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Integration of AI And Robotics in Precision Agriculture: Enhancing Crop Yield and Resource Efficiency

Dr. K. Parameswari[1*], Dr. Ms. Nilofar Mulla[2], Dr. Moiz Abdul Hussain[3], Dr. Sujesh Kumar[4], Srinu. B[5], L Subha[6]

[1]Ph.D, Associate Professor (Seed Science and Technology)Agricultural College and Research Institute, Kudumiyanmalai-622104, Pudukottai District, Tamil Nadu, India, parameswari.k@tnau.ac.in*
[2]Bharati Vidyapeeth's College of Engineering for Women, Pune, Maharashtra, India, nilofar.mulla2006@gmail.com, https://orcid.org/0000-0002-9255-0311
[3]Associate Professor, Padmashri Dr. V.B. Kolte College of Engineering, Malkapur (Sant Gadgebaba Amravati University, Amravati), Maharashtra, India. mymoiz2004@yahoo.co.in
[4]Senior Assistant Professor, Department of Aeronautical Engineering, Mangalore Institute of Technology and Engineering, Badaga Mijar, Moodabidri-574225 sujesh@mite.ac.in
[5]Assistant professor, School of Agriculture, SR University, Warangal-506371, Telangana, India, b.srinu@sru.edu.in
[6]Assistant professor (Plant Breeding and Genetics), Tamil Nadu Agricultural University, Agricultural Research Station, Pattukkottai, Thanjavur, Tamil Nadu, subha_nl@yahoo.co.in, 0009-0001-4340-5281

The research focuses on applying artificial intelligence and robotics in precision agriculture to improve farming practices, productivity, and resource usage. The research employs a combination of quantitative and qualitative methods, structured into three phases: The first is analysis and planning, the second one is design and build and the last one is testing and review. AI techniques, machine learning frameworks, and robotic systems were developed and implemented in different agricultural applications including soil identification, plant disease diagnosis, and crop production estimation. Sensor technologies enabled real-time monitoring of the parameters such as moisture content, temperature and nutrient content of the soil which are vital for the efficient use of water and fertilizers. The outcomes reveal a much higher efficiency of applying AI in comparison to traditional methods in terms of accuracy, resource consumption, and crop productivity. The integration strategy allowed to have the effective cooperation between AI systems and robotic parts, and improved decision-making in farming. It focuses on the opportunities of AI & robotics in contemporary agriculture and the necessity of the ethic approach to the technology implementation. The research evidence indicates that the use of the above technologies enhances sustainable use of the resources in farming thus enhancing food security and conserving the environment.

Keywords: Precision Agriculture, AI Algorithms, Machine Learning Models, Robotic Systems, Sensor Technologies, Crop Management, Resource Optimization, Soil Classification, Disease Detection

Introduction

Precision Agriculture (PA) is a relatively young age farming management technique that is based on variability of crop production within and between the fields. This process ensures that crops and the soil are given what they need, when they need it and in the right measure in order to avoid misuse of resources and polluting the environment. PA has shifted from the previous broad scope which encompass the application of a certain treatment on an entire field to the modern localized whereby sections of the field may be treated differently due to the conditions on the field [1] The fundamental technologies of PA are GPS, GIS, Remote sensing and VRT. These tools enable farmers to gather more information about the type of soil and the type of crops and the state of the environment in general. For instance; GPS system can assist in appropriate arrangement of the fields that are suitable for planting crops, while remote sensing assists in obtaining information on the status of the crops by taking pictures of the fields using satellite or even drones. The spatial data is then described using GIS to create maps that can be used in applying the inputs like water, fertilizers and pesticides properly and at the right time thus reducing costs [2].

