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Artificial intelligence in agriculture: A view from a sustainable development perspective

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Abstract

The current economic system demands, on one hand, a transformation of the model due to its negative environmental effects, but on the other hand, it demands an increase in agricultural productivity in response to food shortages and projected population growth. In this regard, the use of artificial intelligence (AI) is presented as a technological alternative to address these challenges. Therefore, this study explored the use of artificial intelligence in agriculture from the perspective of sustainable development. The research followed a documentary design, reviewing academic literature from the past five years. The review found different automation experiences across the agricultural production chain, including planting, harvesting, crop monitoring, and climate and soil analysis, where artificial intelligence tools are applied. These tools provide accurate and predictive information related to agricultural practices while using machine learning, robotics, unmanned aircraft, conversational intelligence, and sensors, among others. Sustainable development highlights the privilege of the productivity dimension, determined by the optimal use of resources aimed at sustainability in agricultural processes. Finally, it is important to continue investigating the social, political, ethical, legal, and environmental implications of AI in agriculture, since there is a real need to establish regulatory frameworks that allow promoting but also controlling it to ensure an equitable and supportive use for the benefit of humanity and sustainable development.

Keywords: agriculture, artificial intelligence, sustainable development

Inteligencia artificial en la agricultura: Una mirada desde el desarrollo sostenible

Resumen

El sistema económico actual demanda, por sus efectos negativos en el ambiente, una trasformación del modelo, pero al mismo tiempo incrementar la productividad agrícola, pues la escasez de alimentos y los pronósticos de crecimiento poblacional así lo requieren. En ese sentido, el uso de tecnologías como la inteligencia artificial (IA) se presenta como una alternativa ante estos desafíos. Por ello, este artículo exploró el uso de la inteligencia artificial en la agricultura desde la perspectiva del desarrollo sostenible. Se realizó una investigación con un diseño documental, a partir de una búsqueda bibliográfica en bases de datos académicas, centrada en los últimos cinco años. En la revisión se encontraron diferentes experiencias de automatización de la cadena agroproductiva: siembra, cosecha, monitoreo de cultivos, clima y suelos, en donde se aplican herramientas de inteligencia artificial que ofrecen información precisa y predictiva relacionada con la práctica agrícola, con el uso del aprendizaje automático, la robótica, aeronaves no tripuladas, inteligencia conversacional, sensores, entre otras. Desde el desarrollo sostenible se observa el privilegio de la dimensión productivi-

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dad, determinada por una utilización óptima de recursos dirigida a la sustentabilidad en los procesos agrícolas. Finalmente, se considera de interés seguir indagando en las implicaciones sociales, políticas, éticas, jurídicas y ambientales de la IA en la agricultura, pues en la práctica se percibe la necesidad de establecer marcos regulatorios que permitan impulsarla, pero también controlarla, en función de garantizar un uso equitativo y solidario en beneficio de la humanidad y el desarrollo sostenible.

Palabras clave: agricultura, inteligencia artificial, desarrollo sostenible

Inteligência artificial na agricultura: Uma perspectiva de desenvolvimento sustentável

Resumo

O sistema econômico atual exige, devido aos seus efeitos negativos no meio ambiente, uma transformação do modelo, mas ao mesmo tempo um aumento da produtividade agrícola, pois a escassez de alimentos e as previsões de crescimento populacional assim o exigem. Neste sentido, o uso de tecnologias como a Inteligência Artificial (IA) apresentam-se como alternativas a estes desafios. Portanto, este artigo explorou o uso da inteligência artificial na agricultura sob a perspectiva do desenvolvimento sustentável. A pesquisa foi realizada com um desenho documental, a partir de uma pesquisa bibliográfica em bases de dados acadêmicas, com foco nos últimos cinco anos. A revisão encontrou diferentes experiências de automação da cadeia produtiva agrícola: semeadura, colheita, monitoramento de culturas, clima e solo, onde são aplicadas ferramentas de inteligência artificial; que oferecem informações precisas e preditivas relacionadas à prática agrícola, com o uso de machine learning, robótica, aeronaves não tripuladas, inteligência conversacional, sensores, entre outros. Do ponto de vista do desenvolvimento sustentável, é privilegiada a dimensão da produtividade, determinada por uma utilização ótima dos recursos visando a sustentabilidade dos processos agrícolas. Por fim, considera-se de interesse continuar a investigar as implicações sociais, políticas, éticas, legais e ambientais da IA na agricultura, uma vez que, na prática, se percebe a necessidade de estabelecer quadros regulamentares para a promover, mas também para a controlar, de modo a garantir uma utilização equitativa e solidária em benefício da humanidade e do desenvolvimento sustentável.

