Floriculture 4.0 in Ecuador:

Challenges and guidelines for the integration of digital technologies and public policies in genetic improvement and productive innovation

Xavier Rojas-Ruilova [1]
Génesis Vásquez[2]
Isabel Marques[3]

[1]Universidad Nacional de Loja, Facultad de la Salud Humana, Loja, Ecuador,
https://orcid.org/0000-0002-5692-5366
xavier.rojas@unl.edu.ec

[2]Universidad Nacional de Loja, Facultad de Energía, Loja, Ecuador,
https://orcid.org/0000-0002-9632-5429
genesis.vasquez@unl.edu.ec

[3]University of Lisbon, Forest Research Centre, Associate Laboratory TERRA, School of Agriculture, Lisboa, Portugal,
https://orcid.org/0000-0001-9788-4831
isabelmarques@isa.ulisboa.pt

DOI: 10.61854/rccedia.v1n1.006
Sent: January 20, 2026
Approved: April 8, 2026
Published: Tuesday, July 14, 2026

Abstract

Ecuadorian floriculture is undergoing a transformation driven by digitalization, biotechnology, and data science. This study examines the role of Information and Communication Technologies (ICTs), bioinformatics, and Big Data analytics in genetic improvement, with a focus on the national context. Through an exploratory review of the scientific literature, we identify emerging patterns in the adoption of digital technologies for the development of new floral varieties. The results reveal a clear imbalance in the current technological landscape, characterized by a predominance of production-oriented digital tools, such as IoT sensors and artificial intelligence, alongside a still limited integration of bioinformatic and genomic approaches. This asymmetry suggests that innovation in Ecuadorian floriculture is currently driven primarily by crop management optimization rather than advances in the genetic foundation of production systems. Nevertheless, the incorporation of genomic tools in ornamental species shows strong potential to improve the efficiency of breeding programs by enabling the identification of genes associated with key traits and stress tolerance, thereby supporting the development of more resilient and competitive production systems. In this context, the findings highlight the need to strengthen public policies that promote the integration of genomic and bioinformatic capacities within the floriculture sector. This includes investments in scientific infrastructure, the development of specialized human capital, and the promotion of partnerships between academia, industry, and governmental institutions. A coordinated strategy in this direction could position Ecuador as a regional leader in Floriculture 4.0, aligning technological innovation with the sustainable use of its biodiversity.

Keywords:
flowers; bioinformatics; big data; digital innovation; industry; orchids.

Introduction

Floriculture is one of Ecuador's most dynamic agricultural sectors, internationally recognized for the quality and diversity of its cut flowers, particularly roses (Guaita-Pradas et al., 2023). Since its consolidation in the 1990s, this industry has made a significant contribution to the agricultural export gross domestic product (GDP), "generating more than 65,000 direct jobs and 55,000 indirect jobs, with a notable participation of women, who represent 51% of the workforce."[1]

According to data from the Central Bank of Ecuador (BCE, 2024), between January and November 2024, floriculture exports reached USD 925 million, with a year-over-year growth of 2.6% and a volume exceeding 160,000 tons, consolidating the country as the world's third-largest exporter after the Netherlands and Colombia (BCE, 2024). Floriculture production in Ecuador has historically been concentrated in the northern region of the country, particularly in the provinces of Pichincha and Cotopaxi, which together account for more than 80% of national production, while the remainder originates from other provinces, including Guayas, Imbabura, and Azuay (Mañay et al., 2022).

However, the competitiveness of the floriculture sector is currently undergoing a structural transition driven by digitalization, sustainability, and biotechnological innovation. Global demand requires new varieties with longer vase life, disease resistance, transport tolerance, and adaptation to climate change (Casigña et al., 2024). In this context, information and communication technologies (ICTs), together with bioinformatics and big data analytics, are emerging as key pillars of a new phase of agrobiotechnological innovation (García Torres et al., 2024; Chavarro, 2021). Within this framework, ICTs contribute to optimizing resource use, anticipating phytosanitary issues, improving traceability, and reducing postharvest losses, while facilitating data-driven management models and innovation strategies oriented toward sustainability (Vernier et al., 2021; Abbes, 2025).

In practice, these technologies are materialized through multiple applications, including greenhouse automation, environmental sensing, smart irrigation, and digital traceability (Pandiyan et al., 2024; Dai et al., 2025; Peña-Holguín et al., 2025; Kumar & Verma, 2025). For example, IoT sensors installed in greenhouses enable the monitoring of variables such as temperature, humidity, radiation, and CO_2 concentration, with the resulting data processed on cloud-based platforms through predictive models that optimize plant growth and flowering (Hosny et al., 2025; Soussi et al., 2025). At the same time, the use of blockchain technologies strengthens production traceability and enhances transparency in international markets that are increasingly sensitive to sustainability criteria (de Carvalho et al., 2022; Chen et al., 2023; Pang et al., 2024; Thuy et al., 2025).