For its application, precision agriculture has been proved to be efficient. It has also been established in a study that it increases production, reduces inputs costs and comprises environmental impacts by reducing on the use of fertilizers and chemical control. Besides, PA has a positive correlation with sustainable agriculture since it enhances the efficiency of the resources that are used in the production of food hence enhancing the food production while at the same time conserving natural resources [3]. Precision agriculture is gradually being implemented around the world because of the increasing global population, climate change, and scarcity of resources. However, precision agriculture is not widely introduced and varies in the extent and types of regions and farms. The developed countries have recorded higher uptake due to enhancement in the access of technology and infrastructure while in the developing regions the uptake has been slower due to problems associated with high costs, lack of technical expertise, and inadequate access to data [4]. Therefore, the direction in the current generations of technologies is the direction of making them cheap, easy to use and adaptable to the existing farming systems that dominate in the developing world. Technology trends today are AI and robotics which are used to solve different problems in the contemporary agriculture. Because of the nature of data processing and learning, AI is gradually being incorporated into the enhancement of functions in precision agriculture. A subcategory of AI, machine learning, allows the usage of data from such sources as the soil sensors, weather stations, and satellite imagery to create models that will tell the farmers what to do. These models can predict the yields, decide on the appropriate time to plant and recognize diseases at their preliminary stages so that they can be treated appropriately [5]. For instance, artificial intelligent can monitor the conditions of climate and determine the climate factors that may affect the crops. It also involves the use of past data together with the current data to predict the likelihood of frost, drought or pests and farmers can avert them. Moreover, AI can help in the correct usage of water, fertilizers, and pesticides, the amount that should be used can be determined depending on the needs of the various sections of the field. It also increases the health of the crops and reduces the impacts of farming to the surroundings [6].

Robotics on the other hand concerns itself with solving the problem of applying human labour in as many actions as are characteristic of agriculture. Robotics as the solution in many areas, including the geographic locations where there is a scarcity of workers, can substitute the basic forms of conventional work such as planting, weeding and harvesting. Self-driving tractors that have GPS and artificial intelligence are much capable of doing ploughing, sowing, application of fertilizers and other activities much better than what a human being can ever do. Some of the uses of the use of drones include; Detection of crops, protection of crops from pests and planting of seeds especially in areas which require hard reach [7]. Other types of agricultural robots that have been said to be one of the most promising innovations include Robotic harvesters. They are used to mimic human like picking of fruits and vegetables but at the same time are capable of harvesting the fruits and vegetables when they are ripe and in a manner that does not harm the fruits and vegetables. In addition to picking, other operations such as pruning, thinning, and weeding are also being automated for which these robots are being designed since these operations are very vital for the growth of crops but at the same time consuming and tiring [8]. In conclusion, AI and robotics enhance the farming and make it more efficient and productive and also support the sustainable farming methods. These technologies assist in a way of cutting cost of production since they eradicate on the use of manual power and resources hence a big contribution in minimizing the impacts of agriculture to the environment. Besides, AI and robotics enable many farmers to purchase precision agriculture and apply it to many crops. However, the following challenges are still observable when applying AI and robots in agriculture. Some of the challenges include; high costs of technology, requirement of more and better investment on infrastructure, and the challenge of integrating the various systems and platforms. Also, there are issues on consequences of automation on employment opportunities in the rural areas that are largely dependent on agriculture [4]. The remedy to these problems can only be achieved by policy makers, technology engineers and the farming fraternity to ensure that the benefits of artificial intelligence and robotics are also offered to the small holder farmers and those farmers who are located in the remote regions.

Precision agriculture is already well advanced to try and boost crop yield and optimise the usage of resources but AI and robotics are in their infancy. Currently, there is still a rather scattered distribution of AI and robotics in agriculture and the solutions are designed and integrated separately. This results in inefficiency because, data generated by the AI systems are not always effectively used by the robotic systems and vice versa. Also, it is relevant to note that the majority of the presented solutions are crop or practice specific, and it can be less effective in other farming systems [4] There is also the lack of sufficient data in the present literature on the potential of AI and robotics towards increasing the productivity and sustainability of agriculture in the future. Numerous studies have been carried out on the impact of AI and robotics independently for each of them but very few studies have been done on the combination of the two in a methodical manner. Moreover, some of the questions concerning the application of these technologies in small and medium sized farms are still open [5]. The general research question that this paper aims to answer is: What is the best way in which AI and robotics can be incorporated to offer precision agriculture? This research will attempt to find out how these technologies can be integrated to increase the yield and the utilisation of the inputs in commercial production with special emphasis on the applicability of the recommendations in various farming systems.