Palavras-chave: agricultura, inteligência artificial, desenvolvimento sustentável

1. Introduction

Agriculture has been part of human history and has evolved along with the great transformations of humanity, yet today it faces new challenges in the midst of the global food crisis. All of this has led to rethinking production methods in order to respond to the great social needs with an emphasis on hunger mitigation and environmental issues.

In this regard, agriculture has been transformed to respond to social needs. In fact, it was during the seventeenth and nineteenth centuries that an optimization of cultivation techniques began through mechanization, based on the establishment of agro-industrial systems. Subsequently, the so-called green revolution emerged, which implied a techno-scientific revolution that considerably disrupted agricultural practices through the application of technological devices (hybrid or genetically modified seeds, chemical fertilizers, and synthetic pesticides). This increased productivity, but also generated great concerns regarding sustainability and environmental impact, given the pressure applied on agroecosystems[(1)].

Along with environmental concerns, the need to mitigate hunger in the world remains urgent, creating new challenges to food production, since it is affected by various realities such as climate change, the depletion of the ozone layer, widespread pollution, the loss of biological diversity, and deforestation, among others. In fact, it is reported that the current deforestation rate of tropical forests is 17 million hectares, while desertification is estimated at 4 million hectares of arable land lost each year[(2)].

This is added to the new dynamics generated by the development of the biofuel industry and its demand for raw material, which may imply shortages and rising of prices of some items[(3)], as well as price control by the agro-industrial market. These factors build a complex panorama for the food production sector, as there is a clear contradiction between productivity and the sustainability of agricultural processes.

Regarding the climate crisis resulting from rising temperatures and variations in climate patterns, it is one of the most pressing concerns in recent decades. Its relationship with the agri-food chain lies in the fact that estimations determine that it uses a third of the world's energy production in its processes[(4)]. This has led precisely to proposals aiming at making processes more efficient and productive, while reducing energy consumption.

Similarly, population growth projections estimate that it will exceed 9 billion people by 2050, thus intensifying the global demand for food. At the same time, the greenhouse effect describes that emissions from agriculture, forestry, and fisheries have doubled in recent decades. These contradictions reveal that the required increases in the agricultural sector should not continue to be carried out to the detriment of the environment, as has been the case over the last 50 years[(5)].

In fact, both the 2030 Agenda for the Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change emphasize the need to increase food production, while also highlighting the importance of transforming development models toward more sustainable schemes. In this regard, agriculture is relevant to several of the seventeen objectives related to population growth, scarcity of natural resources, climate change, and food waste[(6)(7)].

These realities have led to the search for effective responses to the challenges described. In this context, the application of technological innovations in the agricultural sector represents a viable option, taking into consideration that the development of new techniques has historically led to great economic changes in societies; although, in this case, sustainability must accompany these activities. Nowadays, various virtual technologies are transforming agricultural work practices worldwide. Among them, artificial intelligence (AI) applied to agriculture appears as a strategy to optimize production, which could also contribute to the fight against rising hunger, food insecurity, and poverty. Migration of the young population from rural areas is another aspect to consider, which generates new tensions. Experts point out among its benefits that the use of these technologies can enable the production of more food with fewer farmers[(8)], which will generate new tensions in social, economic, political, and even cultural spheres.

Furthermore, AI can be understood as “a computer science discipline that has gained relevance in various contexts, due to its ability to create systems that emulate intelligent behavior. This allows the creation of decision-making models in complex and non-linear contexts, as is the case with agricultural production”[(9)]. However, these agricultural innovations must be framed within sustainable development, so as not to repeat the mistakes of the past. Based on the reality described above, this study explores the use of artificial intelligence in agriculture from the perspective of sustainable development.

Although the breadth of AI applications in agriculture is recognized, this research seeks to conduct an exploratory review of the experiences that have been developed worldwide in this field, whether in family farming or agro-industrial contexts, characterizing the use of these innovations from their contribution to sustainability both on a small scale and in extensive production operations.

2. Materials and Methods

This study was developed through exploratory research, based on a documentary review of the perspectives of artificial intelligence in agriculture. A bibliographic search was conducted in academic-scientific databases

Google Scholar, SciELO, Dialnet, and Science Direct, using a combination of the descriptors “artificial intelligence”, “sustainable development”, and “agriculture”. In addition, a temporal criterion was established: a five-year study period, since, given the topic, it was necessary to ensure access to updated knowledge.