Likewise, the convergence of molecular biology, bioinformatics, and data analytics has driven significant advances in plant genetic improvement (Hasan et al., 2021; Khan et al., 2022; Panahi et al., 2024; Belbase et al., 2025; Li et al., 2025; Salgado-Velázquez et al., 2026). The use of molecular markers, genomic sequencing, and trans-

[1] Ecuador reaffirms its leadership in the global flower industry with the inauguration of Expo Flor 2024 – Ministry of Production, Foreign Trade and Investment, n.d.

criptomic approaches enables the identification of genomic regions and genes associated with traits of interest, such as color, fragrance, pathogen resistance, and tolerance to environmental stress (Kim et al., 2020; Koboldt et al., 2013; Berman et al., 2025; Pei et al., 2026). Similarly, approaches such as QTL mapping, genome-wide association studies (GWAS), and CRISPR-based gene editing expand the possibilities for targeted improvement and functional gene exploration (Doll et al., 2019; Li et al., 2025; Verdezoto-Prado et al., 2025).

Furthermore, the integration of genomic tools with predictive models based on artificial intelligence is accelerating breeding programs and expanding opportunities for the selection of complex traits (Yang et al., 2022; Afonso et al., 2024; Mantilla et al., 2025). International experience demonstrates that these approaches can shorten varietal development timelines and improve the early selection of parental lines. For example, in Chrysanthemum morifolium, genomic prediction has demonstrated potential for identifying combinations with desirable commercial traits (OECD, 2015; Kim et al., 2024; Su et al., 2024).

Despite the growing interest in the digitalization of the floriculture sector, the literature remains fragmented, making it difficult to develop an integrated understanding of the opportunities, limitations, and challenges associated with the transition toward Floriculture 4.0 in the country. Recent studies have examined the adoption of ICT technologies in the floriculture sector, showing that although there is considerable potential to improve efficiency and sustainability, implementation in emerging countries such as Ecuador remains limited due to economic, technical, and training-related barriers (Mantilla et al., 2025). These studies have focused primarily on technological adoption at the production level, whereas bioinformatics, artificial intelligence, and genetic improvement, as key components of floricultural innovation, have received significantly less attention.

In this context, the present study is proposed as an exploratory review with an analytical orientation, aimed at synthesizing and structuring the available knowledge regarding the role of digital technologies in Ecuadorian floriculture by integrating technological, genomic, and production-related perspectives. Based on this approach, the following research questions are formulated:

- (i) Which technologies are shaping the Floriculture 4.0 paradigm in floriculture production and genetic improvement processes, and what is their relevance within the Ecuadorian context?
- (ii) What are the main structural, technological, and educational limitations that condition their adoption in Ecuador?
- (iii) What opportunities emerge from the convergence of ICTs, bioinformatics, and artificial intelligence for the development of innovative genetic floriculture in Ecuador?

Methods

The present study was conducted as an exploratory review with a qualitative approach, incorporating elements of a systematic review based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). Source identification was carried out through a structured search in the Scopus database, using Boolean operators and predefined combinations of terms, including “digital agriculture” OR “bioinformatics” OR “artificial intelligence” OR “floriculture” AND “plant breeding” AND “Ecuador.” Scopus was selected as the primary database due to its broad coverage of peer-reviewed literature across multiple disciplines, ensuring comprehensive and consistent retrieval of relevant studies.

Subsequently, a multi-stage selection process was conducted based on the review of titles, abstracts, and full-text content to identify studies aligned with the objectives of this work. To minimize potential bias, the screening process was performed independently by two researchers. During this phase, 30 records were excluded for not fitting the thematic scope of the study, including works focused on non-technological agricultural practices and crops outside the floriculture sector or unrelated to plant breeding. In addition, 32 further records were excluded because they did not correspond to scientific articles or reviews (e.g., books or other types of non-peer-reviewed documents). As a result of this process, the final dataset consisted of 55 documents, which form the basis of the review.

This dataset includes one review study that integrates evidence from 41 additional works, thereby expanding the empirical scope of the analyzed corpus. Furthermore, the corpus was classified according to technology type and field of application, allowing both thematic and quantitative analyses of the literature. The selected studies were also analyzed using a thematic coding methodology, in which each document was categorized according to its primary technological focus (e.g., IoT, artificial intelligence, bioinformatics, or genetic improvement) and its area of application. For this purpose, a data extraction matrix was developed, including variables such as technology type, application domain, geographic context, and the study’s main contribution. This information enabled the identification of recurring patterns and the quantification of the distribution of technological approaches within the analyzed corpus, thereby facilitating the systematic interpretation of the results.

