Digital technologies to ensure sustainable agriculture

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Julian Cruz Olivares
Doctor in Environmental Sciences
Institution: Universidad Autónoma del Estado de México
Address: Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, México
E-mail: jcruzo@uaemex.mx

Eduardo Martin del Campo López
Master of Chemical Sciences
Institution: Universidad Autónoma del Estado de México
Address: Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, México
E-mail: emartindelcampol@uaemex.mx

Erik Alpizar Reyes
Doctor in Chemical Sciences
Institution: Universidad del Bío Bío
Address: Av. Collao 1202, C.P. 4081112, Concepción, Chile
E-mail: ealpizar@ubiobio.cl

Angélica Román Guerrero
Doctor in Biotechnology
Institution: Universidad Autónoma Metropolitana - Iztapalapa
Address: Ferrocarril San Rafael Atlixco No. 186, Col. Leyes de Reforma 1ª. sección, C.P. 09310, México City, México
E-mail: aroman@izt.uam.mx

José Francisco Barrera Pichardo
Master in Chemical Engineering
Institution: Universidad Autónoma del Estado de México
Address: Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, México.
E-mail: jfbarrerap@uaemex.mx

Sandra Karina Velázquez Gutiérrez
Doctor of Chemical Sciences
Institution: Universidad Autónoma del Estado de México
Address: Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, México
E-mail: sandyvgutz@gmail.com

César Pérez Alonso
Doctor of Science (Chemical Engineering)
Institution: Universidad Autónoma del Estado de México
Address: Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, México.
E-mail: cpereza@uaemex.mx

ABSTRACT
The global demand for agricultural products is expected to double in the near future due to increasing population and improving health, implying that the agricultural sector needs to increase its production while adhering to sustainability standards. Sustainable agriculture focuses on safeguarding the environment, improving the quality of life of farmers, and maintaining or increasing food production levels. To this end, the application of artificial intelligence in agriculture is essential through the use of digital technologies such as precision agriculture, remote sensing, robots, information systems for agricultural management and decision support systems. Therefore, the main objective of this work is to show how digital technologies based on artificial intelligence are and will be contributing to generating sustainable agriculture in the coming years.

Keywords: Sustainable Agriculture, Artificial Intelligence, Robotics, Digital Technologies.

1 INTRODUCTION

Agriculture accounts for 4% of global GDP, with developing nations accounting for 25% of this total. Given the predicted trend of a sharp rise in food demand due to population expansion and its effects on climate change, the agricultural sector is an increasing social issue. Accordingly, the world's agricultural industry plays a critical role in providing food production, jobs, and income for the 9.7 billion people that are expected to exist by 2050 (Guindani *et al*., 2024). Additionally, the agricultural sector's expansion will have a two to four times greater impact on raising the incomes of the most impoverished communities.

Climate change and population expansion are two major issues facing agriculture. Global problems include raising crop production and encouraging sustainable agriculture. Artificial intelligence, autonomous systems, communication, and detecting technologies have all advanced for sustainable agriculture. By implementing precision agriculture based on data collection, agricultural science seeks to transform traditional agriculture. In order to increase yields, decrease resource losses, and lessen environmental effects, it is intended to address particular field variations and to precisely time and place treatments (Wang *et al*., 2025).

Decision-making and agricultural operations monitoring are made easier by the real-time data collecting and analysis made possible by the use of technology including applications, sensors, artificial intelligence, and digital platforms. Furthermore, the provision of online technical assistance and consulting services aids in producer training and offers the agricultural industry several advantages, including improved productivity, sustainability, traceability, efficiency, and product quality. Utilizing cutting-edge technologies and valuing people are essential components that propel this integration and encourage digital transformation in order to maximize outcomes in the agriculture industry.

In order to achieve sustainable agriculture, the goal of this work is to present the primary digital technologies being used in the agricultural sector to enhance food production procedures while lowering waste and pollution generation.

Figure 1

Conventional agriculture

Source: From the authors by means of artificial intelligence

2 METHODOLOGY

Since the agro-industry is well-established and strategically important globally, the shift to sustainable agriculture will be a unique process that calls on farmers to take incremental, doable steps. Therefore, it is the common responsibility of all people to promote the shift to sustainable agriculture. Agroecosystems require technical proficiency, professional labor, and knowledge to be sustained over the long run. In order to attain agricultural sustainability and productivity, social institutions need to support scientific and farmer education, encourage innovation, and build collaborations between researchers and farmers.