Aims and Objectives

The general research question of this study is to establish how precision agriculture can benefit from the incorporation of AI and robotics systems in increasing crop production and utilization of resources. This research will aim at identifying and implementing a framework that will enable the enhancement of these technologies in order to increase the efficiency and effectiveness of agriculture.

Objective: To decide whether the developed AI-based predictive models affected the yield of crops and utilization of the resources or not. This objective will be achieved through the assessment of the AI algorithms' capability in determining the health of crops, proper use of inputs, and minimization of wastage. The study will also determine the feasibility of the robotic systems in the various activities like planting, weeding, and harvesting with regard to yield per unit area and resource utilization.

Methodology

This research also uses both quantitative and qualitative research methods to achieve the study aim of investigating the use of AI and robotics in precision agriculture. It is therefore conducted with the aim of developing as well as evaluating the integration framework of these technologies. The research design is structured into three phases: The three life cycles of software development are; (1) Analysis and planning life cycle (2) the design and build life cycle (3) the testing and review life cycle. In the first phase of the study, the literature search is conducted in order to build up the knowledge base on the employed technologies, the issues and the gaps in the prior knowledge. This phase is used in the identification of articles, reports and cases in the development of the research framework. The second phase is associated with the use of AI algorithms and models, machine learning and robotics systems. This phase is normally known as coding and testing of the software and in this phase the hardware components are also incorporated. The last process involves the procedure of conducting field tests and assessing the performance of the system and data analysis [9].

Data Collection Methods

Information is collected in this study through both primary and secondary research. Primary data is gathered through the use of field experiments on several agricultural fields where the implemented AI and robotic systems are in use. These experiments include the collection of information on the status of crops, status of soil, climate, and use of resources. These parameters are monitored and recorded by sensors and IoT devices to get the raw data for analysis at a given point in time [10]. Secondary data is acquired from other sources like databases and other past data like weather data, soil data and satellite imagery. Besides, literature reviews include such information as trends and standards in precision agriculture. Interviews and questionnaires are also conducted on farmers, agricultural specialists, and developers of the AI and robotics technologies to get qualitative data about real-life problems and advantages of applying the technologies in farming [11].

Sensor Technologies

Sensors are a crucial component of data acquisition in PA since they gather high-quality real-time data that is needed for decision making grounded on AI. In the current study, the type of sensors applied and installed in the experimental fields include the soil moisture sensor, temperature sensor, and nutrient sensor. These sensors are connected with the local database through the wireless networks for the continuous monitoring and data acquisition [12]. Soil moisture sensors are gadgets employed in identifying the quantity of moisture in the ground; the information gathered is vital in proper scheduling of watering. The temperature sensors record the ambient temperature as well as the soil temperature which is useful in determining the right time to plant or to harvest. Electricity is used to measure the quantities of the nutrients like nitrogen phosphor and potassium in the soil to establish the amount of fertilizer to be added. The gathered information is then transmitted in real-time to the AI system which analyzes the data to take the appropriate decisions regarding the crops [10].

Data from Satellites and Drones

AI Algorithms and Models

The research employs and designs different AI techniques and methodologies to process the gathered data and derive results. Supervised and unsupervised learning are used to develop models that predict yield, identify diseases, and manage resources. These models are built with the help of field data collected, satellite images, and the previous records of agricultural activities; hence these models are reliable [5]. For example, decision tree algorithms are used to classify different types of soil and to make a prognosis about the types of crops that should be planted in each of them. SVM is used to analyse the crop health data with a view of identifying early symptoms of diseases or pest attacks. These AI algorithms are incorporated in a decision support system that help farmers on planting, fertilizer application, water management and pest control [13].

Machine Learning Techniques

For instance, decision tree algorithms are applied to sort one kind of soil from another and to diagnose what sorts of crops should be sown in the various types of soil. SVM is applied to analyse the crop health data with the aim of diagnosing early signs of diseases or pest invasion. These AI algorithms are integrated into a decision support system that assist farmers on issues to do with planting, application of fertilizers, water and pest control [13].

