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Floriculture under climate change: Modelling impact, adaptive strategies and global trends

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Abstract

Floriculture, a rapidly growing sector of horticulture, faces significant challenges in the face of climate change. Rising temperatures, altered precipitation patterns, elevated CO_2, and increased frequency of extreme weather events are already influencing flower production, quality, and trade dynamics. This review synthesises current knowledge on the impact of climate change on floriculture, integrating insights from crop modelling, experimental studies, and industry reports. It discusses species-specific responses, modelling approaches used to project climate impacts, and adaptive strategies ranging from cultivar selection and protected cultivation to technological innovations such as precision agriculture and AI-driven forecasting. Special attention is given to socio-economic and trade implications, as floriculture is increasingly globalised and sensitive to shifting climate zones. Case studies from major floriculture hubs, including India, the Netherlands, Kenya, and Colombia, highlight regional adaptations and policy frameworks. The review also identifies critical research gaps, such as integrating climate modelling with genetic improvement, assessing ecosystem services of ornamental plants, and designing sustainable supply chains. By combining ecological, agronomic, and economic perspectives, the article aims to provide a roadmap for future research and policy interventions to ensure resilience and sustainability of the floriculture sector under climate change.

Keywords: Floriculture, climate change, crop modelling, adaptive strategies, global trade trends

1. Introduction

1.1 Definition and Scope of Floriculture

Floriculture is a specialised branch of horticulture that focuses on the cultivation of flowering and ornamental plants for use in gardens, landscaping, and the commercial cut-flower industry [1, 2]. It includes a wide range of crops such as roses, chrysanthemums, carnations, orchids, lilies, tulips, gladiolus, gerbera, and numerous foliage plants [3, 4]. Beyond field production, floriculture also encompasses greenhouse cultivation, protected environments, tissue culture propagation, and advanced post-harvest handling systems. It is distinct from food and industrial crops in its emphasis on aesthetic, cultural, and recreational value, but it shares similar vulnerabilities to climate change [5, 6]. The sector operates at the intersection of agriculture and trade. It significantly contributes to livelihoods, especially in developing countries, and forms a cornerstone of the global ornamental industry, which is closely tied to consumer preferences, festivals, and international markets [7, 8].

1.2 Historical Development of the Global Floriculture Industry

Floriculture has evolved from localised, culturally embedded practices to a highly globalised sector. Historically, ornamental plants were cultivated for religious rituals, social symbolism, and aesthetic purposes. Ancient civilisations, including the Egyptians, Greeks, and Chinese, domesticated flowers for cultural and medicinal uses [9, 10].

During the twentieth century, floriculture transformed into a commercial enterprise with the development of greenhouse technologies, cold storage, and long-distance transportation systems. The Netherlands emerged as a global hub due to innovations in greenhouse cultivation and auction-based flower trading, laying the foundation for international floriculture markets [11, 12].

In recent decades, production has increasingly shifted to tropical and subtropical countries such as Kenya, Ethiopia, Colombia, and India, where favourable climates and lower labour costs make production more competitive.

This transition reflects both market forces and climate suitability, underscoring the intimate link between climate and the geographical distribution of floriculture [13, 14].

1.3 Current Market Size, Value Chains, and Export-Import Dynamics

The global floriculture market is valued at USD 50-60 billion annually, with steady growth driven by rising incomes, urbanisation, and increasing demand for ornamental plants in both developed and emerging economies. The cut-flower segment accounts for the largest share, followed by potted plants, bulbs, seeds, and nursery crops [9, 10].

The value chain encompasses multiple stages, including production, post-harvest handling, cold chain logistics, auction systems, retail, and consumption. Highly integrated markets such as the European Union dominate imports, while production is concentrated in climate-favoured regions [11, 12].

- The Netherlands remains the nerve centre of global trade through the Royal FloraHolland auction system [11].
- Kenya and Ethiopia supply roses and carnations primarily to Europe [12, 13].
- Colombia and Ecuador export flowers, especially roses, to North America [14, 15].
- India, China, and Vietnam are rapidly expanding in domestic and regional markets [16, 17].