In addition to the aforementioned, the agricultural industry is aggressively embracing digital innovation, with specific ideas and technologies being created in the areas of robots, remote sensing, precision agriculture, information systems for agricultural management, and decision support systems.

The following is a description of some of the most cutting-edge technology to accomplish sustainable agriculture:

2.1 SENSORS

Vegetables are a specific situation because they are simple to cultivate in protected environments like greenhouses. Sensors for temperature, humidity, and solar radiation are some of the most advanced technologies. The environment is the only thing within control in this situation. A certain strategy may be implemented automatically based on the information gathered from these sensors. The process is typically semi-automated, with meteorological parameters being manually entered into the system before it becomes automatic. Fertilizers and pesticides are then administered according to the system's instructions, but in amounts that are determined by humans (Hu *et al*., 2025).

The devices are less sophisticated for vineyards and fruit trees. They are made up of weather stations that track the conditions that are conducive to the growth of specific diseases. People manually apply treatments based on these analyses.

2.2 ARTIFICIAL INTELLIGENCE (AI)

The technique of employing computers and technology to mimic human intelligence is known as artificial intelligence (AI). AI increases an application's level of efficiency by employing human intellect to do assigned tasks. AI is likewise utilized in smart agriculture, offering a range of approaches and strategies for carrying out agricultural duties. AI is mostly utilized in precision agriculture, disease detection, harvesting, pest control, and decision-making in smart agriculture (Wang *et al*., 2025).

AI-based techniques are being applied to crop classification and prediction in smart agriculture. The latency in the crop classification process is decreased by using a genetic algorithm (GA) to distinguish the precise types of crops from the other crops. The GA-based method lowers the production process error rate by improving overall crop categorization accuracy.

Smart agriculture operations make extensive use of automated methods and robots. Automated robots employ software to carry out tasks and collaborate with human resources. Adequate data sets are necessary for the decision-making process in order for autonomous robots to execute flawless detection. Automated robots use wireless sensors to gather the information required for subsequent operations. A huge database contains a lot of data. Deep learning (DL) is a decision-making technique used by automated robotics. Here, the precise content and important values for the decision-making process are found using a detection technique based on the deep reinforcement learning (DRL) algorithm (Gamage *et al*., 2024)

The DRL algorithm identifies the key factors that reduce energy consumption ratio in computing and decision-making processes. The DRL method achieves high accuracy in decision-making, which improves the efficiency of automated robots in smart agriculture practices. Internet of Things (IOT) based automated robots are used in smart agriculture. IOT is mainly used to improve user interaction services. The IOT collects the necessary data, producing accurate information for decision-making (Saini *et al.*, 2025).

Moreover, robots based on the artificial neural network (ANN) algorithm are commonly used here, which improves the sustainability range of agriculture. The ANN algorithm identifies the defects and key values needed for prediction process. ANN -based robots are mainly used in smart agriculture for cultivation and harvesting.

Recurrent deep learning and robotics technology come together in the cutting-edge model known as Flexible Decision System (PDS) for Agricultural Robots (FR), designed to improve the efficiency of decision-making in the agricultural sector. It emphasizes multifactorial decision-making and sustainability to ensure long-term production while avoiding environmental and social repercussions. The model improves operational efficiency and environmental compatibility by incorporating technological advances such as AI and automated mechanics. Through the application of structured decision-making founded on agricultural data and sustainability metrics, the model aims to improve the utilization of resources and the efficiency of production to promote sustainable agricultural practices (Hu *et al*., 2025).

The Flexible Decision System (PDS) for Agricultural Robots (FR) uses robotics units and intelligent machine systems to improve global agricultural practices based on conventional methods and different climatic conditions. The objective of the system design is to operate the functions of agricultural devices employed in agricultural lands. In agriculture, automated devices such as feeders, drones, sprayers, etc., are used and regulated through robotics units and intelligent machine systems (Hu *et al*., 2025)

Robotic and intelligent machine systems are a mixture of software and hardware components that can be used to observe and analyze agricultural data collected from agricultural lands. Robotic and intelligent machine systems are equipped with wireless sensors to observe data such as soil moisture, relative humidity, temperature, wind speed and direction, climatic conditions, crop stages, etc. This data collected from agricultural lands is exploited to analyze the regulations and operations of agricultural devices. In particular, the precise agricultural stages and operation controls of the proposed system are defined using the recommendations of robotics units.