From this process, scientific articles and conference papers were obtained. The selection process was developed through the establishment of inclusion and exclusion criteria in order to choose those linked to the research objective. To this end, the following inclusion guidelines were defined: studies addressing the issue of artificial intelligence in agriculture and sustainable development, with open access, both empirical and theoretical research, with reliable, substantiated information, and from recognized organizations, in Spanish and English. Those from non-institutional or academic-scientific sources or those dealing with the topic of artificial intelligence and agriculture from another approach were omitted, as well as duplicate documents or documents that repeat the information of other selected articles.

For the document selection process, a first selection was made based on the review of the titles. Subsequently, abstracts were read, and for the final selection, the entire texts were analyzed. The publications were processed in the Zotero reference manager. From this point, the technologies linked to artificial intelligence used in agricultural processes, in connection with sustainable development, were explored. The eighteen (18) selected publications are presented below.

Table 1. Selected articles

AUTHORS	YEAR	TITLE	COUNTRY
Hoyos J, Carrascal B, Bautista D & Díaz N[9]	2023	Impacto transformador de la inteligencia artificial y aprendizaje autónomo en la producción agropecuaria: un enfoque en la sostenibilidad y eficiencia	Colombia
Rambauth G[11]	2022	Agricultura de Precisión: La integración de las TIC en la producción Agrícola	Colombia
Ramón Fernández F[12]	2020	Inteligencia Artificial y Agricultura: nuevos retos en el sector agrario	Spain
Monasterio A[17]	2021	Inteligencia Artificial para el bien común (AI4SG): IA y los Objetivos de Desarrollo Sostenible	Spain
Segovia J, Rojas F & Quishpe M[14]	2021	Estudio del uso de técnicas de inteligencia artificial aplicadas para análisis de suelos para el sector agrícola	Ecuador
Mateos Espejel L[15]	2021	Desarrollo de habilidades digitales en el proceso de difusión de la Agricultura 4.0	Mexico
Vásquez A, Vásquez N & Conde R[4]	2023	Impacto del uso de las tecnologías de la información en la agricultura de precisión	Peru
Forero MG, García-Vanegas A & Betancourt Lozano J[16]	2022	Uso de tecnologías avanzadas de inteligencia artificial en aplicaciones agrícolas y botánicas	Colombia
Sánchez J & Castillo G[19]	2022	Algoritmos y su efecto en la agricultura: automatización de procesos	Peru
Ahmad A, Noor S, Cartujo P & Martos V[21]	2022	Artificial Intelligence (AI) as a complementary technology for agricultural Remote Sensing (RS) in plant physiology teaching	Spain
Ponte D, Espinosa A, Gibeaux de González S & González C[22]	2021	Estado actual del aprendizaje automatizado aplicado al internet de las cosas para automatizar procesos agrícolas.	Panama
Siche R & Siche N[23]	2023	El modelo de lenguaje basado en inteligencia artificial sensible-ChatGPT: Análisis bibliométrico y posibles usos en la agricultura y pecuaria	Peru
Santos S & Kienzle J[25]	2021	Agricultura 4.0: Robótica agrícola y equipos automatizados para la producción agrícola sostenible	Italy
Coello M, Guerra E & Quishpe M[27]	2021	Inteligencia artificial enfocada al uso y distribución de terrenos para procesos de producción agrícola	Ecuador
Tovar-Quiroz A[20]	2023	Agricultura 4.0: uso de tecnológicas de precisión y aplicación para pequeños productores	Colombia
Sachithra V & Subhashini L[24]	2023	How artificial intelligence uses to achieve the agriculture sustainability: Systematic review	Sri Lanka
Jha K, Doshi A, Patel P, Shah M[18]	2019	A comprehensive review on automation in agriculture using artificial intelligence	India
Sharma S, Verma K, Hardaha P[26]	2022	Implementation of Artificial Intelligence in Agriculture	India

3. Results

3.1 Sustainable Development and Artificial Intelligence (AI)

Sustainable development is a concept that has been gaining relevance in international politics, given the growing visibility of the environmental damage of the prevailing production model, represented, among other phenomena, in global warming, climate change, and the loss of biodiversity resulting from human activities, with emphasis on the burning of fossil fuels. In this sense, sustainable development is understood as the need to constitute a model of economic-social development that reconciles economic growth with the balance of ecosystems, intending to protect the planet's natural resources.

