Agriculture 5.0: Cutting-Edge Technologies, Trends, and Challenges

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In the evolution from Agriculture 2.0 to Agriculture 5.0, the agricultural sector has witnessed transformative changes. Agriculture 5.0 represents a revolutionary phase, integrating advanced technologies to enhance efficiency and sustainability adapted to individual field and livestock needs. The integration of robotics, extended reality, and 6G technologies marks a significant leap, enabling real-time monitoring and automation in farming practices. Artificial intelligence and big data are pivotal in Agriculture 5.0, offering insights for decision making and predictive analytics. Natural language processing plays a crucial role in facilitating efficient communication and data processing. The transition to Agriculture 5.0 should also consider societal challenges, in terms of technology lock-ins and the need for behavior shifts among stakeholders for faster adoption and customization of the solutions. This article presents a comprehensive description of Agriculture 5.0, underscoring the potential and hurdles in reshaping the future of farming.

The advancement of digital technologies has radically transformed the way agriculture is done over the past three decades. In the beginning of 1990s, the terms *precision agriculture* and *precision farming* were introduced to refer the use of Global Navigation Satellite Systems (GNSS) and sensing technologies at the field/livestock level to map the actual needs and apply variable-rate applications or inputs. Later, two other terms, *digital architecture* and *smart agriculture*, were coined to describe the precision agriculture technologies used to manage spatial and temporal variability at the field/livestock level, together with more advanced technologies, first introduced in the agricultural domain in the early 2010s, namely, artificial intelligence (AI). Therefore, digital architecture or smart agriculture includes all available technologies to measure field and livestock parameters, namely, GNSS systems, robotics (ground and aerial), satellite imagery and the Internet of Things (IoT), and sensing systems. It further encompasses data analytics tools for data analysis and interpretation, using big data analytics, computer vision, and machine learning as well as farm management information systems and decision support systems (DSSs) for assisting farmers to register inputs and outputs and present the aggregated data in a user-friendly manner. Digital farming or smart farming is also synonymous with Agriculture 4.0. Although strides have been made in technology development, there are still significant challenges to be overcome as the adoption of digital technologies is still slow in many parts of the world, while additional technologies have entered the agricultural domain.

The aim of this visionary article is to present the transition of Agriculture 4.0 to the new era of Agriculture 5.0 by providing our own definition of Agriculture 5.0, presenting the main technologies, including spatial and temporal technologies, robotics and artificial technologies, and how these will be integrated into Agriculture 5.0. The article will also present additional technologies, including extended reality (XR) and natural language processing (NLP), to make digital technologies more tailored and provide specific information. Finally, although the use of technologies will be abundant and cost-efficient in the future of agriculture, the behavioral change of farmers and farm advisors and their willingness to adopt such technologies will be a necessity and factors affecting the transition will be presented in this article.

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AGRICULTURE 5.0: OUR DEFINITION

Agriculture 5.0 signifies future developments in farming, characterized by the customized application of digital solutions to meet the diverse needs of individual fields, animals, and farmers. This paradigm goes beyond traditional precision agriculture by emphasizing a highly tailored and adaptable approach, using advanced technologies such as AI, data analytics, and automation to deliver personalized solutions. Agriculture 5.0 envisions a future where digital technologies are seamlessly integrated into the intricacies of farming to optimize resources, improve productivity, and promote sustainable practices at a granular level. At its core, Agriculture 5.0 aims to not only empower farmers with precision tools tailored to the specific needs of their farming sectors but also design transformative ways of change that will create behavioral shifts and increase farmer adoption of these technologies. The new era of agriculture places emphasis on the range of individual, technological, institutional, and policy factors that affect transition to Agriculture 5.0. Therefore, the definition of Agriculture 5.0 that we propose is broader and acknowledges the importance of advancements in digital technologies, together with the behavioral changes needed to realize the transformation.

