Enabled ML-Based Fertigation Systems

LoRa is one of the best options for **IoT-based fertigation systems**. Its capability to carry the signal in the long range, **very low power consumption** and **good infrastructure** makes it well-suited for **rural environment as well as large-scale agricultural** where the distance between sensors and central systems can be significant. LoRa offers a **range of up to 15 km** and can handle relatively **low data rates**, which is adequate for many fertigation systems where periodic monitoring of soil moisture, temperature, pH, and other parameters is required.

NB-IoT is another strong contender for regions where cellular networks are available, providing **reliable data transmission** with **low power** and relatively **low latency**. It offers better coverage than LoRa in urban or suburban areas but requires infrastructure that may increase costs in remote areas.

Zigbee can be suitable for **smaller farms** with a **local network of sensors**, especially when a **mesh network** is desired, but it has a **shorter range** compared to LoRa and NB-IoT.

8. Prediction and Implementation

SVR model with the RBF kernel can be used for predicting irrigation or fertilization levels based on real-time sensor data. The model will generate predictions like:

- The volume of water required for irrigation based on soil moisture, temperature, and other factors.
- The concentration of fertilizers needed for optimal crop growth.

These predictions can be used to adjust the **fertigation system** in real-time, ensuring optimal resource utilization.

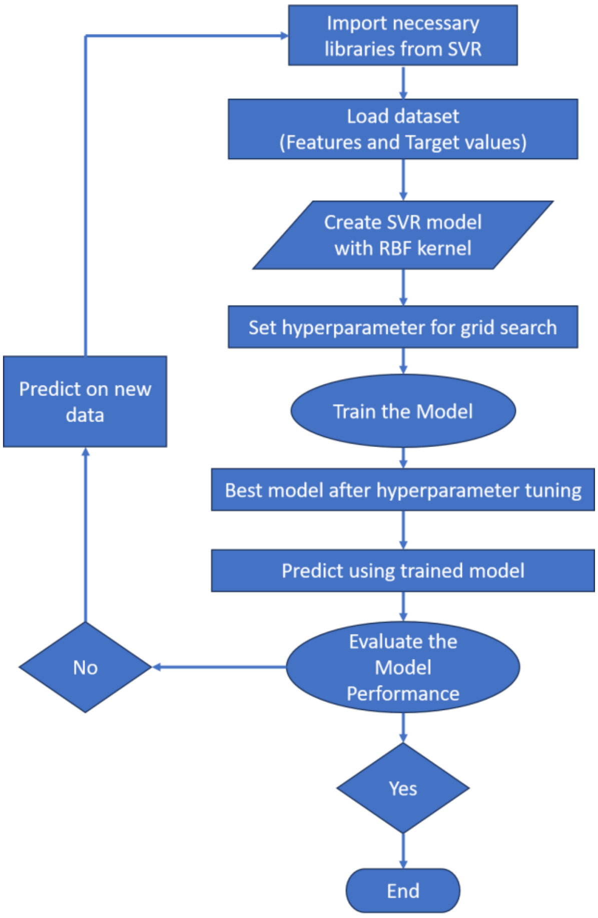

Figure 2. Proposed algorithm of Fertigation System.

Libraries in Proposed Algorithm

The nonlinear relationship between fertilizers and water are to be handled by using kernel function. Support Vector Regression (SVR) model uses regression task to predict continuous values. Grid Search CV is a hyperparameter tuning technique used to find the best combination of model by evaluating multiple combination of hyperparameter using cross validation. For non-linear relationship between water irrigation and fertilizers concentration, SVR model is best suited to get the high accuracy and efficiency in fertigation. Performance of the model can be evaluated by using Mean Squared Error, by measuring the average squared difference between the predicted and set or target value. Numpy is library for handling the arrays and numerical operation for creating input data.

Data Set, Model and Performance

X_train, X_test, y_train, y_test = load_data[ ]

load_data [ ]: This step is used for loading actual data set.