The term sustainable development is perceived as the possibility of enhancing the quality of life through the improvement of the human-environment relationship, in which the survival of ecosystems is guaranteed[(10)]. It involves a series of systems or dimensions: political (participation of actors), social (equity in distribution), cultural (consideration of local culture), technological (innovative solutions), productive (efficient use of resources), ecological (ensuring the balance of ecosystems and diversity), and international (sustainable trade models), among others. Therefore, it is considered a complex notion, since it involves multiple aspects that go beyond the responsible use of natural resources, moving towards a true balance between different systems[(2)(10)].

In this way, sustainable development is constituted as a holistic category integrated by various dimensions, where ecological sustainability, social equity, and the global-local relationship acquire relevance, in addition to democratic participation and joint action on the different problems generated by climate change to promote the preservation of the planet and the quality of human life[(2)].

Given its importance, in 2015 all members of the United Nations adopted 17 goals with 169 targets, which include eradicating hunger, achieving food security, guaranteeing healthy lives, ensuring access to water and energy, promoting sustained economic growth, adopting urgent measures against climate change, among others[(6)]. In this way, sustainable development appears as a strategy to meet present needs without compromising the capacity of future generations, implying the need to balance economic growth, environmental protection, and social welfare.

This perspective is gaining strength in the need to establish a sustainable and productive model for the agricultural sector at a global level, where a new relationship is established with the planet and territories, ensuring a sustainable management and use of soils, water, and plant genetic resources, which are essential for food production[(5)].

Moreover, by promoting sustainable development, the conservation of natural resources is supported, pollution is reduced, and social and economic equality is promoted, guaranteeing the long-term health of the planet. For this, innovation and efficiency in the use of resources in all economic areas are necessary. Thus, it is a great challenge for the agricultural sector, on the one hand, to increase food production to mitigate world hunger, but also to reduce the use of resources such as water, energy, fertilizers, and others.

These pressing needs are crossed by the accelerated technological development of recent decades, focused on the automation of various human practices, including the activities derived from agriculture. These technologies have driven the evolution of all production processes emerged from the so-called Industry 4.0, highlighting the transition from Agriculture 1.0 to 4.0, with predictions already pointing toward Agriculture 5.0 based on the permanent incorporation of innovations, whose advances are more vertiginous than in previous periods[(7)].

One of these is precision agriculture (PA), which seeks to optimize crop yields through technologies that enhance accuracy in agricultural practices and decision-making. It is highlighted that PA incorporates sustainability considerations such as soil conservation, rational use of water, among others[11]. In fact, by using technological applications, PA reduces the use of pesticides, fertilizers, and water, while promoting the optimization of soil fertility and crop yield. The aim is to make the use of agricultural resources more efficient, thus promoting a model of sustainable development[9].

Within PA, reference is made to artificial intelligence, as its use has demonstrated the possibility of optimizing crop management, improving efficiency in the use of resources, preventing and controlling diseases, and providing accurate real-time data for decision-making. This enables more efficient crop management through the application of specific treatments and precise use of resources such as water and fertilizers[12].

Among the most prominent technological applications in PA are artificial intelligence, robotics, unmanned aircraft or drones, high-performance computing, and the Internet of Things. These innovations can increase efficiency and, at the same time, promote environmental sustainability by reducing the use of resources. Notably, they enhance the entire process from cultivation to commercialization[12].

Artificial intelligence, in particular, is understood as "a combination of technologies that brings together data, algorithms, and computing capacity. Advances in computing and the increasing availability of data are, therefore, a fundamental driver in the current pronounced growth of artificial intelligence"[13]. Every day, new advances emerge, and the forecasts in this field are impressive.

From this perspective, AI refers to machines with cognitive functions similar to humans, which manage to learn, understand, reason, make decisions, or interact. Therefore, AI systems integrate recognition and understanding of meaning, signal detection, intelligent control, and simulators through the combination of hardware components (sensors, chips, robots, etc.) with algorithms and software. As described, AI is a diverse and continuously growing field[7][13].

AI is thus a rapidly growing discipline whose promises even tend to defy science fiction. In agriculture, the incorporation of AI systems provides predictive information related to agricultural practices. For instance, AI can determine optimal sowing and harvesting dates; by enhancing crop performance, it reduces the use of resources such as water, fertilizers, and pesticides, thereby improving both efficiency and sustainability[9][14].