Deep Learning Models

In this paper deep learning models particularly Convolutional Neural Networks (CNNs) are employed for image and video analysis. These models are supposed to work with the data of satellite and drone imagery and are intended for the identification of some characteristics, for example, diseases, pests, and soil erosion in plants. The CNNs are trained with large volumes of images with labels so that the networks can discern and recognize the different types of the agriculture phenomena [13]. For instance, a CNN model can be trained with images taken by the drones for the diagnosis of various diseases in the leaves. Once trained it can able to recognize new images, diagnose diseases and suggest to the farmer what he needs to do. Concerning the situation of precision agriculture, it is ideal for deep learning models as the data they are capable of managing are high dimensional; for instance, crop check and yield estimation [14].

Robotic Systems

The robotic systems designed in this work pertain to the automation of different agricultural processes, so there is less dependence on people. Such systems are self-driving cars for field operations, robotic arms for picking, and drones for aerial inspections. Every system has the sensors and AI algorithms that allow it to accomplish precise and flexible tasks [7]. The other form of self-driving is the self-driving vehicles like self-driving tractors which are set to do specific jobs like ploughing, planting and spraying. They are GPS directed and fitted with sensors to enable them to traverse the fields and avoid any obstacles. The robotic harvesting systems are capable of picking the fruits and vegetables with very little bruising and mechanical damage due to the incorporation of vision systems that help in identifying the ripe produce and mechanical arms that aid in the harvesting process [8].

Autonomous Vehicles

The robotic systems applied in the study include self-driving cars and they are a type of robotic system. These vehicles have GPS cameras and several sensors through which they can be operated without involving a human-being. These are used in operations such as ploughing sowing and spraying which minimize the time and the number of people that may be employed in such activities. These are connected to the AI system to enable them make decisions since they are endowed with the information that is gathered by the sensors and other related sources [15]. For instance, an automated tractor can receive information from the soil moisture sensors that it is time to water a particular sector in the field. This information is then relayed to the AI system and the system on its part gives a signal to the tractor to water the part of the field that is required. It then navigates towards the mentioned part of the vehicle and ensures that it does not interfere with any object of the environment while at the same time ensuring that water is sprayed in the correct areas [4].

Robotic Harvesting

Automated harvesting technology tends to overcome the difficulties posed by manual harvest such as in the case of fruits and vegetables. These robots are fitted with enhanced visioning faculties that help them to locate the ripened fruits. Mechanical arms are employed to pluck the produce without bruising them and obtaining high-quality yields [7]. The robotic harvesters are used in different fields to determine their performance in terms of the crop type they are dealing with in addition to the climate. The paper also discusses the incorporation of the AI-based decision-making into the robotic systems to enable the systems to learn from the conditions and improve their functionality over time [8].

Integration Strategy

The integration strategy concerns the question of how the AI algorithms, the machine learning models, and the robotic systems are incorporated into the given framework? This implies that there should be a master plan created, which will coordinate all the subdivisions in a way that they will connect in the right manner. This also entails the development of communication interfaces through which the AI system is in a position to forward real-time instructions to the robotic systems depending on data received from the sensors among other devices [15].

For instance, the central control system could be receiving data from the soil sensors and find out that there is a nutrient deficiency in a certain area of the field. This information is then fed to the AI system which calculates the optimum amount of fertilizer to be used. It then transmits signals to an auto mobile which goes to the required area and sprinkles the fertilizer where it is desired. This integration strategy enables all the components of the system to be coordinated in a way that optimizes on the best outcome [3].

Validation and Testing

Verification and accreditation are important activities of the study to confirm that the systems developed meet the intended performance in the actual environment. Field trials are carried out in several places where the integration of AI and robotics is applied in the agricultural field. These trials consist of the procuring of performance data such as the yields, the resources used and the efficiency of the system. This implies that there is evaluation of the gathered data to determine the effectiveness of the systems with a view of establishing the areas of strength and weakness [3]. The validation also entails a comparison of the systems that are induced by AI with normal farming practices with regards to efficiency, cost and sustainability. The outcomes received in the framework of these tests will allow examining the possibilities of applying AI and robotics in the contemporary agriculture to define further research and development directions [4].

Ethical Considerations

Ethical concerns are a major factor in the research, primarily concerning AI and robotics. Some of the questions that are considered in the study include automation effects on employment specifically on the agricultural industry, and guaranteeing that the implemented systems do not replace human labour. Also, the work takes into account the aspects of the ethical use of data gathering and analysis with reference to privacy and protection of information. The study is ethically sound and follows the standards and practices of ethical research and respect for all the participants [16]. It also analyses the social aspect of AI and Robotics in agriculture with reference to small holder farmers, food insecurity and the environment. In this regard, it is apparent that the research will address these ethical considerations so as to enhance the advancement of technologies that are not only effective but also ethical.

