Smart Agriculture Prediction Using IoT in Al-Bahah Province

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Abstract

The integration of Internet of Things (IoT) and Machine Learning (ML) in agriculture may revolutionize the way farming is done, enhance productivity, increase resource efficiency, and promote sustainability. This paper explores the influence of IoT and ML adoption in agriculture in the Al-Bahah region on crop yields, water efficiency, and environmental sustainability. The research indicates that smart farming techniques can help in overcoming issues such as water scarcity, soil degradation, and pest control by using sensor-based data collection, predictive analytics, and automated decision-making. Results show that the IoT-based precision irrigation system has decreased water consumption by 25%, while crop selection and pest monitoring driven by ML have enhanced the quality of yield and reduced pesticide usage by 66.7%. Real-time monitoring of soil leads to better management of nutrients. It results in sustainable farming activities. The article has recommendations to the farmers and the policymakers; these include a call for the need for subsidy, investment in digital infrastructure, and capacity building. The utilization of IoT and ML can facilitate better food security, economic stability, and conservation of the environment by the Al-Bahah agricultural sector toward more general and comprehensive global goals for sustainability. This study highlights the potential of digital agriculture to transform the sector and promotes a collaborative approach between government agencies, private sector stakeholders, and agricultural communities in maximizing the benefits of smart farming in Al-Bahah and beyond.

Keywords: IoT, Machine Learning, Smart Farming, Precision Agriculture, Sustainability.

Introduction

Smart farming refers to the use of advanced technologies, such as IoT and ML, to enhance agricultural practices (Mohamed et al., 2021). Smart farming will foster higher efficiency, higher crop quality, and better resource utilization through automation and use of IoT sensors and data analytics. Smart farming can help to feed these people while solving concerns of an ever growing population – with some water scarceness and soil degradation (V. Sharma, Tripathi, & Mittal, 2022).

The farming landscape of the region is heterogeneous. The local farmers have problems with insufficient water resource, poor soil and instable climatic conditions. Farming in the traditional way mainly depends on hand work and outdated methods, consequently, the farmers are unable to overcome these challenges and engineered a low production and misuse of resources (Fischer & Connor, 2018). These are the type of challenges that draw attention to the need for modern approach to agriculture, embracing technological advancements to improve productivity and sustainability.

The first objectives of this research work are (a) to comprehend the role of IoT and ML integrated to change agriculture in Al-Bahah, a region in Saudi Arabia. The investigation on how such technologies can help solve unique problems in agriculture and, in particular, how to increase respective crop yield, water use optimization and climate and soil problem reduction is conducted in this paper. An in depth analysis of smart farming techniques, experimental setups as well as the effectiveness of IoT and ML interventions in agricultural practices in Al-Bahah are the scope of the study.

Problem Definition and Motivation

The traditional farming in Al-Bahah is less mechanized and based on seasonal rainfall and manual irrigation. Yet it destroys water efficiency and makes yields precarious, and is climate vulnerable. Apart from this, the soil is usually not fertile enough because more than enough land is over exploited and there is no available knowledge in modern farming techniques (Gomiero, 2016).

Such challenges require technological interventions, and there is growing need for them to be provided. New smart farming technologies such as IoT and ML can deliver the real time environmental information, soil health, crop performance information for better farm decision-making (Dhanaraju, Chenniappan, Ramalingam, Pazhanivelan, & Kaliaperumal, 2022). It automates irrigation, pest control and crop monitoring, but it makes the whole operation more efficient and thus saves costs (Abioye et al., 2020). The first motivation for using IoT and ML in the agriculture of Al-Bahah is to make the culture more sustainable and profitable. IoT gives farmers the ability to monitor the crops and environmental conditions, remotely and ML algorithms can learn based on the collected data, and predict what the optimal farming practices should look like (Rezk, Hemdan, Attia, El-Sayed, & El-Rashidy, 2021). These technologies present an opportunity to change the face of farming in Al-Bahah, economically, optimizing production through efficiency, producing sustainably and resilient against climate challenges.

Motivations and Objectives

One of the most driving forces to introduce IoT and ML in agriculture is to improve the crop quality and yield. IoT devices will help the farmers to gather soil condition, weather pattern and the health of the plants and provide real time feedback that the farmers can use to make the best possible practice based on the appropriate conditions. Further, the interpretation of weather forecasts and soil moisture is advanced in machine learning algorithms and irrigation needs can be predicted to further optimize.

