Adoption of robotics and artificial intelligence in agriculture

Calderón-Carrasco, P.[1*]; **Vega-Argüello, L.**[2]

[1] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Roque, Celaya, Guanajuato, México. C.P. 38110.
[2] Universidad Autónoma Chapingo. Texcoco, Estado de México, México. C.P. 56230.
* Correspondence: pabloalan.pac@gmail.com

ABSTRACT
Objective: to analyze research trends on the adoption of robotics and artificial intelligence in agriculture between 2020 and 2025.
Design/Methodology/Approach: this research is based on a systematic review and bibliometric analysis of articles on robotics and artificial intelligence in agriculture; which were retrieved from the Scopus database. Key players, core topics, and implementation strategies were identified in those articles. Subsequently, the main advantages and challenges, were analyzed in the well-known strategies. Our findings were contextualized with studies on agricultural mechanization and technology transfer to provide a comprehensive perspective looking forward to their adoption.
Results: analysis showed that this technological framework, although emerging, has experienced sustained growth in recent years. India and the United States are notable as the countries with the greatest scientific production. Thematic clusters revealed a shift in dominant terminology, moving from concepts such as "agriculture 4.0" and "agricultural robots" to "smart agriculture" and "digitalization." Relevant barriers, such as financial and technical limitations, were also identified along with some effective strategies applied in other regions.
Limitations/Implications of the study: this study is limited to Scopus-indexed publications, as well as documents in English and Spanish. However, it offers valuable insights for researchers, policymakers, and other stakeholders in the agriculture sector.
Findings/Conclusions: our research underscores the need to design tailored strategies to overcome adoption barriers, especially among small-sized and medium-sized farmers. The importance of participatory approaches, cooperative models, and the use of multifunctional robots is emphasized as key tools to facilitate effective technology adoption, and to address current challenges.

Keywords: technology transfer, innovation, autonomous systems, precision farming, digitalization, public policy.

Citation: Calderón-Carrasco, P. &Vega-Argüello, L. (2025). Adoption of robotics and artificial intelligence in agriculture. *Agro Productividad*. https://doi.org/10.32854/x9bdf747

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Daniel Alejandro Cadena Zamudio

Received: January 27, 2025.
Accepted: August 11, 2025.
Published on-line: October XX, 2025.

Agro Productividad, 18(9). September. 2025. pp: 123-132.

INTRODUCTION

Innovation and technology transfer in Mexico's agriculture, livestock farming, and fisheries play a key role in increasing productivity and sustainability. Agriculture represented 3.8% of the Gross Domestic Product (GDP) in 2023 according to the World Bank; and

is relevant not only for economic contribution but also for the employment generated, importance in feeding the population, and for the resources utilized. According to the 2022 Agriculture Census (INEGI, 2023), Mexico has 29.8 million hectares dedicated to farming, and the agriculture sector employs more than 27 million people, including permanent and temporary jobs. Globally, these figures rank Mexico in the 11th place in agricultural crop production. These data underscore the importance of studying the adoption of technologies such as robotics and artificial intelligence. Because of their potential to optimize resource use, and to address sustainability challenges, especially in a context where a significant portion of the workforce depends on agricultural activities.

Robotics and artificial intelligence (AI) are technologies, and as such, they are comprised of a set of theories and techniques that enable the practical use of the scientific knowledge, according to the definition by the Royal Spanish Academy of Language (RAE). Therefore, technology transforms the abstract knowledge produced by scientific research into know-how (Pereira, 2018) that involves the use of goal-oriented tools. Technology transfer from one organization to another generally requires a favorable context formed by economics, politics, and cultural aspects. In addition, the management entity that receives innovation technology should have the technical capacity to receive new technology, and the transferred technology needs to be compatible to some degree with the one existing in operation.