This globalisation of floriculture highlights its sensitivity to international trade policies, phytosanitary measures, and environmental changes, making it highly exposed to climate disruptions [11, 12].

1.4 Cultural, Social, and Economic Significance of Ornamental Plants

Flowers and ornamental plants hold unique positions in human society. They are symbols of celebration, mourning, and ritual across cultures. Ornamental landscapes enhance urban environments by improving aesthetics, reducing stress, and contributing to a sense of cultural identity [13, 14].

From an economic perspective, floriculture generates employment for millions of smallholders, women, and rural youth. In many low-and middle-income countries, floriculture is a high-value export crop that contributes to foreign exchange earnings and rural development. For example, in Kenya, the flower industry employs over 200,000 workers directly and supports more than one million livelihoods indirectly [12, 13].

The sector also provides ecosystem services, such as pollinator support, biodiversity enhancement in urban areas, and psychological benefits to human well-being. These roles expand their importance beyond market value, making their sustainability under climate change a matter of broad concern [14, 15].

1.5 Overview of Climate Change as a Cross-Cutting Challenge in Horticulture

The Intergovernmental Panel on Climate Change (IPCC) reports that average global temperatures have risen by approximately 1.1 °C since pre-industrial levels, with substantial regional variability [14, 15]. For horticulture, including floriculture, climate change manifests through:

- Rising mean and extreme temperatures.
- Altered rainfall distribution and increased frequency of droughts and floods.
- Elevated atmospheric CO_2 concentrations.
- Greater frequency of extreme weather events (storms, heatwaves, frost).
- Shifts in pest and disease pressure.

These drivers directly affect plant growth, phenology, flower initiation, and post-harvest quality. For floriculture, which depends on precise quality attributes (colour, shape, fragrance, vase life), even subtle deviations in climate can compromise marketability. Unlike food crops, ornamental crops cannot be substituted by imports in terms of consumer preference for particular varieties, making them highly sensitive to local production conditions [17, 18].

1.6 Objectives and Scope of this Review

Given the increasing evidence of climate-related risks to floriculture, there is an urgent need to synthesise existing knowledge and provide a roadmap for adaptation [17, 18]. The objectives of this review are to:

1. Synthesise current knowledge on how climate change affects floriculture, including crop physiology, production systems, and quality outcomes [19, 20].
2. Evaluate modelling approaches used to project climate impacts and identify their limitations in ornamental crop contexts [21, 22].
3. Assess adaptive strategies spanning genetics, agronomy, technology, and socio-economic policy [23, 24].
4. Identify global trends in floriculture under climate change, including shifts in production zones, trade patterns, and consumer preferences [19, 20].
5. Highlight research gaps and propose directions for the sustainable development of the floriculture sector [21, 22].

The review integrates perspectives from agronomy, climatology, plant physiology, economics, and policy to provide a comprehensive understanding of the challenges and opportunities facing global floriculture in the Anthropocene [11, 12].

2. Climate Change and Floriculture: Theoretical Framework

2.1 Key Climate Variables Influencing Floriculture

Temperature is one of the most important climatic factors shaping the growth and flowering of ornamental crops. Each species has a narrow optimal range, and even slight deviations can disrupt its physiological processes. Roses grow best between 18 and 28 °C, while exposure to temperatures above 32 °C results in smaller buds and faded colours. Tulips and other bulbous crops require chilling to initiate flowering, a process that warming winters increasingly compromise. Orchids are particularly vulnerable because they tolerate only narrow thermal windows, with heat spells leading to poor flower spike development [1, 13].