These solutions have been applied in various experiences, enabling agriculture to produce more with fewer resources. This explains their popularity and rapid extension in the world, especially in developed or developing countries, which report concrete experiences of application and diversification in agricultural environments. AI is considered an emerging field in agriculture that encompasses multiple research and development disciplines such as computing, machine learning, crop improvement, genetics, biology, statistics, physics, and chemistry, among others[15].

For this reason, AI opens up an unprecedented range of options, focused on reducing inputs and automating tasks[4]. In the agricultural sector, specific fields of action stand out, such as crop yield prediction, price forecasting, intelligent spraying, agricultural robotics, crop and soil monitoring, with interaction with the environment being essential in the application of this type of tool[16][17].

It should be noted that among the AI technologies applied to agriculture, machine learning stands out. It applies artificial intelligence through a set of algorithms capable of executing complex tasks without requiring explicit programming. The objective is to feed the machine with data from past experiences and statistical information so that it can perform the assigned tasks and solve problems[9][18]. For example, artificial neural networks in agriculture offer the possibility of predicting and forecasting based on parallel reasoning without continuous programming. They can be trained and can compensate for failures in expert systems by improving prediction methods[18].

In this way, artificial intelligence has revolutionized agribusiness, since, for the first time in the history of humanity, the availability and use of information are enabling the optimization of production processes to reduce input investment[(19)]. Additionally, AI is also proposed as having the potential to develop sustainable agricultural processes.

3.2 Characteristics of Artificial Intelligence Applied to Agriculture

An interesting aspect of the transformations of agricultural practice is its strategy, which combines local agricultural knowledge with technological applications such as the massive acquisition of data and images, artificial intelligence, robotics, and task automation, thus facilitating intelligent decision-making to generate precise actions. Technologies in agricultural processes involve “the use of the Internet of Things, data analytics, artificial intelligence, machine learning, cloud computing, and remote sensors, which have been identified as the ones with the greatest use and impact on agriculture for water management, crop monitoring, climate analysis, agrochemical use, soil assessment, and greenhouse cultivation, among others”[(20)].

Likewise, within the AI techniques applied to agriculture, neural networks, machine and deep learning are noteworthy, allowing the measurements of crop production rates and providing information on supply chains. In addition, with the use of satellites, AI guides the detection of growth patterns in planted areas when applied to PA for crops, forests, or urban green areas, thereby providing strategic insights for effective decision-making[(4)].

One of the innovations from machine learning and analytics has enabled the expansion of the Internet of Things (IoT), so that the data produced by these technologies feed back into them, allowing access to large datasets that can be managed more quickly[(11)]. For example, machine learning is applied to “disease identification, yield prediction and biomass estimation; with prospects to develop simulations of crop growth and yield, machine training models from satellite data available free of charge”[(21)].

Machine learning also enables machines to learn to extract patterns and relationships from data, improving their predictive abilities and decision-making. In agriculture, this includes predicting crop adaptability to soil and environmental conditions, while in livestock, it is used to automate animal tracking, minimizing losses and costs[(22)].

Likewise, ongoing experiments are currently testing the use of robots and artificial intelligence for harvesting, drones or RPAS (Remotely Piloted Aircraft Systems), as well as other tools and instruments to digitalize agriculture. The implementation of sensors and predictive algorithms is also being tested to obtain data for crops and livestock management, with applications also extending to product commercialization[(15)(18)].

Another area of AI are conversational tools, which combine natural language processing (NLP) with IoT devices based on advances in neural networks, which have become attractive, affordable and feasible devices for personal use in agricultural production[(8)]. Within the application of conversational AI in agriculture, experiences with the language model based on artificial intelligence ChatGPT stand out; “it is a sensitive artificial intelligence model, capable of learning from the preferences and behavior patterns of users by personalizing their response, even giving advice to personal questions”, with strong potential to positively transform agriculture based on proper information management[(23)].

In this order of ideas, AI in the agricultural sector automates various basic activities across the production chain: planting, harvesting, and crop, climate, and soil monitoring through learning algorithms to process data. Big data techniques and connectivity within an agricultural network (drones, sensors, software) also intervene, registering, storing, processing, and analyzing large amounts of data. Its central objective is thus to ensure optimal decision-making, minimizing uncertainty and, consequently, risks[(4)].

From the heterogeneity that characterizes AI tools in agriculture, image processing, machine learning, and robotic systems are the most widely used and with the greatest growth forecasts[23]. These advances have shaped the reality of agriculture 4.0, constituted from an articulated use of data from sensors, agricultural machinery, satellite images, drones, smart phones, and radio signals to convert them into useful information for crop management.