In particular, it is suggested that the technology transfer such as robotics or artificial intelligence requires to be studied with care and some specific considerations to reduce the risk of digital exclusion. As well as to avoid increasing inequality, while safeguarding human rights of the population as a whole (Pappa, 2024). Historically, technology shapes the way food is produced; but technology transfer is adopted unevenly, because capital-intensive agriculture is the one that, with its own resources and government support, makes the most use of innovations developed abroad and in national institutions.

On the other hand, small producers in Mexico face challenges such as lack of access to financing, technology, and training appropriate to their needs. In addition to difficulties in adopting sustainable agricultural practices for economic and technical reasons (Amaro-Rosales & De Gortari-Rabiela, 2016). This is how the paradigm of technological agriculture tends to marginalize small-sized and medium-sized farmers (Lule *et al.*, 2016). This has led Mexico, despite being a country open to technology developed around the world, to not adopt technology in all levels of production; and certainly not at the speed it progresses in other countries, especially in the most developed countries.

MATERIALS AND METHODS

In the initial stage of the study, three essential research questions were defined that guided the entire analysis and discussion process. Once defined, a bibliometric analysis and systematic review were conducted on the adoption of artificial intelligenc and robotics in agriculture. For this purpose, a search was conducted in the Scopus database on January 6, 2025. A search strategy based on Boolean logic was used with the keywords "digital" AND " agriculture" AND ("robot" OR "AI") AND ("technology transfer" OR "adoption"). The initial selection of documents by thematic areas was limited to engineering, computer science, agriculture, environment, earth sciences, social sciences, mathematics, physics, decision sciences, energy, and multidisciplinary studies.

In order to ensure the quality and relevance of the documents, only research articles (ar), conference proceedings (dp), and review papers (re) were considered. After manual data cleaning and homogenization of these results, a bibliometric analysis was performed using the VOSviewer version 1.6.20 tool to create co-citation and keyword co-occurrence maps. In addition, the bibliometrix extension of R version 4.0.5 and the Biblioshiny command were used to obtain metrics on scientific production, collaboration between authors and countries, and analysis of subject evolution. Finally, a manual selection of the documents was done to extract the challenges and solutions in the adoption of AI and robotics in agriculture, as reported by other authors. Also, to compare what was found with other studies related to the adoption of mechanization and overall agricultural technology transfer to contextualize those findings.

The three research questions posed were; What studies exist on the technology transfer of robotics and AI in agriculture, and how has this field of knowledge evolved over time? What are the main challenges in the adoption of AI technologies and robotics in agriculture? What solutions have been proposed or implemented to overcome those challenges?

RESULTS AND DISCUSSION

The delimited search yielded 45 documents, of which 64.4% were research articles and 35.6% were review papers. These articles are from the fields of agriculture and biological sciences, computer science, social sciences, engineering, and others (Figure 1).

Publications on the adoption and technology transfer of AI and robotics in agriculture are on the rise, but still is not a trending topic of study when compared to the number of publications on artificial intelligence applications in agriculture. The latter accounts for 5585 publications in Scopus over the past 5 years (Figure 2).

A map was prepared with the bibliometrix tool in the statistics program R, which shows the countries where the transfer and adoption of robotics and artificial intelligence in agriculture is studied. India and the United States were the countries with the most papers produced; US was the country with the most citations (Figure 3).

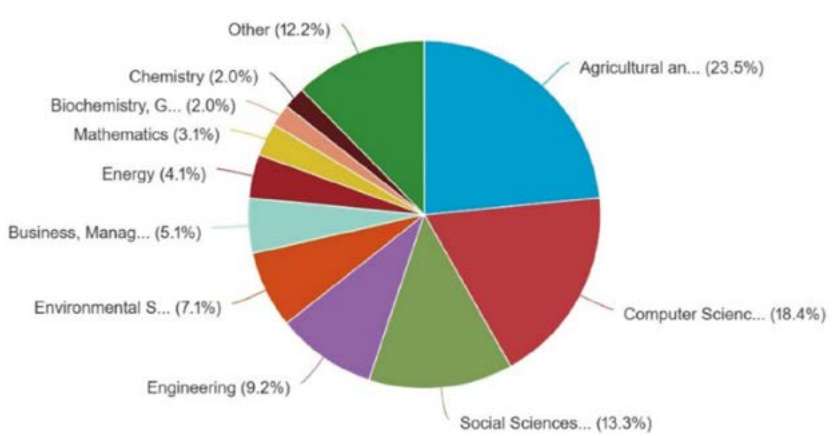

Figure 1. Papers found in the delimited search grouped by subject area.