Changes in rainfall patterns and water availability further intensify climate risks. Both drought and excess water affect the size, stalk strength, and vase life of flowers. Rain-fed systems, such as marigold cultivation in India, are vulnerable to erratic monsoons, while commercial rose production in Kenya faces increasing irrigation costs as drought frequency increases. In regions dependent on

groundwater, these changes also pose long-term threats to sustainability [14, 15].
The rise in atmospheric carbon dioxide adds another layer of complexity. Although elevated CO_2 can stimulate photosynthesis and increase vegetative growth, the benefits do not necessarily extend to floral traits. Chrysanthemums, for instance, often produce more leaf biomass under high CO_2 without corresponding improvements in inflorescence quality. Altered carbon allocation between vegetative and reproductive organs, as well as increased night respiration, reduces the net positive effects of enrichment [17, 18].
Humidity, light intensity, and photoperiod shifts also affect ornamental crops. High relative humidity encourages fungal diseases such as powdery mildew in roses and botrytis in carnations, while changes in light intensity alter photoperiodic responses. Crops such as chrysanthemums and poinsettias depend on precise daylength cues, and shifts in cloud cover and solar radiation complicate the scheduling of harvests for festivals and export markets [19, 20].

2.2 Plant Physiological and Phenological Responses
Flower induction and blooming cycles in floriculture species are susceptible to temperature, light, and hormonal regulation. Climate variability disrupts these signals, leading to delayed or asynchronous flowering, shortened developmental phases, and smaller flowers. Such irregularities reduce market uniformity and compromise consumer satisfaction [21, 22].
The balance between photosynthesis and respiration is another critical factor. Higher atmospheric CO_2 may enhance photosynthetic activity, but warming accelerates respiration, particularly at night. This imbalance reduces the carbon available for flower development and limits the biosynthesis of pigments and fragrance compounds that define ornamental quality [21, 22].
Water stress exerts additional physiological pressures [11, 12]. Drought conditions typically lead to smaller flowers, premature senescence, and loss of turgor, while heat stress exacerbates transpiration. In protected cultivation systems, evaporative cooling and irrigation demand rise sharply in response to climate stress, thereby increasing production costs. At the biochemical level, abiotic stress triggers the accumulation of reactive oxygen species and stress proteins. These changes interfere with pigment formation and fragrance pathways, leading to duller colours and weaker scents [13, 14].

2.3 Comparative Vulnerability of Floriculture and Food Crops
Compared with food crops, floriculture species display unique vulnerabilities. The thresholds for acceptable quality are much narrower. Minor deviations in size, colour, or freshness render flowers unsellable, whereas food crops may tolerate greater variability before being rejected by consumers [11, 12]. Floriculture demand is also closely tied to specific occasions, such as weddings, religious rituals, and global holidays like Valentine's Day or Mother's Day. Disruption in flowering times during these events results in direct financial losses. Post-harvest sensitivity compounds these challenges because cut flowers deteriorate rapidly under high temperatures and transport delays. Unlike staple foods that can often be substituted across origins, consumer preference for specific flower varieties and cultural symbolism restricts flexibility [13, 15]. As a result, the floriculture sector is disproportionately exposed to the risks of climate variability [16, 22].

2.4 Conceptual Framework Linking Climate Drivers with Floriculture Outcomes
A conceptual framework for understanding climate change in floriculture begins with the primary drivers, including shifts in temperature, rainfall, CO_2, humidity, and the frequency of extreme weather events. These drivers act upon the crop system, producing physiological, morphological, and pathological responses. At the crop level, they influence processes such as photosynthesis, respiration, and floral initiation. At the product level, they alter flower size, stalk strength, colour, fragrance, and vase life. They also shape pest and disease dynamics, increasing the prevalence of new pathogens and insect outbreaks [23, 24].
The consequences extend beyond plant biology. Farmers and producers are compelled to adapt through irrigation management, greenhouse modification, and chemical interventions, which increase production costs. At the socio-economic level, these changes influence market availability, price stability, and the competitiveness of export-oriented supply chains. Employment, rural livelihoods, and the resilience of smallholders are also affected. This framework underscores the multidimensional nature of climate change impacts, where biological processes intersect with trade and livelihood outcomes [25, 26].

2.5 Lessons from Other Horticultural Systems
Although ornamental crops have been less studied than food crops, lessons from horticultural research provide helpful analogies. In viticulture, rising temperatures have advanced harvest dates and altered grape flavour profiles, a phenomenon that parallels changes in colour and fragrance in floriculture. In apple orchards, the decline in winter chilling hours is similar to the loss of vernalization in tulips and lilies [23, 24]. Vegetable crops have shown increased pest pressure under warming scenarios, offering insight into disease management challenges for flowers. Such comparisons suggest that cross-disciplinary approaches could accelerate adaptation in floriculture, particularly where direct data remain limited [25, 26].