X_train, X_test: Ths data set is used for the input from the sensor like temperature, moisture and pH for training and testing.

y_train, y_test: This set is use for the target values like fertilizers and water for training and testing in fertigation use.

```
svr = SVR(kernel='rbf')
```

Radial Basic function (RFB) kernel is used to capture the nonlinear relationship between predicted and target variable. This pattern is very flexible to use.

```
Parameters = {'C': [1, 10, 100], ' γ ': [0.01, 0.1, 1, 'scale'], ' ε ': [0.1, 0.2, 0.3]}
```

C: - It is a regularization parameter, the higher value of c allow the mode to focus on fitting the data closely, but it may lead to overlifting.

```
grid_search = GridSearchCV(svr, parameters, cv=5)
```

```
grid_search.fit(X_train, y_train)
```

This function provides the cross validation with 5 folds (cv=5). It fits the SVR model to the training data set (X_train, y_train) with different parameter and select the best model for operation.

```
best_svr = grid_search.best_estimator_
```

It retrieves the best model after completing the grid search based on the hyperparameter that gives the best performance.

```
y_pred = best_svr.predict(X_test)
```

From the above step, after selecting the best model from the grid search(best_svr) to predict the target value (y_pred) on the test data(X_test)

```
y_pred = best_svr.predict(X_test)
```

mse = mean_squared_error(y_test, y_pred) to evaluate the model performance

```
print(f"Mean Squared Error: {mse}")
```

Mean Squared Error: {mse} is computed by comparing the average values of actual test data and predicted target data, from this computing tries to bring the lower value of MSE for better model performance.

```
new_data = np.array([[moisture, temperature, pH]])
```

```
 prediction = best_svr.predict(new_data)
```

```
printf("Predicted Fertilizer Concentration or Irrigation Volume: {prediction}")
```

best_svr.predict(new_data) is the trained model used to predict the target variable like fertilizers concentration and irrigation volume based on real time data from the sensor like temperature, moisture and pH of the soil based on the environmental condition.

9. Comparison of Different Machine Learning Models

In this survey and review, it has been found that, various machine learning models used in precision irrigation and fertigation systems based on their performance in terms of accuracy and efficiency. The following table compares various machine learning models used in fertigation systems based on their performance.

Table 2: Comparison of different ML models.

Model	**Key Performance**	**Performance Indicator**
Multivariate Linear Regression (MLR) [6]	Linear model, interpretable, relatively simple	**R²:** Low (0.5–0.7); **RMSE:** High (0.3–0.5)
Support Vector Machines (SVM)[6]	Non-linear model, effective with high-dimensional data	**R²:**0.989–0.997; **RMSE:** 0.089–0.210
K-Nearest Neighbors (KNN)[6]	Non-parametric, instance-based learning	**R²:** Medium (0.75–0.85); **RMSE:** Medium (0.2–0.4)
Extreme Gradient Boosting (XGB)[6]	Boosting algorithm, based on decision trees, focuses on optimization	**R²:** 0.95–0.99; **RMSE:** 0.1–0.2

10. Conclusion

In conclusion, the integration of IoT, machine learning, and fuzzy logic-based optimization has revolutionized precision fertigation and irrigation, leading to significant improvements in water and nutrient management. Advanced ML models, IoT driven monitoring systems, and decision-support techniques have enhanced the accuracy of fertilizer concentration prediction and irrigation scheduling. The incorporation of cloud computing, mobile applications, and renewable energy solutions further strengthens the potential of smart fertigation systems for large-scale implementation. However, addressing challenges such as model adaptability, cost-effectiveness, and real-world deployment is essential for widespread adoption. Future research should focus on self-learning fertigation systems, decentralized data management, and expanding implementation across diverse agricultural regions. By overcoming these challenges, smart fertigation systems can drive sustainable and high-efficiency agricultural practices, ultimately contributing to global food security and environmental conservation.

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