FROM AGRICULTURE 1.0 TO AGRICULTURE 5.0

The use of technologies has been transformative for agriculture since the beginning. Plow and animal power were the first enablers, which led to more productive agricultural systems compared to the days of hand cultivation. However, the vast transformation of agriculture occurred during the 1950s with the Green Revolution. New farm mechanization technologies, such as tractors and appropriate farm implements for all agricultural operations, were combined with advances in agrochemicals and breeding for crops and livestock, thus substantially increasing agricultural production. These advances moved traditional agriculture, otherwise called *Agriculture 1.0*, to Agriculture 2.0. Since Agriculture 2.0, huge leaps have been made in technological advancements from which agriculture has benefited. Specifically, the use of satellite technologies, such as GNSS and Earth observation satellites, along with computer science technologies, led to the emergence of Agriculture 3.0, or precision agriculture. Agriculture 3.0 was humanity's answer to the environmental and health problems that were caused by the illogical use of crop inputs. Agriculture 3.0 allowed a significant decrease in agricultural inputs (e.g., pesticides, fertilizers, nutrients, water, energy, fuel, and labor) consumption while maintaining, or even increasing, crop or animal production.

Agriculture 4.0, also named *digital agriculture* or *smart agriculture*, advanced agriculture further by introducing new technologies and capabilities. AI, big data, the Internet of Things, virtual reality (VR) and augmented reality (AR), 3-D printing, quantum computing, blockchain, and robotics are utilized to create even more sustainable agricultural production.[1] These technologies must be quickly integrated into real-world conditions to address important challenges such as food security (needs for increasing global food production by 60% until 2050 due to population growth), climate change impact (e.g., reduction of greenhouse gas emissions), environmental protection (e.g., reduction of soil and water pollution), and human health protection (e.g., decrease in pesticide use).[2]

AGRICULTURE 5.0: WHAT IT MEANS

Building on the definition of precision agriculture, which answers the questions related to what, where, and when, Agriculture 5.0 can be defined as *the environmentally, economically, and socially sustainable agricultural production system that is performed by the use of advanced technologies with everything, everywhere, and every time*.

"Everything" corresponds to the connectivity that can be achieved in Agriculture 5.0. Every physical and/or digital object, sensor, robot, farm machinery, and person can connect with each other to exchange data, provide insights, and efficiently control various agricultural actuators.

"Everywhere" corresponds to the location where Agriculture 5.0 is applied. Agriculture 5.0 can be applied both indoors and outdoors and to all areas (urban, rural, and coastal) by utilizing technologies such as 6G and nonterrestrial networks.

"Every time" corresponds to the frequency at which Agriculture 5.0 is applied. Agriculture 5.0 utilizes appropriate technologies to ensure seamless connectivity and operation in all types of environments every day.

Thus, Agriculture 5.0 will build on Agriculture 4.0 technologies and couple them with the concepts of Industry 5.0 and Society 5.0 to result in more personalized and efficient agricultural and livestock production. Specifically, Agriculture 5.0 will enhance efficiency, productivity, and resilience from farm to fork by utilizing more sustainable and resilient agricultural practices, which are based on the use of digital technologies—a core part of Society 5.0 principles.[3]

PRECISION FARMING FOR AGRICULTURE 5.0

Currently, to improve operational precision, precision farming uses agricultural knowledge systems and integrates data-driven digital systems to adapt the use of inputs. The evolution in agriculture continues with the introduction of Agriculture 5.0, which is characterized by data-driven farms integrating AI algorithms and robotics. Agriculture 5.0 involves the integration of physical and virtual spaces for smart and sustainable farming systems.

