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Digital and biotechnological interventions in floriculture: A comprehensive review

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Abstract
Floriculture, a rapidly expanding sector of horticulture, plays a vital role in global trade, cultural traditions, employment generation, and economic diversification. However, the industry faces significant challenges including climate variability, pest and disease outbreaks, post-harvest losses, and limitations of conventional breeding. Recent advances in biotechnology such as genetic engineering, CRISPR/Cas9 genome editing, molecular marker-assisted breeding, and tissue culture have enabled the development of ornamentals with novel colors, enhanced fragrance, extended vase life, and improved stress tolerance. In parallel, digital technologies like artificial intelligence (AI), Internet of Things (IoT), smart sensors, robotics, and big data analytics are driving precision floriculture, optimizing input use, and enhancing quality monitoring. The integration of these approaches is reshaping floriculture into a science-driven, technology-enabled, and globally competitive industry. Despite regulatory barriers, high infrastructure costs, and adoption challenges in developing regions, the synergistic application of digital and biotechnological interventions offers transformative potential for sustainability, climate resilience, and market innovation. This review provides a comprehensive overview of recent developments, challenges, and future perspectives, highlighting the role of integrated innovations in advancing global floriculture.

Keywords: Floriculture, biotechnology, genetic engineering, CRISPR/Cas9, tissue culture, marker-assisted breeding, artificial intelligence (AI), internet of things (IoT), precision agriculture, smart greenhouses, digital phenotyping, sustainable floriculture

Introduction
Floriculture, a specialized branch of horticulture, deals with the cultivation, processing, and marketing of flowers and ornamental plants. It has emerged as one of the fastest-growing segments of agriculture worldwide, contributing not only to aesthetic enrichment and cultural traditions but also to employment generation, income diversification, and foreign exchange earnings. Globally, the floriculture industry is valued in billions of dollars, with developing countries such as India, Kenya, and Ethiopia increasingly becoming major players due to their favorable climatic conditions, cost-effective labor, and expanding export potential. Within India, the sector has witnessed rapid expansion under initiatives like the Mission for Integrated Development of Horticulture (MIDH), which has encouraged greenhouse cultivation, polyhouse farming, and export-oriented production systems.

The demands of the modern flower industry have shifted from traditional uses in festivals, rituals, and decorations to more sophisticated requirements such as cut flowers with extended vase life, novel colors, fragrance enhancement, stress-tolerant varieties, and disease-resistant plants. Consumers increasingly seek value-added floral products such as essential oils, nutraceutical extracts, natural dyes, and eco-friendly packaging, widening the scope of floriculture from ornamentals to multifunctional crops with industrial applications.

However, the sector faces persistent challenges. Conventional breeding approaches are limited due to the long juvenile phase, high heterozygosity, and complex genetic background of many ornamental species. In addition, climate change, pest outbreaks, water scarcity, and soil degradation further threaten production and profitability. Post-harvest losses remain high due to inadequate cold-chain infrastructure and inefficiencies in supply chains. Thus, there is a strong need for innovative interventions that can accelerate breeding cycles, improve crop resilience, and integrate real-time management systems.

In this context, digital and biotechnological interventions have emerged as transformative solutions. Biotechnological tools such as genetic engineering, CRISPR/Cas-mediated genome editing, molecular marker-assisted breeding, and tissue culture offer unprecedented opportunities for trait enhancement and rapid multiplication. At the same time, digital technologies including artificial intelligence (AI), Internet of Things (IoT), smart sensors, and robotics are revolutionizing cultivation practices by enabling precision floriculture, resource efficiency, and quality monitoring. The convergence of these two domains is reshaping floriculture into a science-driven, technology-enabled industry that aligns with the global goals of sustainability, climate resilience, and economic competitiveness.

Research Methodology

This study adopts a systematic review approach to analyze and synthesize the existing body of literature on digital and biotechnological interventions in floriculture. The methodology followed includes the following steps:

1. Research Design

The review is qualitative in nature and follows a descriptive and analytical design, focusing on published research, policy documents, and case studies. The purpose was to integrate findings from biotechnology and digital agriculture to provide a holistic perspective on their applications in floriculture.