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Results

Based on the analysis of the 55 selected studies, classified through thematic coding according to their technological focus and area of application, consistent patterns were identified in the application of digital technologies within the floriculture sector. In particular, 15 studies focused on IoT technologies and sensors, 7 on artificial intelligence, and 8 included components related to genetics and breeding. The remaining studies were distributed across other technological categories or mixed approaches, reflecting the heterogeneity of the field analyzed (Figure 1).

The reviewed studies show that artificial intelligence and machine learning are among the most recurrent approaches in the literature, particularly in applications related to disease detection, demand forecasting, flower classification, and the estimation of phenotypic traits through computer vision.

On the other hand, the analysis reveals a more limited presence of studies focused on the application of bioinformatics tools and genetic improvement approaches in the specific context of Ecuadorian floriculture. Likewise, most studies were conducted in international settings, with relatively few investigations specifically focused on Ecuador.

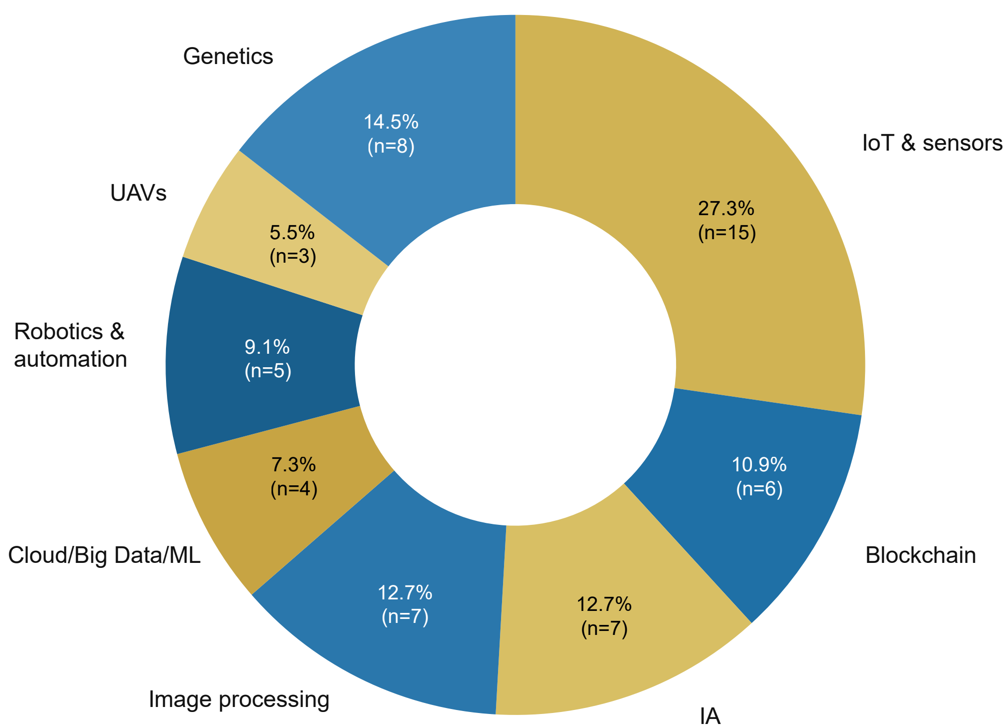

Figure 1

Distribution of studies included in the review according to technological category.

These advances reflect an emerging transition toward data-driven floriculture, creating opportunities for more sustainable, efficient, and traceable production systems. In this regard, Table 1 summarizes the main technologies identified, their applications, and their level of adoption within the Ecuadorian context, highlighting uneven development across technologies, with greater consolidation in monitoring and automation tools and a still incipient stage in bioinformatics and gene editing.