Poor soil conditions, and climate change in general, are the constant challenges Al-Bahah is dealing with. However, IoT sensors used in the agriculture sector can give data of temperature, humidity, as well as soil moisture, so that farmers can adapt in these environmental changes. In addition to that, the ML models predict how different crops would perform in different climatic and soil conditions and farmer's decisions made based on such predictions would be successful.

Literature Review

Review of Existing Research on IoT and ML in Agriculture

Recently, we have seen tremendous integration of the Internet of Things (IoT) and Machine Learning (ML) into agriculture (Raj et al., 2021). As the growing world food demand, along with ever changing climate conditions disrupt the chances of sustainable agronomic practice, using technology driven solutions seem to be the need of the hour (Hemathilake & Gunathilake, 2022). IT and ML have surfaced in precision agriculture as transformative approaches to combat the resource use, improve the yield prediction, and mitigate the risks caused by the climate change, pests, and disease.

An IoT is a technology made up of a network of devices (sensors) and the interconnection between them, which are used to monitor environmental parameters, soil health, crop conditions & resource use such as water and fertilizers (Chamara, Islam, Bai, Shi, & Ge, 2022). The sensor can be embedded in the soil and monitor independently moisture and nutrient levels, attached to farming equipment to monitor efficiency, or (even) part of satellites scanning aerial views over agricultural land. These IoT enabled devices then collects data and then sends this data to a cloud based platform where the processing and analysis of this data can generate actionable insights (Al-kateeb & Abdullah, 2024).

An instance includes the provision of soil moisture sensors to monitor water consumption precisely. These assist farmers avoid the waste involved when water consumption becomes a "guestimate". Likewise, using temperature and humidity sensors can automatically update real time data of weather climate conditions where crops can also be prevented at initial stages in cases of destructive climatic influences (Majumdar, Mitra, & Bhattacharya, 2021). Lastly, water conservation takes the form in using IoT Automated irrigation systems: in the cases that rely fully on data sent at the spot time.

In water-scarce regions, it has shown great effectiveness in adopting IoT. The precision irrigation system based on IoT was seen to reduce the use of water by as much as 35%, yet yield the same or sometimes better output from the crops (Alharbi, Felemban, Abdelrahim, & Al-Dakhil, 2024). This, therefore, will be essential for areas where water is scarce in arid and semi-arid regions, as IoT will increase sustainability in agriculture. Machine Learning is an important tool for improving decision-making in agriculture by processing large amounts of data to spot hidden patterns (Hassan, Kowalska, & Ashraf, 2023). These algorithms process environmental data, historical trends, and weather forecasts to generate decisions that help farmers be proactive about water irrigation, pest management, and crop yield estimation.

Predictive analytics in crop management is one of the most prominent applications of ML in agriculture. Analysis on past climatic trends and soil conditions would enable well-predicted planting and harvesting times to be adopted by farmers for better yields (Araújo, Peres, Ramalho, Lidon, & Barata, 2023). Moreover, with ML-aided image recognition, onset signs of plant diseases and infestations by pests can be identified sooner than later, allowing timely intervention that prevents large-scale losses on the farm (Joshi et al., 2024).

For instance, AI-powered systems with high-resolution cameras can take pictures of crops and use ML algorithms to detect stress indicators like discoloration, lifeless, or fungal growth (Agrawal & Arafat, 2024). Such early detection makes it possible to intervene precisely and target interventions so that pesticides are not used excessively and farming practices are more environmentally friendly. Recently, the application of ML models to optimize fertilizer application using fertilizer inputs data analysis in the storage and prediction of the quantity of the fertilizer per crop has become more common (Musanase, Vodacek, Hanyurwimfura, Uwitonze, & Kabandana, 2023). The health and yield of plants have improved, and less soil degradation and potential for chemicals from fertilizers and pesticides to pollute waters has been prevented.

The power of synergy of IoT and ML in agriculture is very strong, as it makes agriculture more efficient, more productive and more sustainable. Real time data is being collected by IoT devices and then ML algorithm analyze the data so as to generate actionable insight that is used in direction making (Paramesha, Rane, & Rane, 2024). Smart agriculture application with such interconnection system allows us to automate and be a bit more precise in our farming operations and in turn cuts down human effort and uses less resource (Mowla, Mowla, Shah, Rabie, & Shongwe, 2023).

IoT-based smart irrigation system will measure the soil moisture level, send it to the model of ML, which will then predict the best watering time on the basis of weather forecast (Singh et al., 2022). This will hydrate crops without over irrigation, which may lead to soil erosion and nutrient depletion. Also, the real time climate data from IoT based weather stations can be fed to ML models to predict adverse climatic condition of frost or drought and provide recommendations for preventive measures to farmers.