2. Data Sources

Relevant literature was collected from multiple primary and secondary databases, including:

- **Scientific databases**: Scopus, Web of Science, PubMed, AGRIS, CAB Abstracts
- **Journals**: *Scientia Horticulturae*, *Plant Biotechnology Journal*, *Floriculture and Ornamental Biotechnology*, *Frontiers in Plant Science*, *Journal of Horticultural Science & Biotechnology*
- **Official reports and policy documents**: FAO reports, ICAR publications, Government of India's Mission for Integrated Development of Horticulture (MIDH)
- **Books, theses, and conference proceedings** on horticulture, biotechnology, and digital agriculture

3. Inclusion and Exclusion Criteria

- **Inclusion**: Peer-reviewed articles, review papers, case studies, and reports published between **2000-2024**, focusing on genetic engineering, tissue culture, CRISPR, AI, IoT, robotics, and smart farming in floriculture.
- **Exclusion**: Articles not available in English, non-peer-reviewed blogs, and unrelated reports on general horticulture without ornamental crop focus.

4. Data Extraction and Analysis

- Extracted data on key themes such as genetic engineering, genome editing, marker-assisted breeding, tissue culture, AI applications, IoT, robotics, and smart greenhouses.
- Quantitative outcomes (e.g., % yield increase, % reduction in post-harvest loss, vase life extension) were documented where available.
- Qualitative synthesis involved identifying challenges, constraints, and policy perspectives across global and regional studies.

5. Review Framework

The findings were organized under the following thematic areas:

1. Biotechnological Interventions in Floriculture
2. Digital Interventions & Precision Floriculture
3. Integration of Digital and Biotech Approaches
4. Challenges & Constraints
5. Future Outlook and Recommendations

Biotechnological Interventions in Floriculture

Genetic Engineering & Transgenics

Genetic engineering has revolutionized the floriculture industry by enabling the direct transfer of desirable genes into ornamental plants. Several commercially viable transgenic flowers have been developed, the most notable examples being transgenic carnations and the famous blue roses. The blue rose (*Applause*™) created by Suntory (Japan) and Florigene (Australia) was developed through the insertion of the flavonoid 3',5'-hydroxylase gene to synthesize delphinidin-based pigments, marking a $30 million R&D success after two decades of research.

Similarly, transgenic petunias have been engineered to exhibit delayed senescence and extended vase life by incorporating the *etr1-1* gene, which suppresses ethylene sensitivity. Vase life was increased by 30-40% compared to conventional varieties.

Metabolic engineering targeting anthocyanins, carotenoids, and betalains has further expanded the natural flower color spectrum. For instance, overexpression of carotenoid biosynthesis genes in marigold and chrysanthemum led to up to 50% higher pigment accumulation, enhancing both ornamental and industrial (dye) value.

Gene Silencing & Editing

Beyond transgenics, gene silencing technologies such as RNA interference (RNAi), CRES-T (Chimeric Repressor Gene-Silencing Technology), and microRNA-mediated suppression have been widely applied in ornamentals such as chrysanthemum, petunia, and torenia.

RNAi-mediated suppression of the chalcone synthase gene in petunia resulted in stable white and variegated flowers, expanding design possibilities in ornamental breeding.

More recently, CRISPR/Cas9 genome editing has emerged as a powerful and precise tool. For example:

- Editing of DFR (dihydroflavonol-4-reductase) in petunia modified pigment pathways, producing novel flower shades.
- In orchids, CRISPR-mediated knockouts of ethylene biosynthesis genes extended flower longevity by 25-30%.

  CRISPR also offers regulatory advantages since many countries (e.g., USA, Japan, Argentina) classify site-directed mutagenesis without foreign DNA as non-GMO, commercialization may be faster compared to traditional transgenics.

Tissue Culture & Micropropagation

In vitro tissue culture remains the backbone of commercial floriculture biotechnology. It allows rapid, large-scale, and uniform propagation of elite hybrids and genetically engineered lines while maintaining genetic fidelity.

- Orchids dominate tissue culture markets, with Thailand producing over 50 million plantlets annually through micropropagation, contributing to nearly $90 million in exports.
- In India, the micropropagation of gerbera and carnation under protected cultivation has increased productivity by 20-25% compared to conventional propagation methods.
- Meristem culture has been widely used in roses and chrysanthemums to produce virus-free planting material, reducing disease incidence by up to 70% in commercial nurseries.

  Emerging bioreactor-based systems have further enhanced efficiency, reducing costs of micropropagated plantlets by 15-20% compared to traditional flask culture systems.

Marker-Assisted & Molecular Breeding

Molecular breeding has advanced considerably with the use of DNA markers (RAPD, AFLP, SSR, SNPs) to accelerate trait selection in ornamentals.

- SSR markers have been used to identify fragrance-related QTLs in roses, enabling early selection for high aroma cultivars.
- In chrysanthemum, marker-assisted selection has been employed for resistance to white rust (Puccinia horiana), cutting crop losses by nearly 40% in field trials.