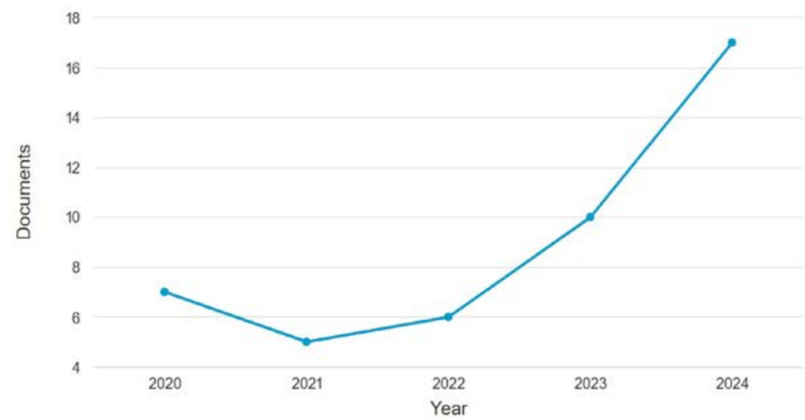

Figure 2. Papers published by year on the adoption of robotics and AI in agriculture that met the searching criteria.

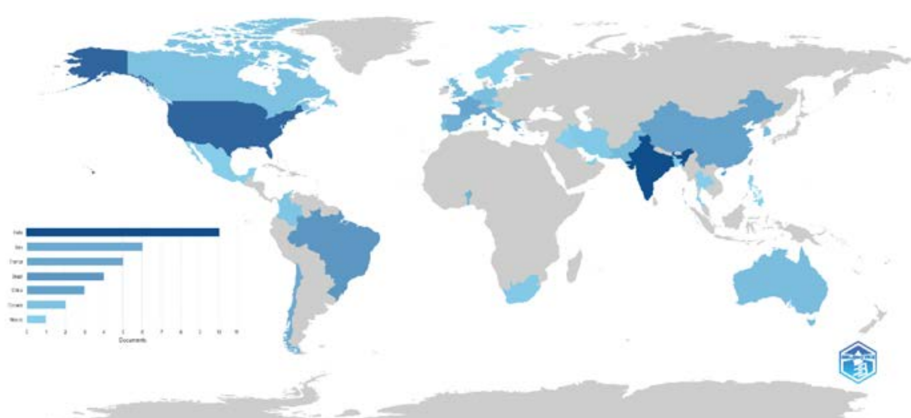

Figure 3. Map of papers published on effective technology transfer to use robotics and artificial intelligence in agriculture by country, generated with R (bibliometrix).

The bibliometric analysis using VOSviewer extracted 469 keywords from the titles and abstracts of the 45 filtered documents. Twenty-two of the most relevant terms that were repeated at least four times were selected. With the keyword co-occurrence map generated, we obtained the main topic clusters of the research (Figure 4).

The analysis results identified four color-coded clusters (red, green, blue, and yellow). Each cluster was manually labeled based on the relationship between the most frequently occurring words that link the terms in the cluster. For example, in the red cluster, the keywords "digitalization" and "agriculture" co-occurred most frequently, leading to labeling that cluster as "agricultural digitalization." Similarly, the green cluster was labeled "technology adoption for food supply"; the blue cluster "technologies for agricultural sustainability"; and the yellow cluster "artificial intelligence in agriculture".