Current methods of yield estimation are performed manually by observing and following the historical trends, which then become inaccurate and slow (Rashid, Bari, Yusup, Kamaruddin, & Khan, 2021). ML models trained to detect soil quality, weather conditions and crop health data from IoT are precisely forecasting the yields, allowing farmers to plan it, manage labor resources and optimize the supply chain logistics. Additionally, controlled environment agriculture has benefited a great deal from IoT ML systems too. Greenhouse farming is included in controlled environment agriculture. IoT sensors and automation using ML help control temperature, humidity, and CO_2 levels, thus controlling environment for the best crops to flourish in smart greenhouses (Ragaveena, Shirly Edward, & Surendran, 2021). In real time, these systems monitor plant health and ensure that the energy used by it is sustainable, further yielding high plants.

Traditionally, the adoption of IoT and ML towards farm efficiency and productivity is meant for environmental sustainability (Rajabzadeh & Fatorachian, 2023). They could play a role in precision farming, which would reduce the use of water greatly, decrease the chemical pollutions caused by fertilizers and pesticides and even reduce greenhouse gas emissions associated with poor farming methods. Additionally, from an economic point of view, IoT-ML solutions bring significant savings to the farmers. Automated irrigation and fertilization system decreases labor and wastage of resources, and using IoT sensors in the predictive maintenance of farm equipment, reduces the shocks and expenses needed in the repair (Wanyama, Kiraga, Bwambale, & Katimbo, 2023). This prediction of crop yield can help the farmer plan better the crop yield better to minimize post-harvest losses and market pricing strategies.

Impact of IoT and ML on Crop Yield

Precisely, more efficient crop management techniques on the fields have been made possible by integrating the Internet of Things (IoT) and Machine Learning (ML) (K. Sharma & Shivandu, 2024). Many of these technologies have made irrigation more effective, predicted diseases better, and effectively optimized farm efficiency. The real benefits of such innovations in terms of crop yield increase with the least wastage of resources are indicated by a number of studies (Maffezzoli, Ardolino, Bacchetti, Perona, & Renga, 2022). Vinod Kumar et al. (2024) examined issues related to a smart irrigation system through the use of IoT in affecting productivity of wheat. This was to indicate a 20% yield of increased wheat crops but concurrently with this reduction, as was established at a water level consumption rate, reduced by up to 30%. Precise water application was used to prevent over-irrigation, which may cause root diseases, and under-irrigation, which can cause crop stress (Anjum, Cheema, Hussain, & Wu, 2023). The results of this research therefore point that the IoT-based ML-driven smart irrigation strategy can play significant roles in relieving food security concerns concerning ensuring optimal plant growth conditions.

Domingues, Brandão, and Ferreira (2022) conducted a study on the impact of ML-based disease prediction models on tomato production. In this study, image processing and ML classification algorithms were used to detect early signs of plant diseases, which would allow farmers to take preventive action before the disease spread extensively. The results indicated a 40% reduction in crop losses, showing the effectiveness of AI-driven disease detection in safeguarding agricultural productivity. By leveraging real-time data, farmers can reduce their dependency on broad-spectrum chemical treatments, which not only lowers costs but also minimizes environmental impact.

One key role ML would play in the agriculture industry relates to forecasting yield crops given that data used and the present situational aspects determine such crop production (P. Mishra, 2024). When factoring weather and other elements and a healthy state, allows yield production estimates of this model by yielding real predictive outcome to schedule actual harvestings better, so with an appropriate balance, avoid or reduce surpluses to mitigate losses following post-harvest (Han, Bishop, & Filippi, 2022).

Water Conservation and Efficient Resource Management

The scarcity of water is one of the most significant issues in modern agriculture, especially in areas where there is a limited supply of freshwater (R. K. Mishra, 2023). IoT-based smart irrigation systems have been highly recognized for optimizing water usage and ensuring that crops are adequately hydrated without excessive consumption. Such a study conducted by Saad, Hamdan, and Sarker (2021) showed that IoT-aided drip irrigation systems consumed water by 35% lesser when crop yields were optimally maintained. The system used real-time data feed from soil moisture sensors to exactly determine the amount of water required, thus avoiding unnecessary irrigation and water wastage. This research explores how IoT technology can be used for the actual support of sustainable agriculture as practiced in water-scarce areas. Beyond real-time monitoring, ML algorithms are important in predicting future water needs. The integration of IoT and ML opens up irrigation along with broader applications in resource management (Nsoh et al., 2024). For example, automated fertilizer delivery can use sensor inputs and ML models to determine accurately the amount required for a type of crop in question. By this precision-farming approach, crop health increases and yield grows, but further, the prospect of soil deterioration and nutrient erosion that could carry pollutants into available water sources for local consumption would be reduced as well (Xing & Wang, 2024). The IoT and ML-based agricultural management system can particularly lead to enhanced efficiency, non-resource wastage, and increased sustainability for a more productive yet more secure food supply with minimal environmental impact.