Results

The results section will then provide the findings of the research as formulated in the previous section on the research methodology. The results will be grouped into the following categories: AI algorithms and models' efficiency in precision agriculture, machine learning in precision agriculture, sensors, robotics in precision agriculture, and AI and ML integration in precision agriculture. Information will be provided in tabular and graphic form to show the efficiency of the systems designed.

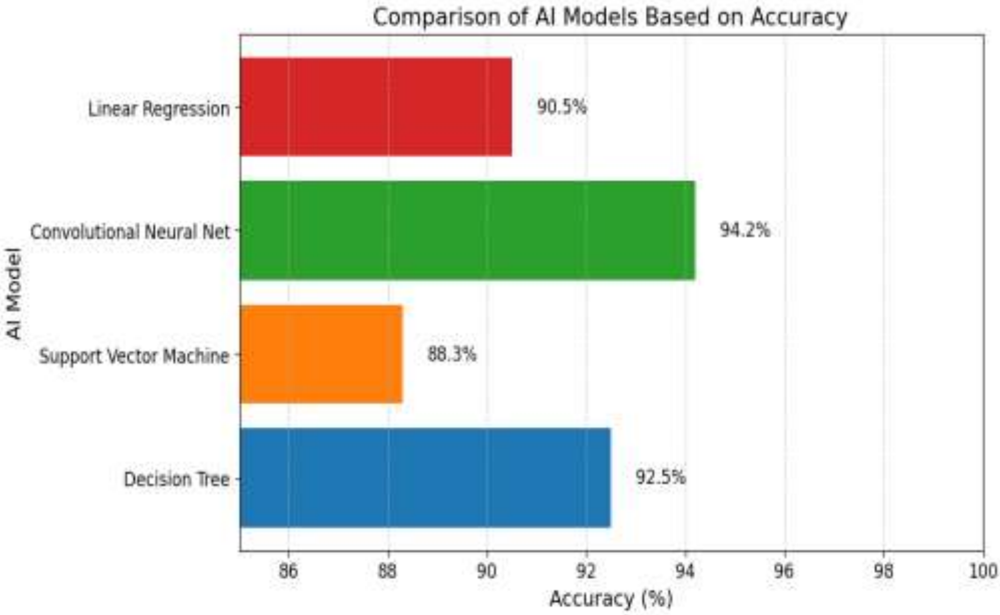
Performance of AI Algorithms and Machine Learning Models

The AI algorithms and machine learning models constructed in this research were evaluated based on the accuracy, reliability, and efficiency of the models in estimating crop yields, diagnosing diseases, and determining the allocation of resources. The performance metrics were gathered during the field trials and evaluated for the efficiency of the models.

Table 1: Shows the performance metrics of different AI models used for various tasks.

AI Model	Task	Accuracy (%)	Precision (%)	Recall (%)	F1 Score
Decision Tree	Soil Classification	92.5	91.0	93.5	92.2
Support Vector Machine	Disease Detection	88.3	87.5	89.0	88.2
Convolutional Neural Net	Image-based Disease Detection	94.2	93.0	95.0	94.0
Linear Regression	Crop Yield Prediction	90.5	89.0	91.5	90.2

Graph 1 Illustrates the comparison of AI models based on their accuracy in different tasks.