Table 1
Technologies considered priorities for the transition toward Floriculture 4.0 in Ecuador, according to their application and level of adoption

Technology	Application in floriculture	Main benefits	Level of adoption in Ecuador
IoT and climate sensors	Environmental monitoring, precision irrigation, and fertilization	Water savings, automated control	Medium
Big data and predictive analytics	Processing of genomic and phenotypic data	Improved varietal selection and traceability	Low
Bioinformatics	Identification of genes associated with color, resistance, and fragrance	Acceleration of genetic improvement	Low
Artificial intelligence (AI)	Flowering prediction, pest control, image analysis	Greater efficiency and reduced losses	Low
Blockchain	Certification of origin and sustainability	Traceability and commercial trust	Very low
Gene editing (CRISPR)	Precise modification of traits of interest	Genetic innovation and resilience	Experimental

Discussion

Potential of digital innovation in ecuadorian floriculture

The results obtained reveal a clear predominance of digital technologies applied to production, such as IoT, sensors, and artificial intelligence, compared with a lower representation of approaches focused on bioinformatics and genetic improvement. This pattern suggests that the digital transformation of floriculture has progressed mainly in the optimization of production processes (Montalvo, 2025), while integration with genetic innovation remains limited.

In this context, the Ecuadorian case represents a strategic opportunity to advance toward more integrated Floriculture 4.0 models, although there are still only incipient efforts by universities, which have initiated pilot projects involving floral image analysis and predictive yield modeling (Pérez-Campdesuñer et al., 2025). The incorporation of ICTs should not be understood merely as technological modernization, but rather as a paradigm shift that transforms the way research, production, and commercialization are conceived.

Despite the contributions of this study, it is important to acknowledge certain limitations inherent to the methodological approach adopted, as it is a review based primarily on the Scopus database. Likewise, the limited availability of studies specifically addressing the Ecuadorian context restricts the generalizability of some findings, highlighting the need for future empirical research that explores in greater depth the incorporation of digital and genomic technologies into national floriculture.

Integration of bioinformatics and genetic improvement

The limited findings of our review reveal constraints in the advancement of genetic improvement in Ecuadorian floriculture. In contrast to the predominance of production-oriented digital technologies identified in the results, there is a lack of molecular-level information. However, the emergence of bioinformatics and big data analytics offers the possibility of transforming this scenario by enabling the processing of large volumes of genetic, transcriptomic, phenotypic, and environmental information with unprecedented levels of resolution.

Ecuador, as one of the most biodiverse countries in the world, has the potential to become a regional center for floricultural big data, integrating genomic information from native species with phenotypic data generated by export-oriented companies. For example, the country is home to more than 4,000 native Orchidaceae species, a large proportion of which are endemic and remain poorly studied at the genetic level (Vega et al., 2013). This biological wealth makes Ecuador a natural laboratory for the application of bioinformatics tools, big data analytics, and artificial intelligence aimed at both conservation and genetic improvement.

International platforms have enabled advances in sequence analysis, gene identification, and the exploration of metabolic pathways associated with floral traits such as color, shape, and fragrance (Chen et al., 2022). Likewise, recent developments in comparative genomics and transcriptome sequencing have made it possible to identify genes involved in floral morphogenesis, pigment production, and resistance to abiotic stress. Exam-

Revista Científica CEDIA - ISSN: 3151-8435

ples such as Vanilla planifolia (Gastelbondo et al., 2025; Hernández-Peña et al., 2025) and Cymbidium goeringii (Ramya et al., 2019) illustrate the potential of these tools for applications related to quality and sustainability.

In the Ecuadorian context, precision floriculture could benefit from the incorporation of molecular markers to accelerate breeding programs targeting commercially valuable traits, such as postharvest longevity, color intensity, and tolerance to diseases and adverse environmental conditions (Abril-Espin et al., 2024). Complementarily, gene editing technologies such as CRISPR/Cas9 would create opportunities to investigate specific gene functions or develop varieties adapted to the country's diverse altitudinal zones without compromising native biodiversity (Motoche-Monar et al., 2023; Gómez-Lama et al., 2025; Verdezoto-Prado et al., 2025). This strategy would enable resource optimization, loss reduction, and the promotion of climate-resilient floriculture, while also diversifying the genetic base of ornamental crops.

The consolidation of these innovations requires progress toward methodological standardization in the management of genomic and phenotypic data, as well as the implementation of reproducible predictive models based on artificial intelligence (Caballero-Ramirez et al., 2023; Montalvo et al., 2025). The use of next-generation sequencing platforms, de novo transcriptomic analysis tools, and deep learning algorithms applied to hyperspectral images will enable the development of more accurate and transferable models across ornamental species (Anastasiou et al., 2025; Cravero et al., 2026). In this way, the integration of genomics with digital phenomics and artificial intelligence will establish the foundation for intelligent floriculture centered on sustainable innovation and scientific knowledge as a competitive advantage.

Challenges and perspectives toward ecuadorian floriculture 4.0

La escasa adopción de herramientas genómicThe limited adoption of genomic tools identified in the results translates into structural barriers to the development of a fully integrated Floriculture 4.0 in Ecuador. Despite the identified potential, the implementation of digital technologies faces obstacles related to technological infrastructure, the availability of specialized human resources, and data governance. In particular, insufficient connectivity, limited data storage and processing capacity, and the shortage of professionals trained in bioinformatics and data science constrain the sector's development.