The total link strength of two related terms (TLS) is used to predict trends and the main research topic. The yellow cluster in Figure 4 contains the largest number of terms and has the highest total link strength, compared to the blue, green, and red clusters. This indicates that the main research trend over the past five years is focused on the study of artificial

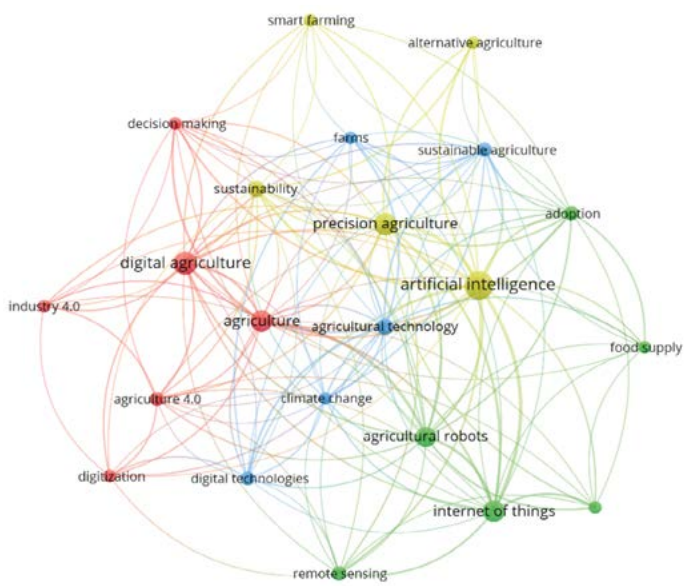

Figure 4. Keywords co-occurrence map of the research on robotics and artificial intelligence used in agriculture, generated in VOSviewer.

intelligence in agriculture, followed by agricultural digitalization, with the adoption of technologies for food supply ranked third, and technologies for agricultural sustainability related to climate change in fourth place (Table 1).

Table 1. Keywords clusters and the total link strength (TLS) value between them.

Cluster	Keyword	total link strength (TLS)
Artificial intelligence in agriculture (yellow dots)	Alternative agriculture Artificial intelligence Precision agriculture Smart agriculture Sustainability	176
Agricultural digitalization (red dots)	Agriculture Agriculture 4.0 Decision making Digital agriculture Digitization Industry 4.0	159
Adoption of technologies for food supply (green dots)	Adoption Agricultural robots Digital storage Food supply Internet of Things Remote sensing	155
Technologies for agricultural sustainability (blue dots)	Agricultural technology Climate change Digital technologies Farms Sustainable agriculture	128

The evolution of related terms has changed over the years due to the introduction of new technologies and the advancement of research fields. Thus, we show the evolution of the most frequently used terms over time, based on their co-occurrence (Figure 5). In recent years, terms such as "smart farming" and "digitalization" are more used, while five years ago terms such as "agriculture 4.0", "industry 4.0", and "agricultural robots" were more common, but their use has declined nowadays.

Reasons to adopt robotics in agriculture

The World Economic Forum emphasized that the adoption of robotics and digital agriculture drives agricultural sustainability and improves the economic viability of farmers through automation. Rial-Lovera (2018) identified labor shortages and high labor costs as the main drivers of adoption, through interviews with experts. Langemeier & Boehlje (2021) emphasized that in the medium term, robotics in agriculture not only reduces costs but also enables the collection of quantitative data on a single-plant basis, thus optimizing agricultural management and providing insights into the ecological footprint of a local food production system (Gil *et al.*, 2023). Optimization may be implemented without a major investment because it can use the same database already collected from the production systems.

Regarding data collection with distributed sensors, Mexico's Federal Telecommunications Institute reported on mobile service coverage in the agricultural areas of the 32 states, that 100% of the production units in protected agriculture have mobile service coverage with at least one type of mobile network (3G or 4G). Also, on average, 94% of the production units in rainfed agriculture have coverage with at least one type of mobile network in 18 of the 32 Mexican states.