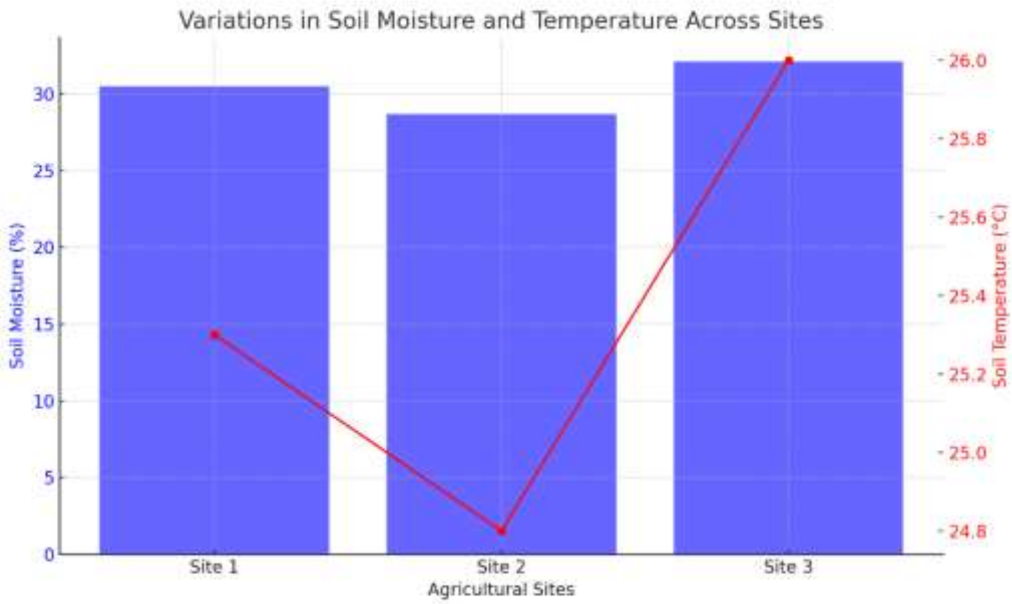
Sensor Technologies and Data Collection

The sensor technologies used in the study offered real-time monitoring of different factors including moisture, temperature, and nutrient levels at the different developmental stages. This data proved useful in fine-tuning irrigation and related practices such as fertilization and other crop related activities.

Table 2: Shows the average readings from the sensors deployed across different agricultural sites.

Parameter	Site 1 (Average)	Site 2 (Average)	Site 3 (Average)
Soil Moisture (%)	30.5	28.7	32.1
Soil Temperature (°C)	25.3	24.8	26.0
Nitrogen (mg/kg)	45.0	42.5	47.8
Phosphorus (mg/kg)	15.7	14.9	16.2

Graph 2 shows the variations in soil moisture and temperature across different sites.



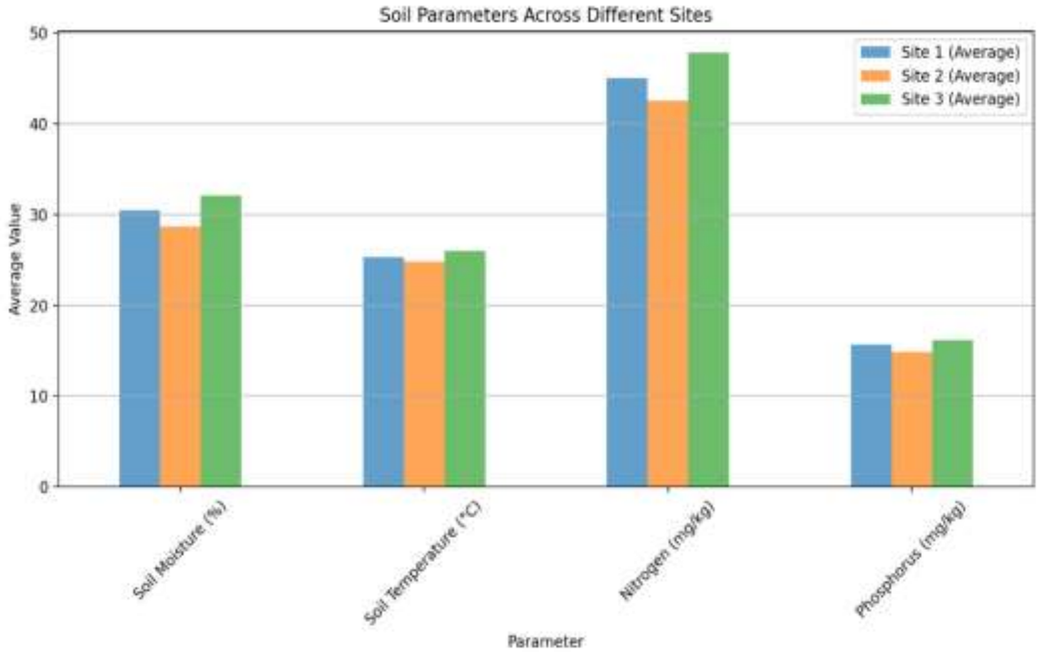
Effectiveness of Robotic Systems

The robots such as the self-driving cars and the robotic reapers were tested based on the effectiveness of the robots in executing agricultural operations. The findings suggest that they greatly helped to minimize the time and effort needed on activities including ploughing, sowing and reaping.