Central to Agriculture 5.0 is precision farming, optimizing input usage through data-driven decision making, and enhancing crop productivity, profitability, and quality while minimizing environmental impact and labor.[2] Precision farming in Agriculture 5.0 relies on four technological pillars: 1) smart sensors, which are strategically placed to collect essential field data, covering soil moisture, temperature, nutrient levels, and pest incidence;[2] 2) information and communications technology, which ensures seamless data transmission to servers, utilizing technologies such as wireless networks, the IoT, 5G, and blockchain;[4] 3) AI and machine learning, which extract valuable insights from data, employing techniques like big data analytics, deep learning, computer vision, NLP, and reinforcement learning; and 4) robotics and automation, which are used for precise field interventions, including seeding, weeding, fertilizing, and harvesting.

Agriculture 5.0 applications include crop, water and soil management, precision fertilization and irrigation, crop disease and pest management, and precision livestock farming. The benefits include improved resource efficiency, enhanced quality and yield, minimized environmental impact, and reduced labor. However, challenges such as data privacy, interoperability, ethical considerations, farmer education, and consumer trust have yet to be fully addressed.

Precision farming for Agriculture 5.0 is evolving rapidly, incorporating innovations to meet emerging challenges. Two key future trends are advancements in automation and the exploration of blockchain technology. Robotics and autonomous machinery already play crucial roles in tasks like seeding, weeding, and harvesting with high accuracy. In the future, the collaboration among various robots will be important to complete more intelligent functions. Blockchain ensures traceability and transparency in the supply chain, offering benefits like improved food safety and reduced fraud.[5] These trends, along with ongoing innovations, emphasize the need to stay informed about precision farming for Agriculture 5.0 and its potential implications for the future of agriculture.

ROBOTICS, XR, BLOCKCHAIN, AND 6G IN AGRICULTURE 5.0

As stated previously, robotics will be a key technology in Agriculture 5.0. The maturation of this technology in Agriculture 4.0 will enable the development of new applications in the context of agriculture. Specifically, swarm robots of heterogeneous (e.g., ground and aerial robots) or homogeneous (e.g., aerial and aerial robots) robotic systems coupled with AI will enable more accurate applications (e.g., crop protection).[6]

XR will emerge as a key technology in Agriculture 5.0. XR covers VR, AR, and mixed reality and provides a better understanding and experience in the agricultural sector through computer-generated virtual environments. XR can impact and substantially transform all operations of agriculture. Some examples include the teleoperation of agricultural tractors and cooperation with autonomous robotic systems, and inspection of animals for certification purposes[7].

Blockchain offers a new degree of trust, which leads to a more sustainable agriculture. Although ensuring traceability using blockchain technology appears promising, several limitations must be recognized and handled, such as rules, stakeholder relationships, data ownership, scalability, and so on. Researchers and developers would benefit from the establishment of a universal assessment model to better understand the technology and, maybe, build new implementations. Blockchain can assist to accomplish traceability by permanently and immutably storing data. Thus, its deployment enables 1) cost reduction, 2) risk reduction, 3) time savings, and 4) increased trust and confidence.[8]

On top of that, 6G will be the main wireless communication protocol. The adoption of 6G will act as a catalyst for the efficient use of all technologies in Agriculture 5.0. This will be achieved because 6G will offer higher throughput, lower latency, higher energy efficiency, massive connectivity, full use of nonterrestrial networks and AI, and global coverage compared to 5G, and thus, seamless connection, data exchange, and operation among sensors, actuators, farm machinery, and people across the agricultural value chains.[9]

AI AND BIG DATA FOR AGRICULTURE 5.0

In the context of AI, the relationship between machine learning and agricultural computer vision has been transformative in recent years, leading to significant advancements in the sector.[10] Specifically, deep learning algorithms have arisen as the most promising path to deliver state-of-the-art performances in several agricultural problems like weed detection or disease identification. Deep learning provides the means to extract insights and patterns from big data that traditional machine learning models, like support vector machines, or human analysis could not extract.

