

Navigating Transformative Agricultural Technologies on the Path to Food System Transformation

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Abstract. *Modern agriculture encompasses various existing or emerging technologies, such as robotics, nanotechnology, synthetic proteins, cellular agriculture, gene-editing technologies, artificial intelligence, blockchain, and machine learning, which can have a significant transformative impact on the future of agricultural and food systems. These technologies underpin concepts such as vertical farming, digital agriculture, the bioeconomy, circular agriculture, and aquaponics. Examples of these concepts include different strands of agroecology, such as permaculture, regenerative agriculture, and ecological intensification, which may themselves require the use of various technologies and often incorporate indigenous knowledge. These approaches can also be connected to and integrated with digital technologies. This requires responsible innovation processes that entail anticipating the potential impacts of agricultural technologies through inclusive processes, as well as responding to emerging outcomes and adjusting the direction and course of transition pathways. This paper emphasizes the need to pay greater attention to the inclusion and exclusion effects associated with agricultural technologies and to anticipate their potential impacts through inclusive processes.*

Keywords: *agricultural technologies, innovation systems, food system, sustainability transitions, agricultural innovation*

Introduction

Technology is most commonly believed to create advantages for large-scale production (i.e., economies of scale), associated with notions of modernization, advancement, improvement automation, physical capital, and digital processes. Historically, agricultural technology developed in the industrialized West and is thus suitable for large areas of monocropping using labor-saving technologies. This was especially true of Green Revolution technology, which was an adaptation of the modern agricultural technology used in Western countries.

Agricultural technology has largely been capital-intensive and labor-saving, and more recently it has moved toward genetic modification. Its effects in the West have produced monocropped patterns of land use, and agriculture has developed as an industry requiring large transportation networks and supply chains, finding ways to produce vegetables and fruits that will withstand mechanical harvesting and transportation over long distances. Processed and ready-to-eat foods have also been one of the outcomes of the agricultural technologies that have been developed over the past 50 or 70 years. Simultaneously, there is a move in industrialized countries to reclaim local crops and farms in order to produce crops and fresh food locally.

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Received: 22 April 2026; Accepted: 27 August 2026; Published online: 25 October 2026

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This paper examines issues related to the development of agriculture—specifically, the implications of associated narratives regarding inclusion and exclusion, their potential impact, and how mission-oriented agricultural innovation systems can responsibly organize the transition toward sustainable agriculture.

Materials and Methods

This article employs descriptive, analytical, and explanatory methods to highlight key issues relevant to the study. To formulate the concept, the views of various researchers were cited, serving as a basis for illustrating the arguments and conclusions. Within the framework of innovative agricultural systems, the primary objective is to propose methods and ideas regarding how such a process can be organized responsibly. The paper provides an overview of frequently used methods and formal frameworks, such as technological innovations across various sectors of agriculture. These methods are primarily applied to synthetic data, generating a wide range of solutions.

Results and Discussion

Significant technological progress is currently being observed in the agricultural sector across fields such as robotics, nanotechnology, gene technologies, artificial intelligence and machine learning, energy production, and many other areas (De Clercq et al., 2018).

Future agriculture and food systems—some of which are already developing and operating, though not yet implemented on a full scale—encompass concepts such as vertical farming, digital agriculture, the bioeconomy, circular agriculture, and aquaponics (Hermans, 2018).

These technologies have the potential to radically impact the processes of food production, processing, trade, and consumption. These include technologies such as gene editing, synthetic food production (e.g., synthetic protein), lab-grown meat—or cellular agriculture technologies—microalgae bioreactors, drones, the Internet of Things (IoT), robotics and sensors associated with precision farming technologies, 3D food printing, artificial intelligence and machine learning, as well as blockchain.

Some authors view the use of technologies as part of the digital revolution in agriculture, which could ultimately lead to "Agriculture 5.0". Influential international organizations working in the fields of food and nutrition security—such as the World Bank, FAO, and OECD—discuss the potential of agricultural technologies and the global landscape in this regard in their recent reports (Jouanjean, 2019).

Currently, significant financial resources are being spent worldwide on the development and implementation of Agriculture technologies. For instance, investments are being made in large-scale digital transformation research and innovation programs, such as the DigiScape platform and Food Agility Hub in Australia; the #DigitAg program in France; and the "Internet of Food and Farming" program, along with Digital Innovation Hubs (or SmartAgriHubs), in the European Union (Klerkx et al., 2010). Research institutes such as Wageningen University and Research (Netherlands) and AgResearch (New Zealand) maintain strategic investment programs addressing "Protein Transitions" and "New Zealand's Bioeconomy in the Digital Age," respectively. Organizations such as CGIAR and CSIRO collaborate on initiatives like "Wild Futures," which focus on technologies that accelerate innovation within food systems to achieve the Sustainable Development Goals (Herrero et al., 2019).