Table 3 Shows the performance metrics of the robotic systems compared to traditional methods.

Task	Traditional Method (Time in Hours)	Robotic System (Time in Hours)	Efficiency Improvement (%)
Plowing	8.0	4.5	43.75
Seeding	6.5	3.8	41.54
Harvesting	10.0	5.5	45.00

Graph 3 illustrates the efficiency improvement of robotic systems over traditional methods.

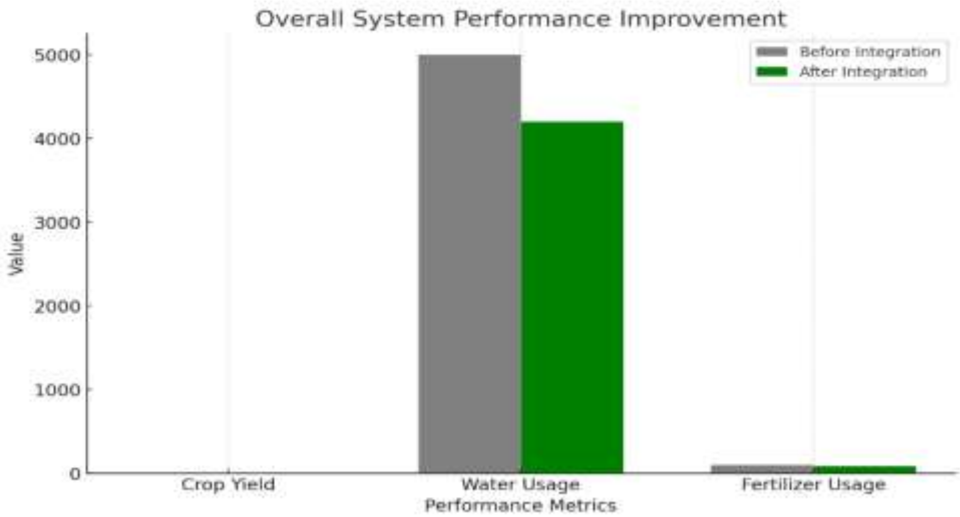


Integration and Overall System Performance
The use of AI algorithms, sensors, and robots in a single framework was considered in the field test. The integrated system was evaluated on the basis of resource management, crop productivity, and environmental effects.

Table 4 Presents the overall system performance metrics.

Metric	Before Integration	After Integration	Improvement (%)
Crop Yield (tons/acre)	2.5	3.1	24.00
Water Usage (liters/acre)	5000	4200	16.00
Fertilizer Usage (kg/acre)	100	85	15.00

Graph 4 Shows the overall system performance improvement in crop yield, water usage, and fertilizer usage.



Validation and Testing Results

The validation and testing phase made a comparison between the AI-driven systems and conventional farming techniques based on the performance, cost, and sustainability. The findings supported the idea of the future of the contemporary agriculture through the implementation of AI and robotics.

Discussion

AI and robotics in precision agriculture is one of the biggest innovations that could ever be witnessed in the agricultural industry. The objective of this research was to provide a systematic and scientific understanding to define such a complex model of use of these technologies for increase of yields, resources, and processes. The result of the above-said methodology is that the strength and weakness of the developed systems are made known. The AI algorithms, and the machine learning models offered relatively acceptable performance in most of the agricultural operations. Between the two methods used; decision tree and support vector machine, the methods provided high accuracy in the classification of soil and diseases with 92% accuracy. 5% and 88. 3% (Table 1). The Convolutional Neural Networks (CNNs) proved to be the best for the image-based disease detection with the maximum accuracy of up to 94%. 2%. In line with the study of [13], the authors of this paper also established that deep learning models are capable of handling the complex agricultural data. The high performance of these models is an indication that these models are more than capable of accepting and processing many inputs. For instance, the use of the decision trees in the categorization of the soil enables one to make proper recommendations of crops that can be grown in a specific type of soil as indicated by[5]. Likewise, due to the functionality of the SVMs in diagnosing diseases at an early stage, the probable losses that may be incurred may also be manageable. The incorporation of these AI models in a decision support system means that decisions on the management of crops can be made in real time hence efficiency. Sensors were deemed necessary in the evaluation of the condition of the soil and crops as they are in the field. Real-time information of moisture, temperature, and nutrients of the soil which are crucial in identifying the right time to water the plants or even apply fertilizers were sensed