In this context, the creation of centers of excellence and technology transfer platforms is essential for connecting research and production. Likewise, the implementation of living labs in floricultural regions would provide real-world environments for validating, adapting, and scaling technological innovations. Within these spaces, Ecuadorian orchids and other native ornamental species could serve as reference biological models for integrating artificial intelligence, genomics, and digital phenomics. This approach would transform biodiversity into biotechnological capital, fostering a new knowledge economy in which genetic and phenotypic data are considered high-value strategic assets.

From an institutional perspective, the State plays a fundamental role in establishing regulatory frameworks and incentives that promote technological adoption (De Leon Nazareno, 2024). This is reflected in the Public Policy for Ecuador's Digital Transformation 2025–2030, as established within the legal framework of the Organic Law for Digital and Audiovisual Transformation, the Organic Telecommunications Law, the Organic Law on Identity Management and Civil Data, the Organic Law of the National Public Data Registry System, the Organic Law for the Optimization and Efficiency of Administrative Procedures, and the Organic Law on Personal Data Protection (MINTEL, 2025).

Advancing toward Floriculture 4.0 requires a coordinated vision centered on sustainability, innovation, and the valorization of biodiversity, as summarized in Table 2. The integration of ICTs, biotechnology, and the circular economy will not only improve production efficiency but also position Ecuador as a regional leader in intelligent floriculture, capable of exporting not only flowers but also knowledge, technology, and sustainable management models. This emerging paradigm redefines the country's role in the global bioeconomy, promoting production systems that are more resilient, traceable, and aligned with the conservation of natural heritage.

Table 2

Strategic framework for the implementation of floriculture 4.0 in Ecuador, integrating technological, socioeconomic, and environmental dimensions

Strategic Axis	Technological component	Expected impact	Stakeholders involved
Productive digitalization	IoT, automation, data analytics	Efficiency, cost reduction	Floriculture companies, universities
Genetic innovation	Genomics, bioinformatics, CRISPR	New varieties, climate resilience	Research centers, universities
Environmental sustainability	Clean energy, blockchain, circularity	Reduced ecological footprint, green traceability	Government, certification bodies
Education and talent development	STEM education, technology networks	Skilled employment, local innovation	Universities, government
Data governance	Digital infrastructure, legal frameworks	Biogenetic protection, scientific sovereignty	Ministry of Production, academia

Conclusions

In response to the research questions posed, the results of this study reveal an asymmetric development in the transition toward Floriculture 4.0, characterized by the predominance of production-oriented digital technologies and the limited adoption of bioinformatics tools and genetic improvement approaches. This imbalance highlights a strategic opportunity to advance toward more integrated models based on data, genomics, and innovation.

In this context, Ecuador, owing to its biodiversity and export leadership, possesses favorable conditions to establish itself as a regional hub for digital floricultural innovation. The incorporation of technologies such as IoT, artificial intelligence, and big data will enable the optimization of production processes, improved traceability, and accelerated development of varieties adapted to climate change.

Nevertheless, realizing this potential depends on overcoming structural limitations related to technological infrastructure, the development of specialized human capital, and data governance. In this regard, investment in interdisciplinary training, data standardization, and the strengthening of collaborative networks will be essential for consolidating a sustainable innovation system. Overall, the integration of ICTs, biotechnology, and biodiversity positions Ecuadorian floriculture as a strategic sector within the bioeconomy, with the capacity to promote a more resilient, competitive, and knowledge-based production model.

Conflict of interest statement

The authors of this article declare that they have no conflicts of interest.

Funding sources

This research was funded by National Funds through the Foundation for Science and Technology (FCT) under projects UID/00239/2025 (CEF) and LA/P/0092/2020 (Associated Laboratory TERRA), as well as by I.M. through the Scientific Employment Stimulus Program—Individual Call (CEEC Individual)—2021.01107.CEECIND/CP1689/CT0001.

Declaration of authorship contributions (CRediT):

Xavier Rojas Ruilova: Conceptualization; methodology; formal analysis; investigation; validation; writing – original draft; writing – review and editing; visualization; resources; supervision; project administration.

Génesis Vásquez: Conceptualization; methodology; formal analysis; data curation; investigation; validation; writing – original draft; writing – review and editing; visualization; software.

Isabel Marques: Conceptualization; methodology; formal analysis; investigation; validation; writing – original draft; writing – review and editing; resources; supervision; funding acquisition.

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