In terms of diversity, the coexistence of agricultural and food systems is possible. However, when there is no longer room for diversity and certain systems assume a dominant and hegemonic position, this can give rise to inequality and injustice—outcomes that are undesirable from the perspectives of human well-being and ecosystem integrity and sustainability.

Different agricultural technologies—and the systemic concepts upon which they are based and which they encompass (or exclude)—follow distinct trajectories. They shape the development path of agricultural and food systems through the technologies, markets, institutional arrangements, and values they integrate, as well as the transformative outcomes they aim to achieve (Kanger & Schot, 2019). Precision agriculture (PA) represents a transformative approach to modern farming, leveraging advanced technologies such as GPS-guided machinery, drones, and remote sensing to optimize agricultural practices (Fig. 1) (Gebbers & Adamchuk, 2010).

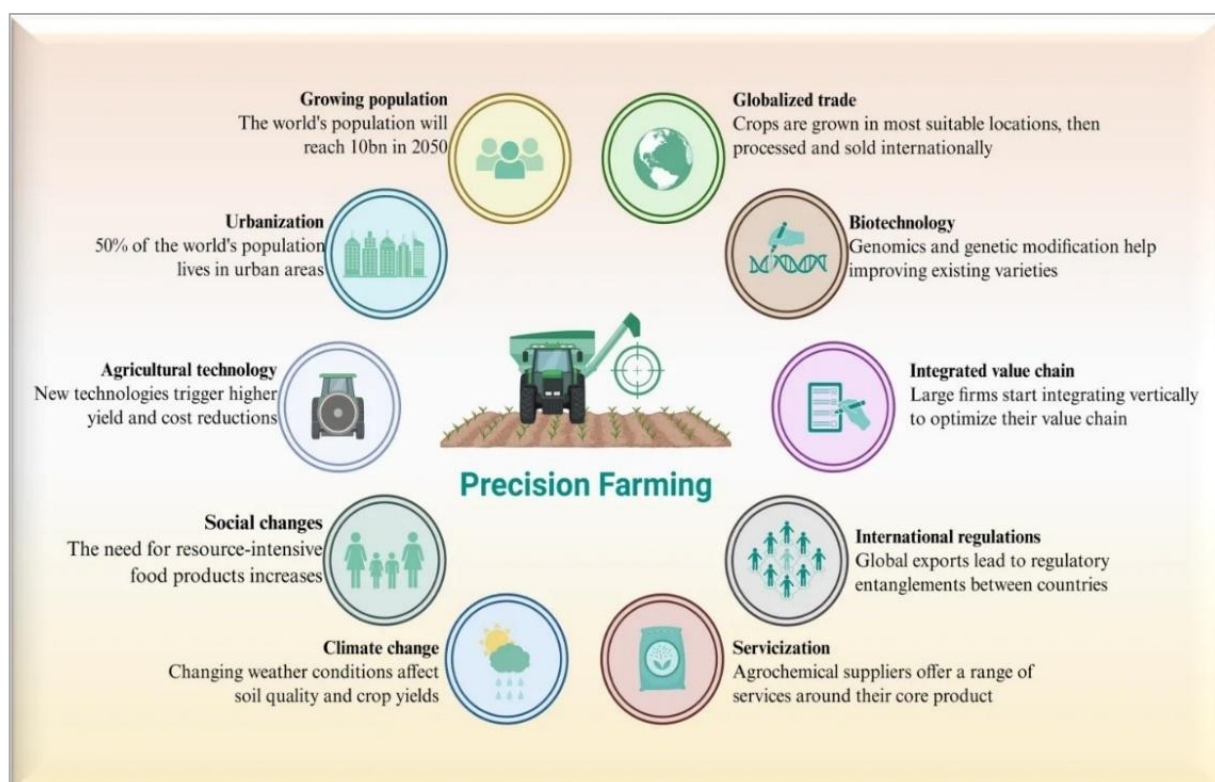


Figure 1
Precision agriculture as one of the modern agricultural technologies
 (www.biorender.com)

Recent advances in biotechnology and genetic engineering have revolutionized agriculture by developing drought-resistant crops, CRISPR-edited varieties, and genetically modified organisms (GMOs), each playing a critical role in enhancing food security under climate change (Fig. 2). Drought-resistant crops, such as Water Efficient Maize for Africa (WEMA) and drought-tolerant wheat, are engineered to thrive in water-scarce conditions by modulating genes like OsNAC9 in rice and ZmPYL in maize, improving water-use efficiency by up to 30% (Varshney et al., 2021).