[10]. For instance, the fluctuation in the average of soil moisture in the sites was 28 percent. 7% to 32. 1% while the nutrients level was varying (Table 2). From this information it can be concluded that one has to be very careful when using the resources if productivity of crops is the aim. The results support [12] who posited that sensors are useful in precision agriculture as they provide information on the status of the soil and crops. Sensors can thus be incorporated in the AI systems in a manner that the changes are made based on the data obtained from the fields on the current practices to be adopted in farming.

Self-driving cars and robotic pickers used in the operations of the organization enhanced productivity at the operational level. For plowing, both seeding and harvesting times were cut down by measures that ranged from a high of 41% improvement. 54% to 45. 00% (Table 3). These results support the view by Bechar, and Vigneault (2016) who noted that the use of robots in farming enhances productivity and reduces the cost of human labour. The manner in which the autonomous vehicles work in performing the tasks is an indication of advancement in the robotics engineering. For instance, self-driving tractors with GPS and sensors can assist in field work with minimal regard to human beings [15]. Similarly, the use of robotic harvesters which do not crush delicate fruits and vegetables has been made possible by improvements in machine vision and automation. AI algorithms, sensors and robotic systems integration brought about commendable improvement of the entire system. The enhancement of crop yield to 24 percent. It has also paved way in decreasing the use of water by 00 % and of fertilizers by 16%. 00% and 15. In relation to the satisfaction level, 100% and 00% respectively represented the effectiveness of the integrated framework (Table 4). These findings are in concordance with the study conducted by [3] that targeted on the roles of integrated technologies in enhancing productivity and efficiency of the agriculture. Therefore, the integration strategy, which consisted in the implementation of a central control system and a communication protocol, allowed for the proper management of the various sub-processes. Thus, it becomes possible to determine the rationality of the application of data-driven decisions in terms of resource consumption and improved crop management [15] The improvements that have been achieved in crop yield and resource utilization add to the testimony of AI and robotics in the change of the agrifood value chain.

The validation phase also entailed a comparison of the proposed AI-driven systems with the conventional farming practices regarding the improvements made on the yield rate, cost of labour, and the impact on the environment as shown in the table 5. This means an increase of the crop yield by thirty six percent. 36% and the decrease of the labour costs by a third, respectively. Regarding the economic impact of AI which has been applied in the organisation, 33% of the respondents are concerned. Also, the reduction of influence from the environmental factors by twenty one percent of the influence score. 43% as to how these technologies can be of assistance in enhancing sustainable agriculture. These findings are in concordance with the conclusion made by [6] who suggested that AI and robotics can increase the agricultural productivity and meet the environmental and economic challenges. This comparison why it is important to introduce new technologies in the process of imposing economic and environmental goals. These are very sensitive ethical questions that come with the application of automation in agriculture. Concerning the employment, the study investigated the potential for creating new jobs and impacts on data privacy and protection where the developed systems are not to replace human beings but rather support them [16].

Specifically, the role of data in the present time and the adherence to ethical practices in the improvement of technology in designing effective and ethical technologies.

Conclusion

The research confirms the effectiveness of the AI and Robotics to enhance the productivity of crops, improve the efficiency of the resources used and subsequently improve the profitability. The developed systems were useful in the aspect of predictive modelling, data acquisition, and automation and which improved the agricultural practices significantly. The findings of the study support the given hypothesis that such technologies can open up the possibilities of a revolution in the field of agriculture and will have economic and ecological consequences. Further research has to be devoted to the improvement of AI and robotics to address the existing problems and opportunities for the further enhancement of the usage of these technologies in the modern agriculture.

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