In short, AI applications are making it possible to increase productivity, reduce costs, and reduce the environmental impact of agricultural practices[4]. Some AI tools stand out for their agricultural improvements, such as remote sensors for detecting soil moisture, temperature, and pH, as well as automated irrigation guided by GPS. But, in practice, they often face challenges related to farmers' knowledge and implementation capacity[14].

The implementation of robotic systems and artificial intelligence is also pointed out, since the robotic arm has proven effective at harvesting fruits and vegetables without damaging the plant, as well as selecting seeds, reducing failures, costs, and time, thus meeting productivity standards. Likewise, the use of autonomous robots for weeding is also highlighted, based on technologies such as GPS and drones, to detect signals and transmit instructions for the execution of weed treatment, with effective reports to increase accuracy[24].

As demonstrated, advances in AI, understood as the ability of a machine to perform activities associated with intelligent beings, have led to the constitution of programs capable of operating like humans, with their own rational way of processing information[25]. In agriculture, AI has a preponderant role within digital agriculture or 4.0. This involves the implementation of AI algorithms and models in various areas, such as crop monitoring, irrigation system management, pest and disease detection, production optimization, and data-based decision-making. While these tools offer intervention options, it is still the farmer who makes the final decision; in short, a strategic integration between farmers and technologies is proposed.

The logic of AI technologies in agriculture seeks to improve the resources needed for production, not only water, soil, fertilizers, and pesticides, but also labor management. AI supports crop selection, the development of more resilient seeds, the optimization of irrigation and fertilization systems, and the identification of the best harvest times through autonomous robots and drones[26].

The application of such innovations in activities derived from agriculture has undoubtedly brought several benefits, including improved decision-making, effective use of information to optimize agricultural production, detection and prevention of plant diseases, abstention from accurate forecasts for climate management, and even supply chain management[23]. Together, these advances increase yields, reduce costs, and minimize environmental impacts.

It should be considered that AI applications to agriculture are not limited to production, they also involve consumers, from the so-called “smart cities”, which facilitate product access, or the also mentioned “smart farming”, which aims to enhance resource efficiency through feeding or irrigation systems that use software to provide high-quality and sustainable products[12].

For these reasons, AI has become increasingly significant in agriculture, offering major opportunities to improve productivity, efficiency, and sustainability, given that “(AI) refers to computer systems with the capacity to perceive the environment, learn from experience, process large volumes of data and make decisions based on the information received”[9].

3.3 Sustainable Development in the Use of Artificial Intelligence in Agriculture

As with any transformation generated in production processes, artificial intelligence presents a series of challenges. From the reviewed literature, a series of concerns emerge, including the need to promote sustainable increases in agricultural production, from its strategic integration with biotechnology, robotics, big data, simulation, and geostatistics[19].

Despite the above, although innovations generated by AI tools in the agricultural sector are highlighted, they are valued as incipient when compared to other areas of the economy[14]. It is expected that the applications of these technologies in agriculture will continue to diversify, gradually incorporating them into all the activities that constitute agricultural practice worldwide.

It is important to mention that technological development in this field is not static; rather, it responds to an almost ephemeral dynamism, so it is essential to recognize the growing importance of data and how it is used. Due to the great benefits and implications AI has over the transformation of productive practices, further research is needed to assess its uses, advantages, disadvantages, and to identify opportunities for improvement. This, in turn, requires an adequate regulatory and ethical framework, which is not yet fully defined, although advances have been made, especially in Europe. Because of the aforementioned dynamics, ongoing evaluation is necessary[23].

Several key actors are identified in the process, on the one hand, the industries that produce these technologies and farmers who apply them, and on the other hand, governments, universities, and research centers, since not only knowledge of technologies and agronomy is required, but also infrastructure, legislation, knowledge, and even regulations on privacy and ownership of the data generated[27].

Most applications and experiences with AI, such as machine learning, have the potential to improve productivity and efficiency in agriculture and livestock, since they allow contextualized decision-making and efficient crop management through modeling strategies, classification, decision-making, and price predictions. In addition, studies emphasize socio-environmental benefits with an encouraging impact[9].

AI in agriculture is therefore seen as a valuable tool for advancing sustainable development[9][23][25]. "Artificial intelligence is involved in the agricultural sector not only to benefit farmers but also to reduce pollution, care for and preserve natural resources and ecosystems by facilitating accurate information processing"[27].