  Recent advances in whole-genome sequencing (e.g., rose genome, 2018; chrysanthemum transcriptome, 2021) have provided breeders with valuable genomic databases, allowing candidate gene identification for traits such as stress tolerance, pigment biosynthesis, and vase life.

Enhancement of Floral Traits

Biotechnology has been pivotal in tailoring floral attributes for market-driven demands:

- **Fragrance**: Overexpression of the *BEAT* gene (benzyl alcohol acetyltransferase) in petunia increased emission of floral volatile compounds by 60%, enhancing consumer appeal.
- **Extended vase life**: Carnations transformed with anti-ethylene genes (*ACC oxidase suppression*) showed a two-fold increase in vase life, reducing post-harvest losses significantly.
- **Disease resistance**: Roses expressing chitinase and glucanase genes exhibited 70% reduced susceptibility to powdery mildew and black spot diseases.
- **Morphological modifications**: Biotechnology has introduced dwarfism, compact plant architecture, and altered flower forms. For instance, engineered compact petunias require 30% less space during cultivation and transportation, reducing logistics costs.

These advancements not only benefit consumers (with novel, longer-lasting, and higher-quality flowers) but also support growers and exporters by reducing costs, minimizing losses, and improving sustainability in the global floriculture supply chain.

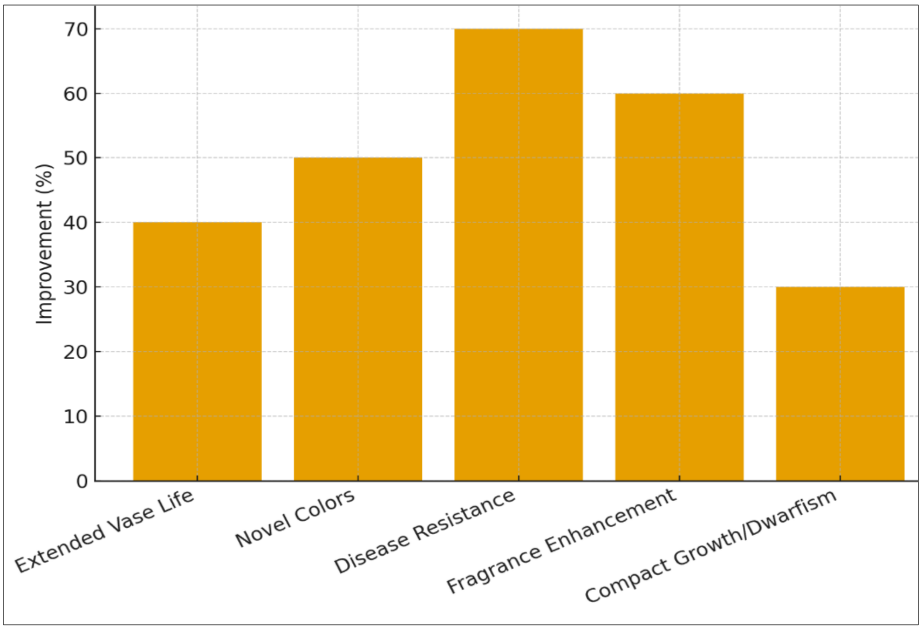

Fig 1: Impact of biotechnological Interventions in Floriculture

Digital Interventions & Precision Floriculture

Precision Agriculture & Automation

The adoption of precision agriculture technologies in floriculture has transformed traditional greenhouse and open-field flower cultivation into highly data-driven production systems. Smart irrigation systems using soil moisture sensors and automated fertigation units ensure optimal water and nutrient delivery, reducing input costs by up to 30-40% compared to conventional methods (FAO, 2022) [6]. Similarly, climate control systems equipped with temperature, humidity, and CO_2 sensors maintain ideal growth environments, leading to significant yield improvements in flowers such as roses and gerberas.

In India, studies have shown that automated polyhouse cultivation of roses increases flower yield by 20-25% while reducing pesticide usage by nearly 35%, contributing to sustainability and export competitiveness. Global market estimates suggest that the smart agriculture market in floriculture and ornamentals is projected to grow at a CAGR of 9-10% from 2023-2030, reflecting strong industry adoption.

AI, Imaging & Monitoring

Artificial intelligence (AI), machine learning (ML), and computer vision technologies are increasingly being integrated into floriculture for real-time crop monitoring and decision-making. Deep learning models trained on thousands of images can detect powdery mildew, botrytis, and nutrient deficiencies in ornamentals with over 90% accuracy, enabling early interventions and reducing crop losses.

