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Article

Application of Digital Technologies in Horticulture

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RESUMO

O presente estudo discorre sobre as perspectivas no cenário atual das grandes tecnologias digitais na agricultura moderna, observando as suas contribuições para na produtividade, sustentabilidade e segurança alimentar. Para tanto, foi realizada uma busca nas principais bases de dados como PubMed, Scopus e Scielo, foram examinados artigos de 2015 a 2025 relacionados à IoT, drones, sensores, big data e IA, com foco nas aplicações voltadas para a agricultura familiar. Os tópicos refletidos na revisão incluem IoT, drones, sensores, big data e IA. As principais tecnologias mencionadas são drones para monitoramento de pestes e doenças, sensores para maximização do uso da água na irrigação, IoT-based automated irrigation, análises climáticas para previsões e "growth chambers" como hydroponics. Os benefícios observados são uma redução nos desperdícios de até 30% por hectare em água, uso intensivo de insumos, um aumento na qualidade e rastreabilidade do produto e expansão da indústria para o mercado exterior. No entanto, os desafios para pequenos produtores permanecem os custos, falta conhecimento, infraestrutura limitada em áreas urbanas, barreiras cívicas e burocráticas e a ausência de políticas públicas. Para o futuro, propõem-se soluções de código aberto e baixo custo, empresas de agricultores e soluções sustentáveis. A conclusão identificada é a digitalização do setor de horticultura, que promove a inclusão social, reduz a desigualdade e fortalece as necessidades de capacidade e resiliência.

Palavras-chave: inclusão rural; sustentabilidade agrícola; tecnologias emergentes.

ABSTRACT

The present study discusses perspectives on the current role of major digital technologies in modern agriculture, highlighting their contributions to productivity, sustainability, and food security. To this end, a search was conducted in leading databases such as PubMed, Scopus, and Scielo, examining articles published between 2015 and 2025 related to IoT, drones, sensors, big data, and AI, with a focus on applications aimed at family farming. The key topics addressed in the review include IoT, drones, sensors, big data, and AI. The main technologies identified are drones for monitoring pests and diseases, sensors for optimizing water use in irrigation, IoT-based automated irrigation, climate analysis for forecasting, and "growth chambers" such as hydroponics. Reported benefits include a reduction of up to 30% per hectare in water waste, more efficient use of inputs, improved product quality and

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traceability, and expansion of the industry into international markets. However, small producers continue to face challenges such as high costs, lack of knowledge, limited infrastructure in rural areas, civic and bureaucratic barriers, and the absence of public policies. Looking ahead, proposed solutions include open-source and low-cost tools, farmer cooperatives, and sustainable approaches. The conclusion emphasizes the digitalization of the horticulture sector, which promotes social inclusion, reduces inequality, and strengthens both capacity-building and resilience needs.
Keywords: emerging technologies; rural inclusion; agricultural sustainability.

Introduction

Horticulture is one of the main foundations of Brazilian agribusiness, playing a crucial role in both food production and the country's domestic economy (FAO 2020). It is strongly supported by contemporary demand for sustainable agriculture and healthy foods (Godfray et al. 2010). However, the advent of climate change has driven the emergence of technological innovations aimed at optimizing the efficient use of natural resources, thereby benefiting the food production chain (Tilman et al. 2011).

Within this context, Agriculture 4.0 has stood out by incorporating technologies such as artificial intelligence (AI), Internet of Things (IoT), drones, sensors, and big data to improve agricultural production processes (Wolfert et al. 2017). According to Kamilaris & Prenafeta-Boldú (2018), these technologies enable real-time plant monitoring, resource management, and risk prediction, which enhances crop productivity potential. Basso & Antle (2020) further highlight that soil monitoring sensors and traceability systems provide safety and assurance in producing high-quality products.

Nevertheless, it is important to emphasize that despite these initiatives, the management and availability of these technologies still represent a challenge for small rural properties, often becoming a limiting factor. According to Eastwood et al. (2019), obstacles such as the high costs of precision technologies, lack of internet access, insufficient technical training of farmers, technological inequalities, and economic bias restrict the sustainability and competitiveness of family farming. As Klerkx et al. (2019) point out, there is still a significant shortage of research combining horticultural production innovations with smallholder farmers.

In summary, the present study aims to provide an assessment of the current use of digital technologies in horticulture and to analyze their contributions to productivity, sustainability, and food security, as well as to highlight the challenges and opportunities related to their adoption in small rural properties.

Material and Methods

This research involved specific searches in major academic databases such as PubMed, Scopus, Web of Science, Scielo, and Google Scholar, specifically regarding the fields of agriculture and digital technology. This made it possible to collect full articles and open-access publications, whether of national, international, or regional scope.

The search terms used were "horticulture," "digital agriculture," "Internet of Things," "IoT," "drones," "precision agriculture," "family farming," and "smallholders." These keywords were searched in both Portuguese and English, allowing the identification of relevant references for the focus of this research.