Pest and Disease Control Using IoT and ML

Among the biggest threats to global agricultural productivity, pest infestations and plant diseases rank very high. Conventional pest control methods have mainly relied on excessive pesticide use, which negatively impacts the environment and human health (Alengebawy, Abdelkhalek, Qureshi, & Wang, 2021). However, with IoT and ML technologies, the approach towards pest and disease management can be much more accurate and sustainable through early detection and targeted interventions.

In response, Ye et al. (2022) have presented this research performed in China that considers the use of image recognition for ML-based models for identifying pest infestations. In this regard, smart traps, equipped with cameras and sensors for capturing images of insects, were associated with IoT. Finally, ML algorithms were applied to these images to sort pest species. The results showed that identification of pests was up to 95% allowing farmers apply pest control measures with more effectiveness (Kariyanna & Sowjanya, 2024). This technology reduce pesticide use by 40% while still being able to control pests precisely on the affected areas.

Fungal infection is also another severe threat to crop health especially when the climate is humid. According to Santana et al. (2024), research was conducted in Brazil to determine how IoT based monitoring systems with ML based predictive analytics would be able to detect fungal soybean infections up to 10 days earlier than traditional methods. Targeted treatments on crops identified to have symptoms in the early stage could reduce crop losses by 25%. The efficiency of food production is enhanced by these fungicide-active alternatives to chemical fungicides, while the environmental impact caused by chemical fungicides is decreased.

Especially, IoT and ML can offer early warnings to large scale commercial farming operations on the occurrence of pest and disease outbreak (Delfani, Thuraga, Banerjee, & Chawade, 2024). Satellites can be used to develop predictive models that can detect signs of plant stress over large areas of agricultural land, making it possible to coordinate a better response to potential threats and reduce economic losses; keeping supply chains stable.

Beyond detection, IoT-enabled automated pest management systems can take direct action when an infestation is detected (K. Sharma & Shivandu, 2024). Smart traps and robotic sprayers can selectively apply biological pesticides only to the affected areas, reducing the overall chemical footprint of pest control efforts. This targeted approach enhances the effectiveness of pest management while aligning with sustainable agricultural practices.

Research Gaps

Although lots of research on IoT and ML applications in agricultural systems exists, the aspects to be dealt with for Al-Bahah and similar semi-arid regions are still missing. This paper aims to fulfill these gaps by presenting empirical data about the impact of these technologies in a unique agricultural scenario. Most present works are based on huge farm operations with well-developed technological infrastructure in developed regions. There is little research on how IoT and ML can be applied to smaller farms in regions with specific climatic and soil conditions, such as Al-Bahah. This study fills the gap by examining the effectiveness of smart farming technologies in a local agricultural environment.

Although numerous studies have highlighted the benefits of IoT and ML for crop management, few have gone into the minute details regarding the impact on soil health and water conservation. This study will include real-time soil pH monitoring, water usage tracking, and irrigation efficiency analysis to provide a holistic understanding of how these technologies affect resource sustainability. ML-based crop selection studies are few in number, which have dealt mainly with climatic trends without sufficient details of varieties of crops suited for semi-arid regions. This study analyses the performance of figs, pomegranates, and tomatoes under the IoT and ML-driven farming system. Findings from this research will add a valuable dimension to optimal agricultural practices for similar environments.

Research Design and Methodology

Description of the Research Framework

The case study applied a framework of experimental research for the purpose of evaluating smart farming technologies at Al-Bahah. IoT and ML were to be implemented on selective sites within agricultural regions, and these technologies will enhance the farming practices. The framework used in this case study takes measurements of important factors such as crop yield, water use, and environmental conditions before and after installing the technologies. The study mainly sought to analyze the actual improvement from the combination of IoT and ML on resources, thereby ensuring a more optimized productivity in agriculture.

Data Collection and Analysis

A number of IoT sensors were installed at the experimental farms to collect data from several environmental variables such as soil moisture, temperature, humidity and crop health. In order to analyze the data gathered, we utilized several ML algorithms to derive actionable insights of how to manage the crops, irrigation schedules, and govern over the effectiveness of the whole farm. These technologies were subjected to statistical analysis, consisting of correlation and regression techniques, in order to assess their impact on crop yield, soil health and water usage. The purpose of this study was to quantify the benefits of smart farming techniques by using pre and post intervention data. Through IoT sensors installed throughout the farms, agricultural data was collected continuously through monitoring environmental conditions.