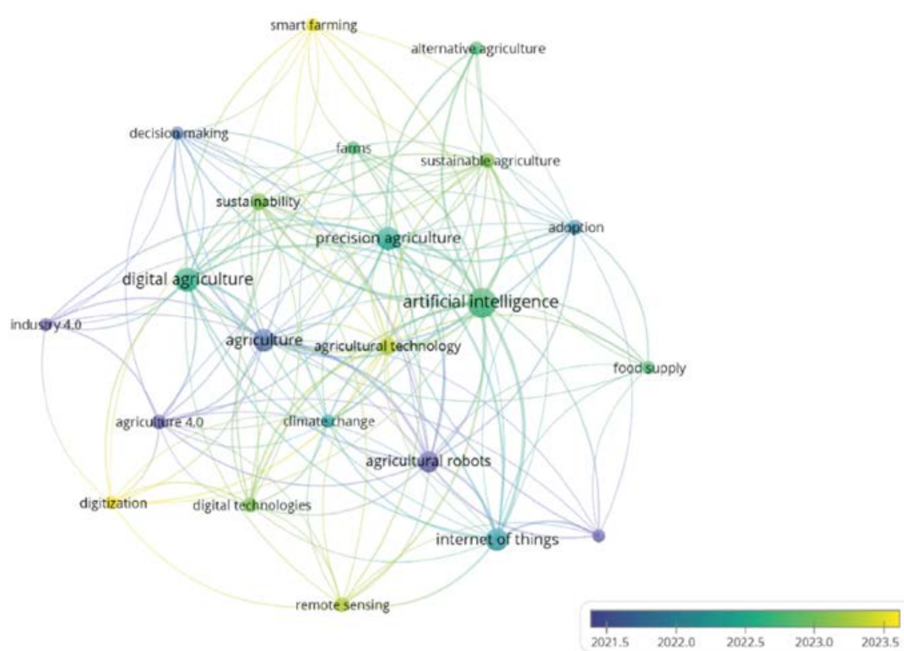

Figure 5. Representation of keywords in relation to the year of publication.

This represents an opportunity, in those places with mobile coverage, for the adoption of robotics in agriculture, especially for the optimization of resources and applications with distributed sensors in lands destined to agriculture. Digital technologies integrated into agriculture promote efficient resource use and waste reduction, aligning with circular economy and environmental sustainability models (Boz & Martin-Ryals, 2023).

Barriers to the adoption of robotics and AI in agriculture

Acquiring advanced technologies, such as robots and AI-based systems, involves high initial costs, which are a significant barrier, especially for small-sized and medium-sized farmers in developing countries (Smidt & Jokonya, 2022). Gil *et al.* (2023) observed that the higher cost of robots compared to other machinery occurs because those AI-based devices have to be prepared to withstand changing environmental conditions; those robots use expensive hardware and sensors, the greater capacity, the higher the cost. Dainelli *et al.* (2021) stated that robustness in the face of environmental conditions is a necessary condition for success in their implementation. Another associated cost is the training of operators in equipment maintenance, which requires some specialization due to the lack of standardization of agricultural robots (Rial-Lovera, 2018). The lack of adequate training programs in rural regions (Bampasidou *et al.*, 2024) is also added as a cost.

On the other hand, cultural and social resistance to change is a phenomenon experienced in farming communities, with a strong reliance on traditional farming methods. This is combined with skepticism toward the usefulness of new technologies, particularly when immediate benefits are not seen (Srivetbodee & Igel, 2021). The lack of local data demonstrating their effectiveness in different climatic and soil conditions hinders their acceptance (Pappa, 2024). And security issues in the use of agricultural data shared with technology providers is also identified as a concern associated with digitalization (Khanna *et al.*, 2022).