The search period ranged from January 2015 to September 2025, in order to reflect recent developments in Agriculture 4.0 technologies and ensure that the data and information were up to date. The choice of this timeframe aimed to focus on recent innovations and applied work in practice, highlighting their implementation in horticulture while ensuring transparency and methodological rigor.

Emerging Themes in the Literature

Digital Technologies Applied to Horticulture

Agriculture 4.0, through the use of digital tools, has made horticulture more economical, sustainable, and productive. To this end, five technological tools stand out in this field: sensors, drones, Internet of Things (IoT), big data-based climate modeling, and controlled environment production systems.

Sensors

The fact is that advances in technology have significantly improved the ability to monitor environmental factors in real time. Zhang et al. (2025) add that soil moisture, temperature, and nutrient conditions can lead to excessive application of fertilizers as well as overuse of water. Furthermore, the researchers point out that it is now possible to use electrical conductivity sensors, which measure conductive soil moisture, thus enabling demand-controlled irrigation. They also note that, despite their availability on the market and ease of use, caution is necessary, since environmental conditions can generate disparities in the use of the mentioned device. As with all equipment, routine maintenance and proper care prolong its effectiveness.

Drones and Aerial Imaging

The NDVI (Normalized Difference Vegetation Index) enables horticultural crop monitoring through drones equipped with thermal and multispectral cameras. According to Tsouros et al. (2019), it is now possible to identify pests, planting failures, and water stress in crops at an early stage using these devices. They also report that the use of drones can reduce inspection time by up to 70% compared to traditional methods. However, the initial acquisition costs, operational training, and data analysis requirements especially for small producers still represent challenges to be overcome.

Internet of Things (IoT)

IoT makes it possible to automate irrigation and fertigation by integrating sensors, actuators, and digital devices. According to Goep et al. (2018), sensor-based irrigation systems using microcontrollers can reduce water use by up to 30%, lowering costs while maintaining system efficiency. Despite its undeniable advantages, the researchers warn that adoption in isolated rural areas is a limiting factor, whether due to implementation costs or the need for reliable connectivity.

Climate Modeling and Big Data

Big data and climate modeling can be used to predict yield rates, assess crop disease risks, and even develop more efficient plans and guidelines in response to the impacts of abrupt climate changes. According to Kamilaris & Prenafeta-Boldú (2018), vegetable yields can be predicted with up to 85% accuracy using machine learning algorithms and neural networks that analyze large volumes of climate and agricultural data, provided that producers have access to reliable, real-time computing systems.

Controlled Environment Production Systems

In hydroponics and vertical farming, nutrient flow monitoring, light control, and temperature regulation are fully automated and digitalized, using sensors and software to dynamically control or predict variables. This can increase productivity by up to tenfold per area compared to conventional cultivation (Kozai et al. 2019).

Potential for Horticulture

One of the greatest advantages of integrating technological advances into agriculture is the efficiency in the use of available resources, which minimizes the waste of water and inputs, meaning less impact on the environment. According to Majsztrik et al. (2017), Getahun et al. (2024), and Hutchinson et al. (2025), adequate and well-planned irrigation significantly reduces the amount of water and sediments that run off the fields, allowing real-time adjustments and consequently minimizing overapplication and greenhouse gas emissions. Zhang et al. (2017) and Breure et al. (2022) add that monitoring the vapor pressure deficit (VPD) allows control without compromising plant development. Furthermore, such practices save resources and contribute to more sustainable agriculture.

It is important to highlight that IoT-enabled smart sensors and real-time AI-based monitoring systems enable more informed decisions, optimizing horticulture and its management. According to Miller et al. (2025), predictive models based on machine learning, including SVMs and CNNs, are combined with networks of optical, acoustic, and electromagnetic sensors to monitor crop and environmental conditions, ensuring optimized management of pests, fertilization, and irrigation. The fact is that field automation in agriculture has become feasible, and it is now possible to overcome challenges, support integrated management choices in horticulture, and achieve all this in real time with precision and efficiency (Barker & Phenological 2023). According to probabilistic cost-benefit analyses, intensive monitoring increases net gains in 68% of cases (Ruett et al. 2022).

Another important point is traceability and certification of sustainable and healthy products, which aim to improve the quality of horticultural goods. According to Ben Ayed et al. (2022), verifying the authenticity and nutritional composition of products gives consumers confidence in the food on their tables. Ensuring traceability and certification compliance is essential (Fang et al. 2014). Thus, safety and standardization in horticultural production create new markets and meet the global demand for sustainable food.

Precision technologies significantly reduce post-harvest losses and improve food security (Gelaye 2025). Ezeonyejiaku et al. (2017) warn that horticultural fruits must be continuously inspected for metal contamination, such as arsenic and mercury, which can pose risks to public health. Kalischuk et al. (2019) further highlight that multispectral monitoring enhances the final quality of products through faster disease detection, increasing productivity and resistance to abiotic stress (Sihag et al. 2021).