Overview of the Experimental Setup in Al-Bahah

The experimental setup was fitting the IoT sensors in different farms in various areas in Al-Bahah. These sensors were linked to a central data platform; here, real-time data was constantly collected and analyzed. For monitoring and optimizing agricultural practice, ML algorithms were used for predicting the need for irrigation, crop performance, and any other key factors based on real-time data. It provided an insight into the best farming practices to be shared immediately with the farmers for them to adopt.

Machine Learning Algorithms

Several well-known machine learning models were used in the study to analyze the agricultural data such as Decision Trees, Random Forests, and Support Vector Machines. These models have been applied to the historical farm data to predict crop yields, optimize the irrigation schedule, and recommend the best local farming practices under environment. These models were chosen on the basis of their ability to capture complex, nonlinear relationships between the input variables such as soil moisture, temperature, and humidity, and the output variables, crop yield, and quality.

Data Preprocessing and Feature Selection

A very rigorous preprocessing of the collected data was performed on the data, which was used to remove noise, correct errors, and handle missing values. To allow the models to understand the variables, data normalization and scaling was performed. I applied feature selection techniques like PCA and Mutual Information to find the most important variables like soil moisture and temperature that greatly impact crop yield and water usage.

Model Training and Evaluation

Historical data of Al-Bahah farms has been used to train the models. Some of the data were separated aside to be used for validation. Model performance was determined using some of the metrics like accuracy, precision, and recall. The cross validation technique helped on ensuring that the models were not over fitting to the training data. The model evaluation yielded insights and served as a basis for determining the best farming practices and the irrigation schedule.

Implementation of IoT Systems in the Selected Agricultural Sites

Different environmental variables are being monitored in selected farms in Al-Bahah for IoT systems. Soil moisture sensors, temperature and humidity sensors, and automatic irrigation systems were included in this. With the help of IoT, farm conditions were monitored from afar and irrigation, and other farming practices were adjusted in real time.

The focus of the design of the IoT system was on energy efficiency and robustness to harsh environment of Al-Bahah. For the electrical setup, I was given input in such a way that only little power would be used in the system in order for it to function properly, and to implement an anticipated telecommunications network with reliable data transmission from the sensors to the central platform where all the sensed information will be collected. The cloud platform served not only as the center for data storage, aggregation and real time analytics, but also promoted automation methodologies and defined the necessary technologies to be adopted.

Real time data of the soil moisture, temperature, humidity, and health of the crops was collected by several sensor nodes around the farms. This information was sent by the cloud and would be analysed and processed further. This meant that the data would become available to be accessed and analyzed from anywhere in the world, giving farmers the ability to make well informed decisions from wherever they might be located.

Crops Production

The selected crops were chosen by the authors based on the relevance of the selected with regard to the region agricultural practices, and the climate. Figs, pomegranated and tomatoes were the main crops. The crops in question were chosen as for economics and differences in irrigation and environmental conditions, they are economically important in Al-Bahah.

The research was conducted on the farms, which were at different altitudes and at different soil conditions so that the researchers could understand how the IoT and ML technologies will work under different environmental settings. Among other benefits, this allowed a more detailed understanding of how smart farming technologies can optimise agricultural productivity in different settings.

The crop performance was adopted based on a combination of the yield, crop quality and resistance to pests and diseases indicators. So, it is a bit like having environmental parameter altered by acquiring all these data from IoT sensors, irrigation as an example and also changing the environment to be on the most optimal level for each crop. Aspect of crop performances are also tested against different altitudes and the whole conditions in order to learn good ways of practicing agriculture in Al-Bahah region.

Results

The data collected through the IoT and ML interventions were analyzed with the help of several statistical methods and techniques, such as correlation analysis, regression analysis, and t-tests, in order to determine changes in key agricultural parameters such as crop yield, water usage, soil health, pest infestation, irrigation efficiency, and energy consumption due to these technological interventions in the productivity of farms in Al-Bahah.

The traditional farming system was compared to the interventions integrated with IoT and ML technologies at the initial phase of data collection. KPIs monitored include crop yield in kg/m^2, water usage in liters/day, soil pH, and rates of infestation by pests in percent and irrigation efficiency by measuring water use per crop unit.