A common problem is that most advanced deep learning architectures, such as vision transformers or convolutional neural networks, require a massive numbers of data to learn effectively.[11] Indeed, these models' accuracy and overall performance generally improve as they are exposed to large numbers of data, creating a demand for even larger big data in the shape of datasets. Although significant efforts have been made in agricultural research by publishing large datasets such as DeepWeeds (17,509 images) and PlantVillage (54,303 images), they are still far from the datasets used in general-purpose domains such as ImageNet (more than 14 million images) and Common Objects in Context (more than 330,000 images).

This problem can be further worsened due to the advent of multimodal and foundation models, like CLIP and DINOv2, which represent a paradigm shift that promises to redefine the frontiers of machine learning in general, and NLP and computer vision in particular.[12] These models, characterized by their massive scale and multimodal training datasets, allow the fusion of multiple data types, such as images, scientific texts, satellite multispectral imagery, sensor data, and environmental information, to enhance crop yield, optimize resource usage, and ensure customized sustainable farming practices by using comprehensive assistive technologies.

Integrating these multimodal foundation models in precision agriculture will represent a new approach to reusing the big data coming from other problems and even enriching it with the smaller data released in the agricultural sector. From a technical point of view, these models will be tightly coupled to techniques that aim to leverage the big-data-based knowledge the model has gained from the initial (pre-)training (like feature extraction in images or understanding language structure in text) to perform well on the new customized agricultural task with fewer training data or computational resources. The most notable techniques to be further researched in the context of multimodal foundation models are 1) transfer learning. Once trained, foundation models can be fine-tuned for specific tasks (like a particular type of disease recognition or a specific agricultural regulatory text understanding task) with relatively little additional training data. In the context of foundation models, transfer learning usually starts with a pretrained model used a "static" feature extractor. The obtained features will be used by different types of classifiers on a new, smaller dataset for a specific agricultural task. 2) Knowledge distillation. Given their size and complexity, distilling these multimodal foundation models into smaller, more efficient versions is a significant area of research. Knowledge distillation involves training a smaller and more efficient model (the "student") to replicate the behavior of a larger, more complex model (the "teacher"). Specifically, the foundational model (teacher), already trained and high performing, will generate outputs on a small agricultural dataset. The student model is then trained not only on the actual labels but also to replicate the outputs of the teacher model. This is particularly useful for deploying models to environments with limited resources, like the edge devices widely used in precision agriculture.

Finally, it is important to stress that integrating multimodal foundation models in customized solutions in the context of agriculture 5.0 will require a holistic approach encompassing (besides technical demands) ethical guidelines, regulatory frameworks, and collaborative efforts from diverse stakeholders in the AI community. The main reason is that the reliance on diverse and extensive datasets raises concerns regarding data privacy, the representativeness of training data, and the potential for bias, which could have implications for agricultural decision-making processes.

NLP FOR AGRICULTURE 5.0

Recent advancements in deep learning, apart from the applications in machine vision, have given rise to NLP, which is the understanding and/or generation of naturally spoken language from computers to assist end users to find practical and useful information more accurately and at a faster speed. Large language models (LLMs), which are the current state of the art in NLP, can interact with humans by just using natural language prompts. What makes LLMs unique is their capacity to perform a wide range of complex natural language understanding/generation tasks by just being provided with a few instructions and some illustrative, task-specific examples.[13] The technology behind LLMs is that of transformers, which have revolutionized research in the field of NLP.[14] LLMs allow for the creation of powerful chatbots that exhibit human-like communication capabilities, such as ChatGPT.

The use of LLMs for developing agriculture-related applications needs to be approached with caution. Given that LLMs may lack domain knowledge, they may generate text that appears plausible yet is irrational or scientifically incoherent.[15] Therefore, it is important to augment LLMs with the domain knowledge

FIGURE 1. Overview of the Agriculture 5.0 digital agricultural field that has NLP to interact with the farmer, IoT devices to sense soil moisture, robotic vehicles (ground and aerial) to monitor and conduct farm operations, and antennas to receive satellite images. (Copyright: authors; published with permission.)

captured in knowledge graphs (KGs). This combination of technologies has the potential to lead to the creation of virtual assistants for farmers and advisors capable of responding to text-based queries. LLMs can provide the interface for interaction in natural language (spoken language by end users; in this case, farmers and advisors) for generating scientifically sound responses based on scientifically defined KGs. Farmers and advisors can get feedback tailored to their individual needs without needing to possess specialized knowledge about how to query a KG.