A significant barrier to the adoption of technologies such as robotics and artificial intelligence in the agricultural sector comes from the lack of participatory involvement of producers in the technological development and adaptation process. This can result in the design of functionalities that are not perceived as value, because technological solutions offered are disconnected from local problems, thus limiting their acceptance and practical use in farming lands. The lack of specific incentives or legal frameworks that encourage the adoption of these technologies is also a significant barrier (Pappa, 2024). As an example, ecological benefits are not financially rewarded because there is insufficient evidence on those; but incentives exist in other industries, such as electric vehicle mobility.

Strategies for the adoption of agricultural robotics technologies

Strategies to promote the adoption of technology in agriculture are diverse. Europe and the United States, a more mature first-world market, are promoting the use of agricultural robots through a service delivery model (Pappa, 2024). This option helps the end user to avoid the high initial cost of the robots and the training required for their operation. These robotic agricultural services are offered comprehensively, from land preparation to harvesting. In this way, the contractor extends the period of use of the robotic machines by using them with multiple clients, which allows them to amortize their costs.

Rent-to-own or leasing is an intermediate option that does not require a high initial cost, but does require operator training. This option allows farmers to get used to the technology without experiencing the risk of failing in implementation; also gives them the possibility of constantly renewing the equipment. However, a good advice for a company dedicated to agricultural robotics is, to be successful, they should continue research and development of their products, which may result incompatible with offering low prices (Gil *et al.*, 2023).

On the other hand, the transition to digital agriculture is different in developing countries (Johnson, 2024). To promote adoption among producers, it is suggested that training and practical demonstrations are key to increasing the use of agricultural robotics. The formation of farmer networks can facilitate the exchange of experiences and promote collective adoption (Smidt & Jokonya, 2022). In this regard, various organizations, such as the Autonomous University Chapingo, have proposed encouraging the creation of cooperatives among farmers that can share the use of agricultural robots, which would reduce acquisition cost and operating costs.

Dainelli *et al.* (2021) recommended that successful technological adoption requires user training; machines must be robust enough to adapt to changes in operating conditions, and, in the particular case of forest inventory machines, data must be easy to collect. Emphasis is also placed on education and training to ensure that producers properly understand and adopt technological devices. For large agricultural companies, this is easier; as it can be done by hiring specialized personnel (Milella *et al.*, 2024). For small-sized and medium-sized producers, it is suggested that the development of technological solutions should be accessible and specific to local needs; so considering the type of crops and the climatic or infrastructure limitations in each region (Boz & Martin-Ryals, 2023; da Silveira *et al.*, 2023).

One of the limitations to technology adoption in agriculture is the seasonal nature of production. Agricultural equipment is only used during specific stages of the crop. In contrast, as an example, in the automotive industry that uses the largest number of robotic arms, machinery operates continuously, which facilitates a faster costs amortization. In order to address this challenge, multitasking robots equipped with interchangeable or modular robotic implements could be used (Jensen *et al.*, 2012; Guri *et al.*, 2024). That would allow farmers to acquire technologies in a staggered manner and making them adaptable to different agricultural activities. Another technology adoption strategy is participatory development, with producers bringing together universities and research institutions that provide technical support. In turn, producers contribute ideas to solve their problems, then implementing and testing solutions. This partnership can also reduce the high initial cost of new technologies for producers (Langemeier & Boehlje, 2021).

Governmental role in promoting the adoption of agricultural technologies begins with making the necessary investments in telecommunications in rural areas to facilitate farmers' access to digital and robotic tools, especially in marginalized areas (Parra-López *et al.*, 2024). Furthermore, it is essential to implement public policies that promote digital literacy through training and education programs, allowing farmers to develop the skills necessary to use these technologies (Smidt & Jokonya, 2022). Financial incentives, such as subsidies, loans, and leasing schemes should also be considered to reduce the initial costs of technological adoption, which are a significant barrier for smallholder farmers (Hasan *et al.*, 2024).