Regulations in the agri-food sector promote safe practices and facilitate commercial expansion (Amanda et al. 2015). In this way, precision agriculture increases profitability and meets the growing global demand for safe food (Getahun et al. 2024).

Challenges for Small Properties

Despite the potential benefits of precision technologies in horticulture, small farms face significant obstacles that limit their adoption. These challenges are particularly pronounced in rural contexts and developing countries, where limited resources amplify the barriers.

High Initial Technology Costs

High initial implementation costs represent a major barrier for small horticulturists, who often operate with tight financial margins. Moreover, technologies such as IoT sensors and AI systems require significant infrastructure investments, especially for small farms (Miller et al. 2025). These challenges limit equitable access in developing regions, resulting in productivity stagnation, increased susceptibility to pests, negligible profit gains, and long-term sustainability failures (Subramanian 2023). Similarly, technological inequalities and financial barriers inhibit innovation (Odintsov Vaintrub et al. 2021).

Lack of Technical Training

Communication gaps between researchers, extension agents, and farmers contribute to this barrier, hindering effective knowledge dissemination (Njenga et al. 2021). Furthermore, the lack of technical training leads to negative attitudes and low implementation of technological cultivation systems (Hassan et al. 2024). Social failures due to insufficient training result in limited adoption, even when potential benefits exist (Opio 2001).

Rural Connectivity Limitations

Poor connectivity in rural areas constitutes a fundamental technical barrier, as many technologies rely on real-time data transmission. Connectivity constraints in remote areas limit IoT system deployment, exacerbating inequalities for small producers (Miller et al. 2025). An analysis of barriers to agricultural transformation highlights both fears and facts related to digital infrastructure, emphasizing how the lack of connectivity in rural contexts impedes progress (Taheri et al. 2022).

Cultural Resistance to New Practices

Cultural resistance arises from changes in traditional products and practices, creating social barriers to innovation. Agroecological systems, for example, face cultural obstacles due to alterations in product characteristics, despite their positive image among consumers (Dumont et al. 2025). It is also important to note that cultural and financial barriers limit the adoption of agricultural technologies (Gwyther & Jenkins 1998). Additionally, high transaction costs and collective action issues, including cultural barriers, inhibit innovative collaborations in rural contexts (Aza-Mengoa et al. 2025).

Lack of Public Policies and Specific Incentives for Horticulturists

The absence of targeted policies and incentives discourages adoption, leaving gaps in subsidies and regulations. Financial incentives are essential for scientific research and production, but they are frequently insufficient (Wittwer 1975; Batool et al. 2023; Mattsson et al. 2012).

These challenges underscore the need for integrated approaches, including public-private partnerships and training programs, to facilitate technology adoption in small horticultural farms and promote a balanced transition.

Future Perspectives and Trends

The popularization of horticultural technologies is expected to democratize access to advanced tools for small- and medium-scale producers, resulting in significant cost savings and reduced environmental impact (Sharma et al. 2023). This trend is particularly relevant for horticulture, where cost optimization can enhance producers' competitiveness in the economic market.

Simultaneously, the development of low-cost and open-source solutions facilitates accessible innovation, allowing farmers to customize their tools without making large investments, promoting system interoperability and reducing technological barriers (Benos et al. 2021). Initiatives involving ensemble algorithms and integration with low-cost IoT devices can be adapted for horticultural crop monitoring, fostering more inclusive agriculture.

The initiative and expansion of digital cooperatives for equipment sharing represents a promising perspective, as shared economy models supported by digital platforms enable collective access to expensive equipment, such as drones and sensors, optimizing costs and knowledge while strengthening rural communities (Cembrowska-Lech et al. 2023). This technological convergence points to a more precise, sustainable, and resilient horticulture, with the potential to reduce waste and enhance global food security (Opara et al. 2024).

Conclusions

Technologies such as sensors, the Internet of Things, drones, big data, and artificial intelligence are transforming crop management by optimizing resource use, reducing waste, and increasing productivity. This represents a fundamental advancement in the face of challenges such as climate change and population growth, as these technologies promote efficiency, sustainability, and competitiveness in food production, especially for small-scale horticultural producers.

However, caution is necessary, as high costs, lack of technical training, limited connectivity in rural areas, and cultural resistance hinder technology adoption, deepening inequalities. Overcoming these obstacles requires collaborative efforts, such as public-private partnerships, training programs, and financial incentives, to make digital solutions accessible and inclusive.

Research gaps still need to be addressed, particularly in studies focused on the needs of small producers, the socioeconomic impact of digitalization, and the development of public policies that promote low-cost and open-source technologies. These issues represent opportunities for future investigations, capable of strengthening horticulture by combining technological innovation with social inclusion and sustainability.

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