Apart from the retrieval of knowledge from KGs, LLMs can offer solutions for the update of KGs in a (near-)real-time fashion, enabling virtual farmer assistants to output time-critical alerts for knowledge-enabled crop treatments. Leveraging the data generated by IoT devices, LLMs can undertake the task of integrating them into existing KGs and hence augmenting the domain knowledge encoded in them with time-sensitive information. Combining the robustness of formally described and structured knowledge related to agriculture with data that capture measurements pertaining to a field and crop provides huge potential for crop treatments tailored to field-specific soil profiles, weather characteristics, and climatic conditions. The integration of LLM and KG technologies can, more than ever, enable access to advice and knowledge, assisting farmers to make decisions that would otherwise need lots of time and support from various experts to be taken.

LOCK-INS AND BEHAVIOR SHIFT TO AGRICULTURE 5.0

Transitions to digital agricultural technologies and, consequently, Agriculture 5.0, are long-term, complex, and multidimensional processes that involve specific uncertainties and tradeoffs. The upgrade of farmers to "smart farmers" is dependent on their adoption levels and farmers' willingness to accept the novel digital practices. Despite major technological developments gaining momentum, the steps in farmer technology adoption are slower, and this gap is likely to be more pronounced in the future. It is increasingly acknowledged that farmers' behavior is shaped by multiple factors related to individual, technology-related, farm, institutional, and policy factors.[16]

The sociodemographic characteristics of farmers, especially older age and low education, still characterize the average farmer globally, posing strong barriers to adoption. New technologies need young people who are more open to experiment with new technologies, are less risk averse, and have higher education levels or skills in digital agriculture. However, average farmer age keeps increasing, currently being approximately 58 years old in Europe and the United States, 60 in Africa, and 67 in Japan.[2] Hence, it remains a challenge for policies that aim for generational renewal to reverse the aging crisis and attract the highly qualified young farmers that will transform the agricultural sector.

The costs associated with technologies are an important barrier, especially for small farms that lack economies of scale. Technologies such as robotics and AI are still very expensive and, even though they become more economically accessible over time, they still require significant initial investment. Costs are also associated with the significant time, effort, and training requirements associated with the adoption of these technologies, which render the investment risky for the majority of farmers. Furthermore, technology-related factors such as ease of use, usefulness, and compatibility become crucial determinants in farmers' decision making. Previous studies indicate that technologies, such as DSSs and variable-rate applications, are perceived as complex and difficult to use, which negatively impact perceptions of technology usefulness for farming operations (e.g., the increase in job performance or productivity) and compatibility with current farmer practices, needs, and goals. With the advent of data-driven agricultural technologies, data ownership, sharing, and privacy issues have become a major concern for farmers. Precision agriculture technologies require large numbers of data to be collected from farms to increase their accuracy and reliability. Farmers are usually not informed about how their data are collected, used, and shared, while specific regulations or standards for farm data are limited. Due to the lack of control and transparency, farmers are unwilling to share data with technology providers and to adopt data-driven technologies.[17] Hence, privacy protection and farmer rights will become significant discourses in the forthcoming years to foster transition.