3. Modelling Climate Change Impacts on Floriculture
3.1 Importance of Modelling for Decision Support
Climate change affects floriculture in ways that are highly localised, crop-specific, and often nonlinear. Direct experimentation provides valuable insights, but it is limited by time, cost, and the inability to replicate long-term climatic variability [21, 22]. Modelling, therefore, becomes indispensable for understanding the likely trajectory of climate impacts on ornamental plants. Models allow the simulation of temperature, rainfall, and CO_2 scenarios, helping growers, breeders, and policymakers anticipate risks and design adaptive strategies. In floriculture, where precise flowering times and quality standards determine market value, models provide tools to forecast production cycles, optimise greenhouse operations, and predict regional suitability under future climate conditions [23, 24].

3.2 Process-Based Crop Models
Process-based models simulate plant growth and development by linking environmental variables with physiological processes. Widely used platforms such as

DSSAT (Decision Support System for Agrotechnology Transfer) and APSIM (Agricultural Production Systems Simulator) were initially developed for food crops. Still, they have been adapted for use with ornamental species in experimental contexts. These models rely on physiological parameters, including photosynthetic rates, respiration, transpiration, and phenological stages, to predict yield and quality outcomes [26, 27].

In floriculture, the application of process-based models faces unique challenges. Many ornamental crops have poorly documented physiological data, and the traits of interest differ significantly from those of food crops. For roses or chrysanthemums, the primary concern is not yield in terms of biomass, but flower size, petal number, fragrance, and vase life [21, 22]. Translating these traits into model parameters requires interdisciplinary calibration between plant physiology and ornamental quality assessment. Nevertheless, process-based models remain powerful because they can integrate climate variables with management practices such as irrigation, shading, and CO_2 enrichment [23, 24].

3.3 Statistical and Machine Learning Approaches

Statistical models provide another avenue for linking climate data with floriculture performance. Regression models have been used to predict flowering times in chrysanthemums based on accumulated growing degree days. Time-series models combining temperature, light intensity, and humidity have been employed to forecast cut rose production in controlled environments [25, 26].

More recently, machine learning approaches have advanced predictive capabilities. Algorithms such as random forests, support vector machines, and neural networks have been applied to greenhouse floriculture to predict growth rates, flower induction, and pest outbreaks. These models require large datasets, which are often generated through greenhouse monitoring systems equipped with sensors. Machine learning is beneficial for identifying complex interactions between variables, such as the combined effect of heat stress and photoperiod on flowering synchrony. The key limitation is the need for extensive training data, which are still scarce for many ornamental crops [27, 28].

3.4 Species Distribution and Ecological Niche Models

Beyond controlled cultivation, floriculture also relies on open-field systems and geographically specific production zones. Species distribution models, also known as ecological niche models, are widely used to project the suitability of crops under climate change. These models correlate current species distributions with climatic variables to predict future geographic ranges under different emissions scenarios [29, 30].

For floriculture, ecological niche modelling has been applied to crops such as orchids, lilies, and tulips. Results indicate potential shifts in suitable zones toward higher latitudes and altitudes, as warming makes traditional production areas less viable [31, 32]. For example, the vernalization requirements of tulip bulbs may not be met in parts of the Netherlands by mid-century, potentially shifting large-scale production to cooler northern regions. Similarly, specific orchids that have adapted to narrow humidity and temperature ranges may lose their habitat in tropical lowlands, with cultivation shifting toward controlled environments or upland areas. These models highlight the vulnerability of floriculture to geographic displacement, with implications for trade and livelihoods [33, 34].

3.5 Case Studies of Model Applications

Several case studies illustrate the potential and limitations of modelling in floriculture. In roses, simulation models have been utilised to investigate responses to elevated CO_2 and high temperatures. Results suggest that while vegetative growth may increase, high night temperatures significantly reduce bud formation and shorten vase life, leading to lower market acceptability. In chrysanthemums, models that integrate photoperiod and temperature data have been developed to predict flowering times under different climate scenarios. These tools help growers align harvests with peak demand seasons, such as international holidays [21, 22].