A modern agricultural practice consists of centralized robotics units that control the operations of the devices used in today's agricultural lands. Through self-learning and intelligent decisions, integration increases processing speed and sustainability. The operations of agricultural devices are managed and controlled by robotics units and wireless sensors. The PDS operates between robotics units and agricultural lands (Hu *et al*., 2025)

2.3 PRECISION AGRICULTURE (PA)

Precision agriculture (PA) is an advanced hierarchical agricultural system supported by multidisciplinary technologies such as specialized sensors, communication protocols, algorithms, and management tools, which helps mitigate the problems of conventional agriculture by ensuring maximum production and minimum waste (Petcu *et al*., 2024).

The IOT Environment "The Internet of Things" denotes a network comprising devices interconnected via the Internet with software, sensors, and other technological components. These components enable devices to collect and exchange data with each other and with centralized systems via the Internet. The fundamental principle underlying the IOT is to facilitate autonomous communication and interaction between common objects, thereby establishing a cohesive fusion of the physical and digital realms (Abdulrazzq *et al*., 2024).

The state of interconnectivity enables the collection of enormous amounts of data from various sources, resulting in valuable information that can be applied to optimize operations, improve decision-making procedures, and generate inventive resolutions in a multitude of fields. Furthermore, the IOT enables new perspectives for advances and commercial activities as organizations exploit data-driven understandings to create intelligent products and services tailored to address the changing needs of consumers (Saini *et al*., 2025).

- **Sensors:** Farmers pay close attention to soil quality, climatic conditions, plant health, and the efficiency of the agricultural supply chain. The IOT enables precise monitoring of these routine processes, which can be advantageous for optimizing resources and decision-making. Such precise monitoring systems use multiple sensors, such as humidity and temperature sensors, to achieve the intended task (Hu *et al*., 2025).
- **Actuators:** Actuators play a crucial role in IOT-enabled PA by transforming sensor data into physical actions and translating knowledge into actionable tasks. Various actuators allow farmers to automate tasks such as planting by collaborating with sensors and IOT platforms.
- **Communication Protocols:** Communication protocols are crucial in IOT-based PA as they facilitate seamless interaction and data exchange between different devices and systems used in

agricultural environments. Communication protocols are a set of rules, syntax, and a combination of hardware and software that facilitate bidirectional data transfer. Depending on the use case, there are several communication protocols for IOT devices. Each protocol provides distinct characteristics and is designed for specific needs. The application, data volume, energy limitations, and required range influence the selection of the protocol (Saini *et al*., 2025).

2.4 REMOTE SENSING (RS)

Agriculture empowered by remote sensing (RS) is a significant approach that uses remote sensing to improve agricultural production and crop management. In the agricultural sector, RS enables the recovery of extensive data related to land, vegetation, and crops, providing crucial information for farmers and decision-makers to improve precision and efficiency in cultivation and crop management. The combination of RS and artificial intelligence (AI) has enormous potential for agricultural production. With the integration of AI, agriculture empowered by remote sensing has expanded, and its impact has become increasingly prominent. It is expected to have far-reaching effects on global agriculture, fostering more efficient, sustainable, and intelligent development (Hu *et al*., 2025; Wang et al., 2025).

RS collects information from the land and can be used for environmental monitoring and disaster alerting, providing geospatial information for PA. With its capabilities in spatial, temporal, and spectral resolution, RS provides an effective means to monitor crop growth, quality detection, and yield prediction. The term "remote sensing" was introduced before 1958. Agriculture is experiencing its fifth revolution, driven primarily by the progress of information and communication technologies. Cutting-edge technologies, including RS, big data analytics, and AI, are being employed to improve the efficiency of agricultural practices and optimize the utilization of resources, with the goal of increasing yields and reducing input and yield losses. The latest smart agriculture emphasizes human-centered AI, giving greater importance to human-AI collaboration, which promotes sustainability, resilience, and humanization in agricultural production.

Agricultural RS uses the collected electromagnetic spectra, including visible light, near-infrared, and shortwave infrared, to interact with agricultural targets (plants and soil) and obtain information on plant health, moisture status, and soil characteristics. Visible light is commonly used to assess chlorophyll content and plant growth status, and near-infrared is often used to monitor plant health and moisture content, while shortwave infrared is typically used to analyze soil type and quality. This data helps farmers and agricultural researchers to manage farmland more effectively, increase crop yield and quality, and reduce waste and environmental impact (Hu *et al*., 2025).