Results indicated considerable improvement in most measured parameters. There was an important increase in the crop yield among farms implementing IoT and ML systems, with significant decreases in the usage of water, enhancement in soil health, and reduced cases of infestation by pests. The application of data-driven irrigation systems optimised water use and precision farming methods enhanced crop health and quality.

Table 1: Statistical Results on the Impact of IoT and ML on Agricultural Productivity

Variable	**Pre-Intervention (Traditional)**	**Post-Intervention (IoT & ML)**	**Change (%)**	**p-value**
Crop Yield (kg/m^2)	1,200	1,500	+25%	0.02
Water Usage (liters/day)	2,000	1,500	-25%	0.01
Soil pH	6.2	6.8	+9.7%	0.05
Pest Infestation (%)	15%	5%	-66.7%	0.03
Irrigation Efficiency (L/m^2)	0.5	0.4	-20%	0.04
Energy Consumption (kWh/day)	10	8	-20%	0.06

The table above shows the changes in the most important agricultural variables after IoT and ML interventions. The average crop yield was raised by 25%, while the water usage declined by 25%, meaning the technology had an impact on water resource optimization. The soil pH improved by 9.7%, meaning there was a good management of the soil health by data-driven farming. The rate of pest infestation reduced to 66.7%, implying that automated pest control systems worked well. In addition, irrigation efficiency increased by 20% because ML models predicted the exact amount of irrigation required based on weather and soil data. A decrease in energy consumption by 20% also indicated that IoT and ML technologies made the farming process more energy-efficient.

Adjustments Made to Improve Outcomes

Based on the results of the statistical analysis, several adjustments were made to optimize farming practices and further enhance the effectiveness of the technological interventions. These adjustments included:

1. Real Time Weather & Soil Moisture Data: IoT devices collect the real time weather data and soil moisture data that then get analyzed by the ML algorithms to give insights into optimal irrigation timings based on the real time weather due to which it happens. Along with this, water usage was reduced by 25% as over-irrigation was reduced, and prevented waterlogging and helped the crop to grow better.
2. Based on the data from the IoT systems, crop varieties were modified so as to perform better under specific conditions of soil and climate. Fruits, such as figs, pomegranates, tomatoes etc., which were appropriate to the environmental conditions of the region, were also selected in adjustments as they were more resilient and high yielding. So this decision led to a 25% increase in crop yields.
3. With the help of IoT sensors combined with ML algorithms, the pest control strategies helped in detecting early signs for onset of pest infestation. Upon this, the study implemented automated pest control procedures in these areas that were targeted in the field and dropped 66.7% the amount of pest damage caused. Farming became more sustainable by means of these adjustments leading to a great reduction in pesticide use.
4. Optimization of soil health: The IoT sensors were used to monitor the soil moisture, temperature and pH level, thereby optimizing soil health. This included data from the system that enhanced organic fertilization practices sufficient enough for crop health to increase 9.7% of soil pH.

Table 2: Impact Summary Table

Category	Key Insight	Outcome
Irrigation Schedules	ML algorithms optimized irrigation based on real-time weather and soil data.	Water usage reduced by 25%, preventing waterlogging and improving crop growth.

Modifying Crop Varieties	IoT data identified optimal crop varieties for soil and climate conditions.	25% increase in yield of figs, pomegranates, and tomatoes.
Pest Control Strategies	IoT sensors detected early pest infestations, enabling targeted interventions.	66.7% reduction in pest-related crop damage and reduced pesticide use.
Soil Health Optimization	IoT-monitored soil parameters enabled improved fertilization.	Soil pH increased by 9.7%, enhancing crop health.

Comparison of Productivity Across Different Setups

The comparison between the farms using traditional methods and the ones using IoT and ML systems showed that the latter group was significantly improved in all measured parameters. Traditional farming practices, although effective, did not have the precision and efficiency that IoT and ML technologies brought. The following formulas were used to compute the productivity comparison between tradition and IoT/ML systems.

Since 1 hectare = 10,000 square meters, the conversion is done by dividing the yield per hectare by this factor:

For the traditional method:

$$Crop\ Yield\left(\frac{kg}{sq.m}\right) = \frac{Crop\ Yield\ \left(\frac{kg}{ha}\right)}{10000} = \frac{1200}{10000} \approx 0.12\ kg/sq.m$$

For the IoT & ML method:

$$Crop\ Yield\left(\frac{kg}{sq.m}\right) = \frac{Crop\ Yield\ \left(\frac{kg}{ha}\right)}{10000} = \frac{1500}{10000} \approx 01.5\ kg/sq.m$$

$$Change\ (\%) = \frac{1500 - 1200}{1200} \times 100 = 25\%$$

Table 3: Productivity Comparison Between Traditional and IoT/ML Systems

Variable	Traditional Method	IoT & ML Method	Change (%)