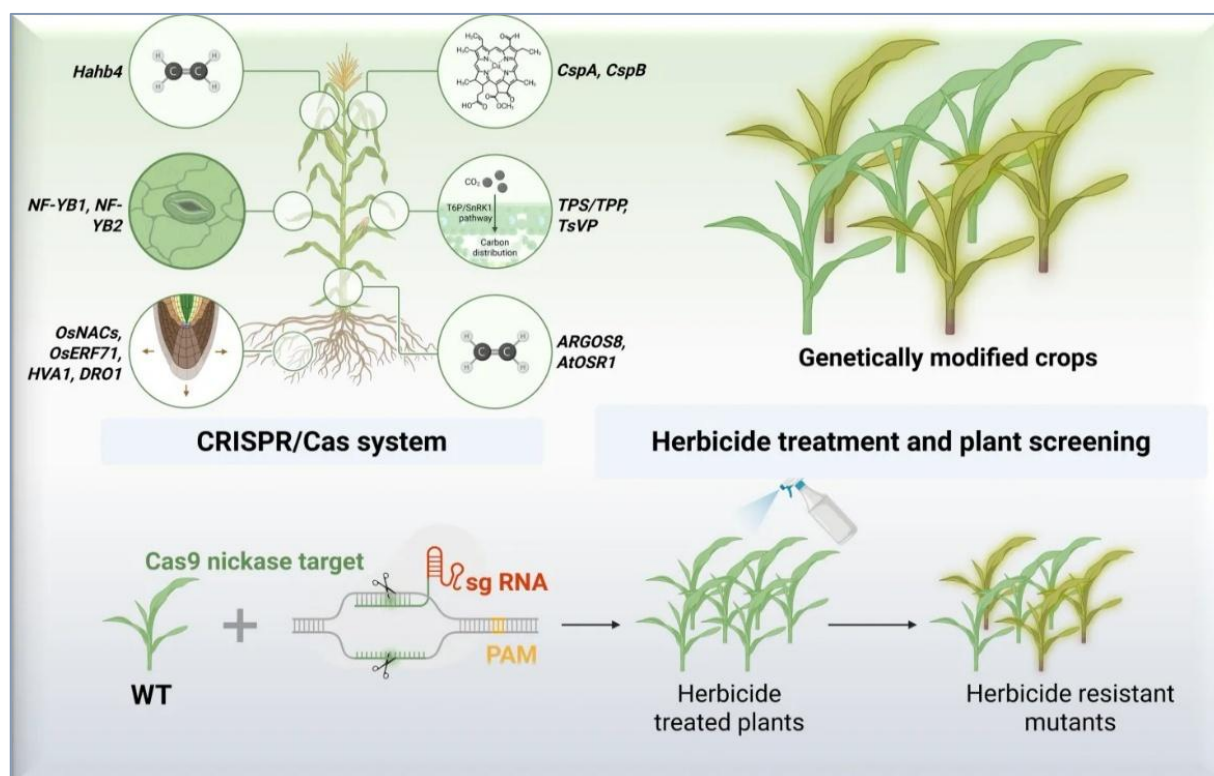


Figure 2

Techniques involved in the biotechnological and genetic engineering for the efficient agriculture production

Moreover, scaling up could lead to unforeseen and unpredictable consequences. Outcomes may also vary across different contexts—for instance, when considering the disparities between developed and developing nations. This is because technology is not context-neutral and is linked to specific configurations of economic power.

Organizing Transition Processes in Agricultural Innovation Systems

It is widely acknowledged that transition processes involve transformative events leading to new technological and economic systems. These processes include co-evolution (where technologies develop alongside and in interconnection with societal structures), selection (where some technologies fail to achieve dominant status), and stabilization/institutionalization (where certain technologies evolve into new dominant models and their corresponding social, market, or political structures) (El Bilali, 2018).

This implies that the ongoing processes of adopting and scaling up agricultural technologies likely involve active interaction between various technologies and the underlying concepts upon which they are based (agricultural and food systems). Such interaction can be "passive"—occurring through the dynamics of competition in global markets—or "active"—taking place through cooperation, competition, or "co-opetition" (a combination of cooperation and competition) among innovators (Planko et al., 2019).