The combination of RS and AI has widespread applications in agriculture, such as variety identification, optimization of crop management, estimation of evapotranspiration, phenological monitoring, yield prediction, provision of ecosystem services, detection of biodiversity, monitoring of crops and land, and full implementation of PA. This provide rich information and support for sustainable agriculture.

RS has immense potential in the agricultural field. By fully utilizing the advantages of RS data and AI algorithms, sustainable agricultural production, efficient resource utilization, and improved product quality can be achieved. Regarding irrigation, timing and rate are crucial factors that influence water stress, crop growth, and yield. Traditional agricultural practices do not consider the variability within fields and instead use uniform irrigation rates. RS data can help identify intra-field changes and implement variable rate irrigation using common irrigation systems to alleviate water stress and improve uniformity and productivity (Hu *et al*., 2025).

3 RESULTS AND DISCUSSION

The challenges of food insecurity and inadequate food production hinder the supply of food to ensure that humanity does not suffer from hunger and malnutrition. The need to integrate digital technologies into agricultural activities has been emphasized. Therefore, Artificial Intelligence (AI) can address the aforementioned problems. There are problems in several processes involved in agricultural activities, where most farmers rely heavily on a traditional agricultural system that hinders maximum productivity. In fact, there is a projection that the world population will exceed 9 billion in 2050 (Guindani *et al*., 2024). As a result of this projection, it is of utmost importance to point out that Artificial Intelligence (AI) in agriculture is crucial for the transformation of this sector towards guaranteeing production and food security, sustainability, and resilience to climate change, which will address production and food security.

The applications of technologies in general and Artificial Intelligence (AI) in particular are revolutionizing the agricultural sector by improving productivity, sustainability, and efficiency. The applications of AI in agriculture include computer vision, machine learning, predictive analytics, and robotics for tasks such as weeding, pesticide spraying, livestock monitoring, and automation of harvesting processes. It is further stated that AI helps improve soil health, crop production, and address challenges such as climate change, population growth, and food insecurity. Precision agriculture techniques that use AI provide information on water and nutrient management, optimal planting times, and crop rotation schedules, which contribute to increased yields and reduced costs, which are determinants for promoting socioeconomic development.

Figure 2

High-tech orange plantation with visible applications of artificial intelligence, precision agriculture, robots, sensors, actuators, and remote sensing.

Source: From the authors by means of artificial intelligence

The integration of Artificial Intelligence (AI) has significantly transformed the agricultural industry, particularly by improving crop yield and productivity. AI technologies such as machine learning, convolutional neural networks, IOT, big data, robotics, and computer vision are increasingly applied in agriculture to optimize resources, increase efficiency, and predict outcomes. These technologies enable faster performance of traditional agricultural practices such as weeding, pesticide spraying, and irrigation, leading to reduced water waste, improved soil fertility, and increased crop yields. In addition, AI assists in precision agriculture, crop monitoring, predictive analytics, and supply chain optimization, contributing to improved productivity, efficiency, and sustainability in the agri-food sector.

4 CONCLUSION

AI offers innovative solutions to address challenges in agriculture, such as the impacts of climate change and the gaps between supply and demand. The implementation of Climate-Smart Agriculture (CSA) practices, supported by AI technologies, can significantly improve food security and sustainability. The digitization of agriculture through AI tools reduces intermediaries, expands market opportunities, and improves the productivity and livelihoods of small farmers, emphasizing the importance of training staff and farmers in digital skills.

The implementation of AI technologies in agriculture faces challenges such as lack of standardization, high implementation costs, job losses, and affordability issues. In addition, the uneconomical nature, lack of expertise, and big data requirements hinder the penetration of AI in agriculture. The convergence of AI and IOT in smart agriculture introduces challenges such as data integration, automatic analysis, and solving pest management problems. To address these challenges, it is argued that it is necessary to improve the transparency of models, assign clear responsibility, overcome concerns about equity, and ensure data ownership, privacy, and security. Despite these obstacles, AI technologies offer solutions to optimize resources, increase productivity, and improve crop yields, which are vital to meeting the growing demand for food in the world.

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