Crop Yield (kg/acre)	485.6	607.0	+25%
Water Usage (liters/day)	2,000	1,500	-25%
Pest Infestation (%)	15%	5%	-66.7%
Soil pH	6.2	6.8	+9.7%
Irrigation Efficiency (L/m²)	0.5	0.4	-20%
Energy Consumption (kWh/day)	10	8	-20%

As shown in Table 3, the overall productivity of the IoT and ML-enabled farms was higher. In the case of an increase in crop yield, decrease in water usage, improved soil health, less pest infestation, and both irrigation efficiency and energy consumption, the IoT and ML systems were highly effective.

Table 4: Impact of IoT and ML on Different Crops

Crop Type	Crop Yield (kg/m²)	Water Usage (liters/day)	Pest Infestation (%)	Soil pH	p-value
Figs	1,000	1,200	10%	6.5	0.04
Pomegranates	1,400	1,500	8%	6.9	0.02
Tomatoes	1,600	1,700	7%	6.8	0.03

Table 4 gives the results and specific crops produced during the study in further detail. Tomatoes were the crop that showed the most improvement across crop yield, as the yield was enhanced by 33% compared to the traditional methods. Pomegranates and figs also experience great improvements in the study with the rate of reduction in water usage and the infestation rate of pests.

Discussion

The results of this study shows the relevance of the impact of IoT and ML technology on the optimization of the important agricultural parameters such as crop yield, water usage, crop yield, pest control, water usage, crop yield, pest control, irrigation system efficiency on farms in Al-Bahah. These results are consistent with previous research showing the contribution of precision agriculture towards efficiency and sustainability of farming practices (Jayaraman et al., 2016; Zhang et al., 2020). Trends in this study indicate that data-driven farming could aid in the development of what is more resource efficient and productive farming and in the improvement of decision making in farming.

The increase in crop yields by 25% was made possible by an application of IoT and ML. The effect of this is similar to previous findings claiming precision farming advances the crop yield. For instance, Sharma et al. (2019) illustrated yield increase from as high as 20% to 30% yielded using smart sensors along with predictive analytics for different crops. Additionally, because the IoT systems monitor the soil conditions and predict the optimal time of irrigation and propose suitable crop varieties to increase productivity. Additionally, tomato, fig and pomegranate varieties with the characteristics of resilience were chosen, based on real-time soils and climatic data, as Abioye et al. (2021) also reported.

Data driven irrigation systems were found to be efficient since the intervention of IoT and ML had reduced water consumption by 25%. This is consistent with Kim et al. (2018, 2022) and Li et al. (2022), who found that ML based irrigation models can reduce water wastage by about 20 – 30 % with or without bad effect on the health of the crop. Reduced over irrigation and avoidance of waterlogging in this study indicate that IoT enabled real time soil moisture monitoring would help in improving the water resource management in arid and semi-arid regions.

The increase in soil pH by 9.7% post-intervention indicates the advantages of smart farming in the optimization of soil health. According to Mishra et al. (2020), IoT-based soil nutrient monitoring improves soil quality through precise and timely fertilization strategies. This study therefore shows that a better pH level was achieved based on organic fertilizer and soil treatment recommendations given through IoT sensors and thus, hence, provided with better conditions of growth for the crops. An infestation reduction of 66.7% was also a result of how effective the strategy of automated control of pests became through IoT and ML. These results were consistent with studies by Patil & Kale (2021), who reported a reduction in crop loss by 50–70% using AI-driven pest detection systems. Application of pesticides with the help of early pest detection, targeted in this case, not only minimized the infestation level but also avoided excessive application of pesticides for sustainable farming practices.

The study achieved a 20% increase in irrigation efficiency and a 20% decrease in energy consumption. These results are in line with the work of Abdelghani et al. (2019), who stated that smart irrigation systems improved efficiency by 18–22% in precision agriculture applications. ML models in irrigation scheduling optimized water use while reducing energy-

intensive irrigation practices. Because of this, water-saving farms by using IoT and ML technologies managed to save the energy consumption that would have gone into the process.
The comparative analysis among traditional farming, IoT/ML-integrated, and other farms further supports this argument that, in general, smart agriculture would increase overall productivity. Table 3 shows conventional methods were capable but lacked accuracy and adaptability as provided with IoT and ML. This research is in conformity with Gebbers & Adamchuk (2019), in which they indicate the shortcomings in resource utilization by traditional farming concerning environmental sustainability by precision agriculture. The results broken down by crop type (Table 4) show the variability in responses to IoT and ML interventions. Tomatoes showed the highest yield improvement at +33%, suggesting that some crops might benefit more from precision agriculture techniques. Similar trends have been reported by Reddy et al. (2021), who found that tomatoes and other high-value crops responded well to IoT-based nutrient and irrigation management.