Tulip cultivation has provided another example where modelling offers critical insights. Vernalization models simulate the number of chilling hours required for uniform flowering. Under warming winters, these models predict a decline in successful bulb flowering in traditional Dutch production zones, suggesting that without adaptive strategies, tulip production will shift geographically or require artificial cold storage. Orchids, which depend on precise humidity and temperature regulation, have been modelled in greenhouse environments using machine learning algorithms that combine climatic variables with growth data. These models improve resource efficiency by forecasting optimal irrigation and shading requirements [23, 24].

3.6 Challenges and Limitations in Modelling Ornamental Crops

Despite these advances, modelling in floriculture faces significant limitations. The first challenge is data scarcity. Unlike cereals or staple horticultural crops, ornamental plants lack long-term experimental datasets on physiology, phenology, and stress responses. This gap limits the calibration of process-based models and constrains the accuracy of predictions [21, 22].

A second challenge lies in the unique quality traits of flowers. Attributes such as colour intensity, petal number, fragrance, and vase life are difficult to quantify within existing model frameworks. While yield in food crops can be expressed in kilograms per hectare, ornamental quality is subjective and market-dependent. Incorporating these variables into mechanistic or statistical models requires the development of new indices and measurement protocols [21, 22].

Third, most existing models treat climate drivers in isolation. In reality, ornamental crops face combined stresses such as high temperature with drought, or elevated CO_2 with increased disease pressure. Capturing these interactions remains difficult. Machine learning offers some promise, but again depends on large, high-quality datasets [23, 24].

Finally, floriculture is highly globalised, and models rarely incorporate trade and supply chain dynamics. Predicting crop suitability without accounting for market access and transportation constraints provides only a partial picture of climate impacts [25, 26].

3.7 Future Perspectives in Integrated Modelling

The future of modelling climate impacts on floriculture lies in integration. Hybrid models that combine process-based simulations with machine learning algorithms can capture both physiological mechanisms and data-driven patterns. Linking species distribution models with trade and logistics data would allow prediction not only of production shifts but also of market realignments. Advances in genomics can further enhance modelling by incorporating genetic information into projections of climate resilience [27, 28].

The expansion of sensor networks, remote sensing, and Internet of Things (IoT) technologies in greenhouses will generate large datasets that can be harnessed to refine models. Cloud-based platforms may enable real-time decision support for growers, integrating weather forecasts with crop simulations. In addition, collaborative modelling initiatives that bring together climatologists, plant physiologists, economists, and industry stakeholders are essential to ensure that projections are both scientifically robust and practically relevant [29, 30].

4. Observed and Projected Impacts of Climate Change on Floriculture

4.1 Regional Evidence of Climate Impacts

Floriculture is one of the most globalised horticultural sectors, with production concentrated in a few key regions and exports flowing primarily to Europe, North America, and Asia. Observed climate impacts are already evident in these production hubs. In the Netherlands, which serves as the world's centre for greenhouse floriculture, rising energy costs linked to heating and cooling have intensified due to warmer summers and erratic winters. Episodes of heat stress within greenhouses are becoming more frequent, resulting in an increased reliance on cooling systems and, consequently, higher carbon footprints [30, 31].

In East Africa, particularly in Kenya and Ethiopia, which together supply nearly half of Europe's cut roses, recurrent droughts and irregular rainfall patterns have disrupted irrigation regimes. Growers situated around Lake Naivasha in Kenya face declining water levels, raising concerns over both sustainability and community conflicts over shared resources. Ethiopia's highland floriculture zones, while still climatically favourable, are experiencing shifting pest and disease pressures under warming scenarios [32, 33].

India presents another illustrative case. The country's diverse agro-climatic zones enable both open-field and protected floriculture [33, 34]. However, erratic monsoons, unseasonal rainfall, and rising summer heat have already reduced yields of marigold, jasmine, and rose. Smallholder farmers, who dominate Indian floriculture, are particularly vulnerable because they lack the capital to invest in climate-controlled infrastructure. In the Andean countries of Colombia and Ecuador, where floriculture is a leading export sector, climate change manifests primarily through increased rainfall variability and higher risks of fungal diseases in cut roses destined for the United States market [34, 36].