Techniques such as image processing, machine learning, and environmental interaction appear as feasible approaches aimed at addressing the major global problems derived from population growth, climate change, and deforestation, helping to build an AI-driven agricultural system based on environmental preservation[16].

Emphasis is placed on the benefits of technological applications, including AI-driven robotics, used to reduce farmers' workloads, increase crop yields, expand and diversify crop types, and thereby strengthen food security. It may also reduce rural-urban migration, due to the creation of new companies and work practices. The intensification of sustainable production through the application of technologies such as no-till, mechanized weeding at the individual level, or very low-volume spraying, leads to greater production with fewer resources, thereby minimizing the use of inputs, soil alteration, and increasing food production without destabilizing ecosystems[22].

This review highlights that the implementation of AI technologies creates the need to build the necessary capacity for the adoption of agricultural practices, raising concern among producers, since it demands higher levels of specialization[25][26]. Resistance to the application of virtual tools is considered a natural phenomenon in the execution of any technological innovation, especially given that many agricultural processes have been carried out in the same way for almost a century.

From an environmental perspective, concerns are focused on reducing the carbon footprint and the efficient use of resources. Automated seed selection, for example, reduces losses caused by poor selection and optimizes the use of waste through proper classification[22]. According to Sachithra and Subhashini, the use of AI in agriculture has the potential to boost the achievement of sustainable development goals by improving farmers' life quality, minimizing the cost of food production, regulating food prices, and ensuring food availability for consumers. However, they note that the goal of alleviating poverty within the farming community remains largely unaddressed(24).

In fact, in the face of critical positions regarding the application of technologies in agro-productive processes, it is estimated that AI can contribute significantly and effectively to achieving the Sustainable Development Goals(17), but to do so, it is necessary to establish public-private partnerships, specifically between industry, academia and government, both to promote the development of technologies and to establish systems of vigilance in the generation and use of these innovations.

Another aspect pointed out is the management of large volumes of data, which implies the need for clear legal frameworks to ensure their security(12). Effective control of resources such as water, chemicals, and energy, while minimizing environmental impacts, also depends on the development of policies and strategies for monitoring and evaluation.

A relevant aspect raised by the European Union is the importance of human supervision in the application of AI tools. From that perspective, human autonomy over machines is emphasized, hence the importance of a control system and regulations in this matter. "The goal of trustworthy, ethical, and anthropocentric AI can only be achieved by ensuring adequate human participation in high-risk AI applications"(13).

4. Discussion

A review of research in the field highlights the growing impact of AI technologies on agriculture, with different applications across the agro-productive chain, including planting, harvesting, and monitoring of crops, climate, and soils, which offer accurate and predictive information related to agricultural practices, from the use of machine learning, robotics, unmanned aircraft, conversational intelligence, and sensors, among others. It also highlights how, through the use of accurate data, it is possible to improve this sector, in the desire to favor an increase in production while minimizing the use of resources and time, since, with the management of large amounts of data on climate, soil, and other factors, crop yields are optimized sustainably.

Although research tends to focus on the benefits of AI in the optimization and increase of productivity, its contribution to environmental sustainability is specified as an added value, which is undoubtedly a great advance based on past experiences. From this perspective, environmental justification often accompanies AI proposals in the agricultural sector, mostly linked to reducing resource use in production processes.

While these presentations of innovation tend to focus on the economic dimension of sustainable development, framed within variables of efficacy and efficiency, other dimensions of this complex notion are overlooked, such as socio-political and cultural aspects. From this approach, these applications could deepen existing inequities, since their use is subject to various factors that include obtaining equipment, infrastructure, and digital connectivity, aspects that have great limitations in rural areas(15), as well as farmers' technical capacity to use them (it requires a technified profile). This suggests greater applicability in agro-industrial sectors and developed countries.

In this way, just as the Green Revolution meant a techno-scientific revolution(1), the digitalization of production processes also changes the producer's relationship with nature. This relationship must be addressed from a socio-cultural perspective, beyond the perspective of productivity, since, although it is important, it fails to encompass all its aspects, including ontological, when the producer or peasant loses centrality in the execution of vital productive practices such as sowing and harvesting.

Most of the reviewed publications establish the implicit hypothesis of AI promoting farmers' well-being or development in rural areas, without delving into central aspects, such as barriers of access and use, and even the deepening of the marginalization of ancestral knowledge, shaping the profile of a global farmer.