Practical Implications

This study implies that farms need supportive policies to encourage new technological innovations. The adoption of IoT and ML in agriculture shows evidence of great promise that government and agricultural regulatory bodies should harness in constructing policies to drive transformation in the sector. For instance, by giving financial incentives such as subsidies or taxations to farmers who adopt smart technologies, their adoption will start quicker and lead to more sustainable agriculture practice.

The need for such frameworks that will prompt responsibly managed natural resources stem from such changes in resource efficiency, especially in water use and energy consumption. It provides the policymakers to create regulation guidelines about sustainable irrigation practices and enables the use of predictive analytics on the basis of machine learning to reduce an over-irrigation and soil degradation.

More importantly, the fact that IoT-based pest control technology has been able to reduce the use of pesticides indicates the prospects of environmental and public health impacts. Policymakers should take steps to further reduce chemical application while maintaining productivity by supporting the research and development of precision pest management.

The impact of IoT and ML on agriculture is more extensive in socio-economic terms, especially for small-scale farmers in low-income regions. These technologies reduce input costs like water, pesticides, and energy while increasing yield, thereby making farms more profitable and contributing to rural economic development. However, there could be issues with initial investment costs and technical expertise to implement IoT and ML systems. Therefore, it should be considered imperative for governments as well as other agricultural organizations to put investments in trainings designed for equipping the farmer.

Moreover, the increased efficiency and sustainability of farming operations could support food security initiatives by enhancing agricultural productivity without over-exploiting natural resources. The ability to grow high-yield, climate-resilient crops, as demonstrated in this study, aligns with global efforts to ensure food security in the face of climate change.

Conclusion

This paper discusses the effects of IoT and Machine Learning in agricultural productivity for Al-Bahah, a region whose climatic and soil conditions are unique and require distinct methods of cultivation. The deployment of real-time sensor data with state-of-the-art predictive algorithms within this study has shown promising gains in making smart farming crucial in critical agricultural parameters, such as crop yields, water use efficiency, soil condition, and pest management.

The study indicated the adoption of IoT-based irrigation scheduling and precision agriculture techniques gave 25 percent crop yield, 25 percent reduction in water use, and improvement in soil health, with a pH level increase of 9.7 percent. The use of automated pest detection systems also decreased crop damage caused by pests by 66.7 percent, thereby decreasing the use of pesticides and ensuring environment-friendly farming.

Moreover, energy consumption was decreased by 20%, which points out the fact that smart farming techniques may optimize usage and lower operational costs while using resources. The findings highlight the idea that data-driven decision-making in agriculture improves productivity and allows long-term sustainability; it is in line with global efforts to ensure food security and environmental conservation.

Recommendations for Farmers and Policymakers

For Farmers

It is recommended that farmers invest in automated irrigation systems that can respond in real time to changes in soil moisture and weather to prevent over-irrigation and improve efficiency in water usage. They could apply ML models for an estimation of crop varieties that could prove suitable for their soil and climate conditions, thereby increasing productivity and resistance to environmental variability. There is also an integration of pest detection using IoT-based tools with targeted control measures to greatly minimize crop damage while eliminating pesticides' potential dangers on the environment.

Continuously monitoring soil pH, moisture, and nutrient levels through the use of IoT sensors will help farmers make smart decisions on how to fertilize and manage their lands. The training and capacity-building programs that involve farmers' education in how to interpret data from IoT collection will benefit them in making data-driven farming decisions to manage available resources intelligently.

For Policymakers

With respect to policy makers and government stakeholders, it is recommended that financial incentives, grants, or subsidies are used to encourage farmers to adopt IoT and ML technologies. Rural internet connectivity investments are needed to ensure that data transmitted from IoT devices can be transferred smoothly to cloud-based analytics platforms. Policymakers are recommended to utilize big data generated by IoT for the formulation of evidence-based policies to optimize water resource allocation, land use, and crop diversification.

Government agencies are recommended to collaborate with universities and agricultural research institutions to train farmers in all these aspects such as digital agriculture, AI-driven analytics, and precision farming techniques. Smart farming technologies should be accelerated in adoption between government bodies, the tech industry, and agribusinesses to increase accessibility and reduce the cost for implementation among small and medium-sized farms.

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