4.2 Crop Growth and Flowering Impacts

At the physiological level, climate change disrupts flowering cycles and vegetative growth. Elevated temperatures often accelerate phenological development, resulting in shorter flowering periods. In roses, warmer night temperatures reduce bud initiation and diminish the number of flowers per plant. In chrysanthemums, the interaction between changes in temperature and day length results in uneven flowering, complicating the scheduling of harvests that must align with global demand peaks [32, 33].

Bulbous crops such as tulips, hyacinths, and lilies are susceptible to warming winters. Insufficient chilling during dormancy reduces the uniformity of flowering and shortens stems, traits that severely reduce their value in international markets. In orchids, which depend on exact temperature and humidity ranges, warming leads to disrupted spike formation, resulting in fewer marketable plants. These physiological shifts collectively reduce both the volume and quality of floral output, with direct consequences for grower profitability [34, 35].

4.3 Flower Quality and Marketability

Unlike food crops, the market success of floriculture products depends almost entirely on quality attributes such as flower size, petal colour intensity, fragrance, stalk length, and vase life. Climate change undermines these traits in multiple ways. High temperatures often result in smaller flowers with faded pigmentation, due to disrupted anthocyanin biosynthesis [35, 36]. Increased respiration reduces the accumulation of fragrance compounds, leading to weaker scents in roses and lilies. Shorter stalks under heat stress reduce the suitability of flowers for the cut-flower trade, where uniformity of stem length is a significant requirement [37, 38].

Vase life, a critical determinant of consumer satisfaction, is also reduced under climate stress. Flowers harvested during heatwaves exhibit higher rates of water loss and wilting, even under cold-chain transport conditions [35, 36]. For exporters, this results in greater rejection rates at auctions and increased post-harvest losses. These quality-related disruptions are projected to intensify under warming and irregular climatic conditions, raising concerns over the future competitiveness of traditional floriculture hubs [22, 25].

4.4 Pest and Disease Dynamics

Climate change influences not only plant physiology but also the prevalence of pests and diseases. Warmer and more humid conditions favour the proliferation of fungal pathogens such as botrytis in carnations and powdery mildew in roses. Viral and bacterial diseases are also expanding into regions where they were previously absent. In East Africa, vector populations, such as thrips and aphids, have increased under warming conditions, thereby heightening the risk of viral disease transmission [26, 27].

In controlled environments, such as Dutch greenhouses, elevated humidity and insufficient ventilation during warmer summers increase the incidence of botrytis blight. Growers respond by applying higher levels of fungicides, which increases both production costs and environmental footprints. Projected climate scenarios indicate that pest and disease pressure will continue to intensify, necessitating a shift toward integrated pest management and the development of resistant cultivars [29, 30].

4.5 Trade and Supply Chain Vulnerabilities

Floriculture is highly dependent on international trade and fast logistics. Climate change introduces vulnerabilities at multiple points along the supply chain. Extreme weather events such as floods, storms, and heatwaves disrupt transportation infrastructure and delay shipments. Even short delays can render cut flowers unsellable due to their short shelf life [31, 32].

In the Netherlands, record heatwaves in recent years have strained cold-chain logistics and forced airports to modify handling procedures. In Kenya, drought-driven water scarcity has increased production costs, eroding competitiveness in European markets. Colombian exports to North America face rising phytosanitary risks as climate-driven pests and diseases raise concerns over compliance with import regulations [12, 13].

Price volatility is another emerging issue. As climate variability reduces supply consistency, auction prices fluctuate sharply. Consumers in importing countries face higher retail prices, while producers in exporting countries struggle with uncertain income. These supply chain disruptions demonstrate that climate change impacts on floriculture extend far beyond the field or greenhouse and directly affect global trade stability [21, 22].