A radical transformation in production processes requires a food system approach, in which farmers are embedded actors in a food system and changes are required in the decision making of individual actors across the entire value chain. Social influence, which depends on the influence of social norms, peer influence (e.g., family, farmers), social networks, and social learning, affects farmers' behavior. The social environment exerts great influence because it sets societal expectations about farmers' behavior. In farming communities characterized as late adopters of new technologies, farmers are less prone to adopt novel practices due to strong peer pressure and neighboring effects. Conversely, social learning, through observing and experiencing firsthand how other farmers use technologies, increases trust and adoption. A novel approach to the adoption of agricultural innovations is the role of participatory and collaborative approaches. The development of partnerships among farmers, processors, retailers, and consumers enables exchange and mutual understanding of the benefits and trade-offs in the transition to digital technologies. Although not sufficiently embedded in food systems to date, the new wave of modern agriculture will benefit from collaboration as it is expected to boost farmers' capacity for adoption of innovations by enabling easier access to resources, knowledge sharing, and cocreation of pathways to change.[18]

Due to their complexity and farmers' lack of skills, advanced agricultural technologies require access to proper training and advice. Extension and advisory services may involve training courses, field visits, demonstrations, and technical support. These will play a significant role in building farmers' knowledge, skills, and confidence and helping them overcome barriers to adoption.

The integration of digital technologies is at the core of agricultural policy design. The policies include a set of financial incentives, mandatory and voluntary environmental schemes, advisory services, awareness-raising campaigns, and measures for generational renewal, among others. Fundamental to the behavioral shift to Agriculture 5.0 will be policy design that is informed by behavioral insights. To this end, segmentation of the heterogeneous farmer population based on their different responses to environmental, institutional, and policy change has been suggested as a key tool to enable the design of tailored policy instruments (e.g., advisory services, nudges, and marketing campaigns).

FUTURE DIRECTIONS

Seamless integration of the aforementioned technologies will benefit Agriculture 5.0. The integration of XR, 6G, and blockchain technology will facilitate remote monitoring and management of agricultural operations. Farmers and inspectors from certification organizations will use XR for virtual field inspections or to simulate various crop management scenarios. 6G connectivity ensures seamless data transfer and real-time communication between different technological components, while blockchain will offer data privacy, increased trust, and time savings. A farmer could inquire about weather forecasts or pest infestation risks using voice commands, and the NLP system would provide an immediate response based on real-time data. A system of robots, designed to work collectively, will greatly enhance efficiency and precision in farming tasks. Imagine a fleet of drones and ground robots working in sync, performing tasks like seeding, weeding, and harvesting. These robots, guided by AI algorithms, can adapt to changing conditions, optimize paths, and perform tasks with minimal human intervention.

Farmers and farmer advisors will have access to specialized scientific knowledge in an easy-to-understand language. With that knowledge being tailored to their individual needs and field/crop characteristics, they will be provided with unique opportunities for tailor-made treatments without spending much time seeking expert knowledge.

The future of Agriculture 5.0 lies in its ability to overcome existing lock-ins, ensuring sustainable and efficient farming practices. Thus, it is expected that future research will focus on ethical considerations and regulatory frameworks. Policies and guidelines that ensure data privacy, ethical technology usage, inclusiveness, and fair market competition are crucial for creating a balanced ecosystem where technology benefits all stakeholders without compromising ethical values.

CONCLUSION

Agriculture 5.0 will advance agriculture and overall agricultural production even further by introducing new technologies or advancing old technologies that provide accurate and more efficient management based on the unique characteristics of each field or animal. Agriculture 5.0 will advance further technologies, such as the use of robots, XR, AI, blockchain, and NLP. However, the success of Agriculture 5.0 will lie in its adoption by agricultural stakeholders and, more specifically, farmers.

Thus, future research on Agriculture 5.0 must not be limited to the seamless integration of all technologies under a more holistic approach but to the development of appropriate policies and regulatory frameworks.

The future of Agriculture 5.0 is poised to be a balanced mixture of technology and sustainability, leading to more efficient, productive, and environmentally friendly agriculture. The direction it takes will significantly influence global food security and environmental health, making it an emerging area of focus in the coming years.

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