On the other hand, collaboration between the public sector, universities, and technology companies can facilitate research and development of solutions tailored to local needs, fostering innovation and sustainability (Adzenga & Dalap, 2023). Likewise, the government should establish clear regulatory frameworks that guarantee the ethical and responsible use of digital technologies, ensuring data protection and user privacy (Bampasidou *et al.*, 2024). Finally, public policies must be aligned with sustainability goals, promoting the use of robotics and AI technologies that reduce greenhouse gas emissions and improve the efficiency of global resources use such as water (Parra-López *et al.*, 2024), and foster environmentally friendly practices such as integrated pest management or organic farming (Ditzler & Driessen, 2022). All of these actions, combined, can create an enabling environment for the adoption of digital technologies in agriculture.

CONCLUSIONS

India and the United States are leaders in the research evolution on the adoption of robotics and artificial intelligence in agriculture, for effective technology transfer to small producers and communities. In Mexico, the main reasons identified to adopt those technologies are resource optimization and increased productivity that contribute to the economic viability of agricultural activities. The most significant barriers identified are high initial costs, lack of regulated financing, and scarce technical training adequate for small farmers.

In order to face the economic and technical limitations of small-scale farmers, we propose alternatives such as the creation of cooperatives to share costs and the implementation of multitasking robots as viable options. Also, we recommend farmer participation in technological development and targeted training in the use of innovation technology, until the market for robotic technologies and services is consolidated.

The adoption of robotics and artificial intelligence in agriculture in Mexico requires tailored strategies to local needs, combining participatory approaches, cooperative models, and public policies that promote sustainability, digital inclusion, and equitable access to these technologies.

REFERENCES

Adzenga, J. I., & Dalap, S. L. (2023). Agricultural Technology Transfer in Nigeria: A Review of the Challenges and Prospects in the Contemporary Times. *Journal of Agricultural Extension, 28*(1), 21-29. https://doi.org/10.4314/jae.v28i1.4S

Amaro-Rosales, M., & De Gortari-Rabiela, R. (2016). Políticas de transferencia tecnológica e innovación en el sector agrícola mexicano. *Agricultura Sociedad y Desarrollo, 13*(3), 449. https://doi.org/10.22231/asyd.v13i3.406

Bampasidou, M., Goldgaber, D., Gentimis, T., & Mandalika, A. (2024). Overcoming 'Digital Divides': Leveraging higher education to develop next generation digital agriculture professionals. *Computers and Electronics in Agriculture, 224*(May), 109181. https://doi.org/10.1016/j.compag.2024.109181

Boz, Z., & Martin-Ryals, A. (2023). The Role of Digitalization in Facilitating Circular Economy. *Journal of the ASABE, 66*(2), 479-496. https://doi.org/10.13031/ja.14924 da Silveira, F., da Silva, S. L. C., Machado, F. M., Barbedo, J. G. A., & Amaral, F. G. (2023). Farmers' perception of the barriers that hinder the implementation of agriculture 4.0. *Agricultural Systems, 208*(January), 103656. https://doi.org/10.1016/j.agsy.2023.103656

Dainelli, R., Toscano, P., Di Gennaro, S. F., & Matese, A. (2021). Recent Advances in Unmanned Aerial Vehicles Forest Remote Sensing—A Systematic Review. Part II: Research Applications. *Forests, 12*(4), 397. https://doi.org/10.3390/f12040397

Ditzler, L., & Driessen, C. (2022). Automating Agroecology: How to Design a Farming Robot Without a Monocultural Mindset? *Journal of Agricultural and Environmental Ethics, 35*(1), 2. https://doi.org/10.1007/s10806-021-09876-x

Gil, G., Emilio, D., Pérez, L., & Verschae, R. (2023). Smart Agricultural Technology Why the low adoption of robotics in the farms? Challenges for the establishment of commercial agricultural robots. *Smart Agricultural Technology, 3*(November 2021), 100069. https://doi.org/10.1016/j.atech.2022.100069

Guri, D., Lee, M., Kroemer, O., & Kantor, G. (2024). Hefty: A Modular Reconfigurable Robot for Advancing Robot Manipulation in Agriculture. 1-8. http://arxiv.org/abs/2402.18710