From a theoretical point of view, the studies reviewed suggest that AI innovations for the agricultural sector contribute to the central aspects of the 2030 Agenda for Sustainable Development(6), particularly Goal 2, focused on ending hunger, achieving food security, improving nutrition and promoting sustainable agriculture; Goal 13, focused on urgent measures to combat climate change and its effects, and Goal 15 to protect, restore and promote the sustainable use of terrestrial ecosystems, combat desertification and land degradation to halt biodiversity loss. From the foundation of AI tools applied to agriculture, they raise the possibility of reducing the use of resources such as water, minimizing agrochemical inputs, improving soil management, and increasing production through the optimization of processes.

However, critical issues remain unaddressed, such as the intensification of monocropping, which at large scales results in biodiversity loss and increased vulnerability to pests and diseases. In this regard, the revised documents propose a discourse focused on technical benefits and resource reduction, but do not address central issues such as agroecology, agrodiversity, or food production, which are key to guaranteeing food security(28).

In this order of ideas, the discourse on the applications of AI must consider traditional agriculture from its subjects, knowledge, and experiences, in order to construct logics that include, rather than exclude, the multiple perspectives that make up agricultural systems, beyond the demands of agro-industrial systems, ensuring the protection of small producers.

From this perspective, various concerns such as information security also arise, since small producers, having to hire external parties to process large volumes of data, risk losing control of vital information. Additionally, in terms of the farmer profile to which these innovations respond, where the cultural, generational, training, and access issues can widen the existing gaps between, for example, family farming and large agricultural corporations, consolidating a prototype of the global farmer.

This implies the potential erosion of locally constructed knowledge, given the undeniable industrial potential in research and innovation of the economic powers, making small producers more vulnerable and strengthening processes of dependence. Hence, there is a need to promote these processes with equity based on global alliances. However, this aspect remains underdeveloped, as a commercial-technical vision of AI tools in agriculture predominates(17).

Therefore, in the reviewed publications, the centrality of AI in agriculture does not lie in its link with sustainable development, food security, crop diversification, and poverty eradication; rather, it revolves around its possibilities to automate processes, reduce the physical participation of farmers, limit resource use, and, of course, increase productivity.

Consequently, the applicability of these proposals must address the great demands linked to the inequities in the access to technologies worldwide. In addition, local experiences and adequate training emerge as central elements, so it is important to establish policies built on dialogue with all actors in local contexts, in order to transcend the technological and productivist vision of AI in agriculture. This requires a comprehensive approach that promotes equitable change, responding to diversity and fostering sustainable development in all its dimensions.

This, in turn, requires greater public, private, national and international commitments, as well as the construction of legal frameworks that regulate AI adoption in agricultural processes without limiting it, maintaining an ethical sense linked to the common good, the centrality of the human being over any political-economic interest, safeguarding biodiversity, and ensuring global food security, without undermining the processes, contexts and socio-cultural particularities of agriculture.

In this sense, although artificial intelligence has the potential to revolutionize agriculture in terms of productivity, it faces significant challenges in terms of transforming the realities that undermine global food security, as well as contributing to the integral well-being of the territories. Coming to terms with these realities requires a collaborative approach among industry, farmers, researchers, and governments to ensure that artificial intelligence is used fairly and ethically without undermining farmers as key actors in this process.

5. Conclusions

The documentary review shows the presence of different experiences and perspectives on the application of artificial intelligence in agriculture, mainly through agro-productive automation. In most cases, emphasis is placed on its importance for increasing productivity, with significant contributions in the reduction of the resources used in the processes for a more effective and precise management of agricultural practices. From this perspective, an environmental justification is established; however, the different social, political, and cultural dimensions inherent to its application in different contexts, key to promoting sustainable development, are not adequately addressed.

Consequently, the search for a balance between social welfare, productivity, environmental awareness, and practice leads to considering that artificial intelligence applied to agriculture should be designed with a vision in line with sustainable development. This requires integrating the social, political, ethical, legal, and environmental implications of these technologies into the productive sector, as there is a clear need to establish regulatory frameworks that both promote and control their use, in order to ensure their benefit to humanity.

Transparency of Data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author Contribution Statement

	AC Boscán Boscán	AJ Boscán Boscán
Conceptualization		
Data curation		
Formal analysis		
Funding acquisition		
Investigation		
Methodology		
Project administration		
Resources		

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Visualization		
Writing – original draft		
Writing – review and editing		

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