Agricultural innovation systems often foster the development of specific sets of technologies, yet the underlying values upon which these technologies are based remain unclear. Furthermore, it is uncertain how they contribute to shaping sustainability-oriented transition processes—specifically, whether they reinforce existing technological and economic paradigms or facilitate "deep transitions". Despite the adoption of sustainable development principles and a focus on critical policy issues such as food and nutritional security, the primary goal of dominant and influential groups within

agricultural innovation systems—the constellation of business, scientific, governmental, and civil society actors that create and disseminate innovations—in many countries is to boost agricultural productivity and growth through a modernization pathway that perpetuates existing practices of food production, trade, and consumption (Pigford et al., 2018).

It is worth noting that a number of countries are adopting "mission-oriented" approaches within their agricultural innovation systems; with a view toward future food systems, these approaches focus on issues such as food and nutritional security and environmental sustainability. For instance, the Netherlands has adopted the "circular agriculture" paradigm and is investing in the "protein transition" (Pyett et al., 2019). Nicaragua places great emphasis on agroecology, while New Zealand has recently focused on developing a "digital bioeconomy".

Conclusion

When shaping future visions, it is essential to consider how agricultural technologies interact with one another and with concepts of sustainable agriculture—such as agroecology or regenerative farming—and what this implies for the future of agricultural and food systems. Naturally, it is difficult to fully foresee the consequences of the large-scale adoption of new technologies. The degree of reflexivity is of crucial importance in strategies aimed at implementing socio-technical transformations. It is important to consider the context and acknowledge that technologies are not universal (as the experience of the "Green Revolution" has already demonstrated); rather, they evolve and become integrated into diverse socio-economic, cultural, and political environments.

Declaration of Competing Interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- De Clercq, M., Vats, A., & Biel, A. (2018, 11–13 February). *Agriculture 4.0: The future of farming technology*. World Government Summit. Dubai, United Arab Emirates.
- El Bilali, H. (2018). Transition heuristic frameworks in research on agro-food sustainability transitions. *Environment, Development and Sustainability*, 22, 1693–1728. <https://doi.org/10.1007/s10668-018-0290-0>
- Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science*, 327(5967), 828–831. <https://doi.org/10.1126/science.1183899>
- Hermans, F. (2018). The potential contribution of transition theory to the analysis of bioclusters and their role in the transition to a bioeconomy. *Biofuels, Bioproducts and Biorefining*, 12(2), 265–276. <https://doi.org/10.1002/bbb.1861>
- Herrero, M., Thornton, P., Mason-D'Croz, D., & Palmer, J. (2019). *Transforming food systems under a changing climate: Future technologies and food systems innovation for accelerating progress towards the SDGs—Key messages*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
- Jouanjean, M. (2019). Digital opportunities for trade in the agriculture and food sectors. *OECD Food, Agriculture and Fisheries Papers*, 122. OECD Publishing. <https://doi.org/10.1787/91c40e07-en>
- Kanger, L., & Schot, J. (2019). Deep transitions: Theorizing the long-term patterns of socio-technical change. *Environmental Innovation and Societal Transitions*, 32, 7–21. <https://doi.org/10.1016/j.eist.2018.07.006>
- Klerkx, L., Aarts, N., & Leeuwis, C. (2010). Adaptive management in agricultural innovation systems: The interactions between innovation networks and their environment. *Agricultural Systems*, 103(6), 390–400. <https://doi.org/10.1016/j.agsy.2010.03.012>

- Pigford, A. E., Hickey, G. M., & Klerkx, L. (2018). Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. *Agricultural Systems*, 164, 116–121.
<https://doi.org/10.1016/j.agsy.2018.04.007>
- Planko, J., Chappin, M. M. H., Cramer, J., & Hekkert, M. P. (2019). Coping with coopetition—Facing dilemmas in cooperation for sustainable development: The case of the Dutch smart grid industry. *Business Strategy and the Environment*, 28(5), 665–674.
<https://doi.org/10.1002/bse.2271>
- Pyett, S., de Vet, E. W. M. L., Trindade, L. M., van Zanten, H. H. E., & Fresco, L. O. (2019). *Chickpeas, crickets, and chlorella: Our future proteins*. Wageningen Food & Biobased Research.
- Varshney, R. K., Barmukh, R., Roorkiwal, M., Qi, Y., Kholova, J., Tuberosa, R., Reynolds, M. P., Tardieu, F., & Siddique, K. H. M. (2021). Breeding custom-designed crops for improved drought adaptation. *Advanced Genetics*, 2(3), e202100017.
<https://doi.org/10.1002/ggn2.202100017>