Hasan, M. K., Mun, H. S., Ampode, K. M. B., Lagua, E. B., Park, H. R., Kim, Y. H., Sharifuzzaman, M., & Yang, C. J. (2024). A Systematic Literature Review on the Uses, Benefits, Challenges, and Prospects of Digital Twins in Livestock Farm Management. *Advances in Animal and Veterinary Sciences, 12*(12), 2301-2314. https://doi.org/10.17582/journal.aavs/2024/12.12.2301.2314

INEGI (Instituto Nacional de Estadística y Geografía). (2023). Resultados definitivos del Censo Agropecuario 2022, 1–13.

Jensen, K., Nielsen, S. H., Jørgensen, R. N., Bøgild, A., Jacobsen, N. J., Jørgensen, O. J., & Jaeger-Hansen, C. L. (2012). A Low Cost, Modular Robotics Tool Carrier for Precision Agriculture Research. Proceedings of the International Conference on Precision Agriculture.

Johnson, D. (2024). Technology in Society Food security, the agriculture value chain, and digital transformation: The case of Jamaica's agricultural business information system (ABIS). *Technology in Society, 77*(June 2022), 102523. https://doi.org/10.1016/j.techsoc.2024.102523

Khanna, M., Kar, S., Wu, L., Yu, C., & Chowdhary, G. (2022). Digital transformation for a sustainable agriculture in the United States: Opportunities and challenges. May, 924-937. https://doi.org/10.1111/agec.12733

Langemeier, M., & Boehlje, M. (2021). Automation and Robotics in Production Agriculture. *Farmdoc Daily, 11*(57), 1-4. https://farmdocdaily.illinois.edu/2021/04/automation-and-robotics-in-production-agriculture.html

Lule, L., Cobos, V., Vidal, F., & Enrique, L. (2016). Análisis sociológico de la problemática agropecuaria en el municipio de Salvatierra, Guanajuato. *Revista Iberoamericana de Las Ciencias Sociales y Humanísticas, 5*(10).

Milella, A., Rilling, S., Rana, A., Galati, R., Petitti, A., Hoffmann, M., Stanly, J. L., & Reina, G. (2024). Robot-as-a-Service as a New Paradigm in Precision Farming. *IEEE Access, 12*(January), 47942-47949. https://doi.org/10.1109/ACCESS.2024.3381511

Pappa, F. (2024). Sounding the alarm for digital agriculture: Examining risks to the human rights to science and food. *Netherlands Quarterly of Human Rights, 42*(3), 276-296. https://doi.org/10.1177/09240519241270408

Parra-López, C., Ben Abdallah, S., Garcia-Garcia, G., Hassoun, A., Sánchez-Zamora, P., Trollman, H., Jagtap, S., & Carmona-Torres, C. (2024). Integrating digital technologies in agriculture for climate change adaptation and mitigation: State of the art and future perspectives. *Computers and Electronics in Agriculture, 226*(May), 109412. https://doi.org/10.1016/j.compag.2024.109412

Pereira, H. (2018). Transferencia de tecnología: tensiones entre imposición y adopción. *Revista Científica Internacional*, 2, 129-162.

Rial-Lovera, R. (2018). Agricultural Robots: drivers, barriers and opportunities for adoption. Proceedings of the 14th International Conference on Precision Agriculture, 1-5.

Smidt, H. J., & Jokonya, O. (2022). Factors affecting digital technology adoption by small-scale farmers in agriculture value chains (AVCs) in South Africa. *Information Technology for Development, 28*(3), 558-584. https://doi.org/10.1080/02681102.2021.1975256

Srivetbodee, S., & Igel, B. (2021). Digital Technology Adoption in Agriculture: Success Factors, Obstacles and Impact on Corporate Social Responsibility Performance in Thailand's Smart Farming Projects, 24(2), 149-170.