For example:

- In greenhouse chrysanthemum production in the Netherlands, AI-based monitoring systems reduced disease-related losses by 18% while optimizing pesticide applications.
- Robotic platforms using image-guided navigation have been tested for automated harvesting of gerbera and rose flowers, reducing labor dependency by up to 40%.
- Digital imaging combined with IoT-based stress detection has improved flower grading and quality control, particularly in export-oriented crops like orchids, where uniformity is crucial.

Integration: Merging Digital & Biotech Approaches

The future of floriculture lies in the synergistic integration of digital and biotechnological interventions. For instance:

- **Smart Breeding Programs**: Bioengineered traits such as drought tolerance or novel pigments can be rapidly evaluated using digital phenotyping platforms that collect high-throughput data on growth, color, and morphology.
- **Robotics in Tissue Culture**: Robotic arms and AI-controlled systems are being tested to automate micropropagation and *in vitro* regeneration, significantly reducing labor costs and contamination risks.
- **Data-Driven Cultivation**: AI-based predictive models use sensor and genomic data to fine-tune nutrient and environmental regimes for genetically enhanced varieties, ensuring expression of desired traits.

A recent pilot project in Bangalore, India, combining CRISPR-modified marigold lines with IoT-enabled smart greenhouses, demonstrated 25% higher carotenoid yield compared to conventional cultivation, highlighting the transformative potential of this convergence.

Challenges & Constraints

Despite the enormous potential of digital and biotechnological interventions, several challenges continue to limit their large-scale adoption in floriculture:

1. Regulatory Barriers for GM Ornamentals

The commercialization of genetically modified (GM) ornamental crops faces strict biosafety regulations and consumer skepticism. For example, the “blue rose” (Applause™) developed by Suntory in Japan took over 20 years of R&D and nearly $30 million investment before it was approved and released in 2009. Even today, only a handful of countries allow marketing of transgenic ornamentals due to bioethical concerns and import restrictions.

2. High Cost of Digital Infrastructure

Advanced tools such as AI-driven imaging systems, IoT-based greenhouse automation, and robotics involve capital investments ranging from $10,000 to $50,000 per hectare of protected cultivation. This makes them accessible primarily to large-scale commercial growers, while over 70% of floriculturists in India are smallholders cultivating less than 1 hectare.

3. Lack of Skilled Workforce

Integration of digital technologies with biotech approaches requires multidisciplinary expertise in plant sciences, data analytics, robotics, and bioinformatics. Surveys in the Netherlands and India highlight that over 60% of floriculture enterprises report a shortage of trained personnel capable of operating and maintaining smart farming systems.

4. Adoption Barriers in Developing Regions

In low- and middle-income countries, infrastructural gaps such as unreliable electricity, weak internet connectivity, and inadequate cold-chain logistics further constrain technology adoption. Post-harvest losses in flowers remain as high as 25-30% in India compared to 8-10% in advanced economies, largely due to poor supply chain integration.

Conclusion

Digital and biotechnological interventions are no longer emerging trends but have become central pillars in the transformation of the global floriculture industry. Biotechnology, through tools such as genetic engineering, CRISPR/Cas9 genome editing, molecular breeding, and tissue culture, has unlocked the possibility of creating flowers with novel colors, enhanced fragrance, longer vase life, disease resistance, and stress tolerance. These interventions shorten breeding cycles, conserve valuable germplasm, and generate elite cultivars that meet the evolving demands of both domestic and international markets.

On the other hand, digital technologies including AI-driven monitoring, IoT-enabled smart greenhouses, sensor networks, robotics, and big data analytics are redefining how flowers are cultivated, managed, and marketed. They bring precision, efficiency, and scalability, optimizing resource use, minimizing environmental impact, and ensuring high-quality standards in production and post-harvest handling.

Most importantly, the integration of biotechnology and digital agriculture offers a synergistic pathway toward sustainable floriculture. Smart phenotyping systems can accelerate the evaluation of genetically enhanced varieties, while robotics can automate tissue culture and propagation. Data-driven cultivation strategies tailored to bioengineered traits will allow growers to maximize yield and quality with minimal inputs.

However, the true impact of these innovations will depend on equitable access, supportive policies, and capacity building among growers, particularly in developing countries where resource constraints remain significant. If these barriers are addressed, the combined power of biotechnology and digital tools can establish floriculture as not only a profitable industry but also a driver of sustainable development, contributing to global goals of food security, rural employment, and environmental resilience.

Thus, the future of floriculture lies in embracing science-led, technology-enabled solutions, positioning the sector as a globally competitive, innovation-driven, and ecologically responsible industry.

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