4.6 Projected Impacts under Future Climate Scenarios

Climate modelling studies project that many floriculture crops will face significant geographic shifts in suitability. Under high-emission scenarios, traditional production regions such as the Dutch tulip belt may become less viable by mid-century due to insufficient winter chilling [33, 35]. In East Africa, rising mean temperatures, combined with recurrent droughts, are expected to constrain open-field rose cultivation, forcing growers to invest heavily in irrigation or relocate production to higher altitudes.

For tropical orchids, projections indicate habitat loss in lowland regions as suitable temperature-humidity niches become increasingly scarce. Protected cultivation may offset some risks, but energy and resource costs are expected to rise substantially. Global circulation models suggest that suitable zones for temperate ornamentals may shift poleward, opening opportunities for new production hubs in northern latitudes. However, such shifts would disrupt existing trade flows and labour markets, with significant socio-economic implications [37, 38].

5. Adaptive Strategies in Floriculture

5.1 Genetic and Breeding Approaches

Breeding for climate resilience in ornamental crops is a relatively underexplored area compared with cereals and vegetables. Nevertheless, genetic adaptation offers one of the most sustainable long-term strategies. Conventional breeding has been employed to enhance tolerance to abiotic stresses, including heat, drought, and salinity, in selected ornamentals. For example, breeding programs in roses and chrysanthemums have identified cultivars that maintain flower size and colour under high-temperature regimes [39, 40].

The use of wild relatives is an emerging strategy. Many ornamental crops have wild progenitors that harbour genes for stress tolerance. Incorporating these traits through wide crosses can broaden the adaptive base of cultivated varieties. However, ornamental breeding faces the challenge of simultaneously preserving desirable quality traits such as fragrance, petal form, and colour intensity while introducing resilience. Unlike food crops, where yield is the dominant target, ornamentals demand a balance between resilience and aesthetic appeal [41, 42].

Molecular breeding and genomics-assisted selection are opening new opportunities. Advances in marker-assisted breeding, quantitative trait locus (QTL) mapping, and transcriptomics provide valuable tools for identifying stress-related genes and accelerating breeding cycles. Transcriptome studies in orchids, for instance, have revealed gene families associated with heat shock proteins and drought tolerance, which could be targeted in breeding programs [42, 43].

Recent developments in genome editing technologies, particularly CRISPR/Cas systems, have the potential to transform ornamental breeding. Editing genes related to flowering time, pigment biosynthesis, and stress tolerance could enable the rapid creation of resilient cultivars. Research in petunia and chrysanthemum has already demonstrated proof of concept for editing pigment-related genes, suggesting that similar strategies could be extended to climate resilience traits. The integration of genomics with phenotyping platforms will be critical for scaling such innovations [44, 45].

5.2 Agronomic and Management Practices

While genetic improvements take time, agronomic interventions can provide immediate adaptation. Protected cultivation has emerged as a cornerstone strategy in both developed and developing countries. Greenhouses, polyhouses, and shade nets buffer crops against temperature extremes, rainfall irregularities, and excessive radiation. In the Netherlands, advanced greenhouse systems integrate climate control with energy efficiency, while in India and East Africa, low-cost polyhouses are increasingly promoted to shield roses, gerberas, and carnations from climatic variability [45, 46].

Microclimate management within controlled structures has become increasingly sophisticated. Techniques such as evaporative cooling, thermal screens, and fogging systems help regulate temperature and humidity. In warmer climates, shading and ventilation are essential to prevent heat stress, while in temperate zones, heating systems ensure sufficient thermal conditions for winter-flowering crops. These adjustments, however, come with higher energy requirements, underscoring the need for the integration of renewable energy [47, 48].

Soil and water management are equally crucial. Climate change has intensified the importance of efficient irrigation and fertigation. Drip irrigation, combined with automated scheduling based on soil moisture sensors, reduces water wastage and ensures a consistent supply during droughts. Fertigation systems enable precise nutrient delivery, thereby mitigating the risk of leaching during irregular rainfall. In Kenya, rose farms around Lake Naivasha have adopted advanced irrigation scheduling to optimise water use, balancing productivity with ecosystem sustainability [49, 50].

Integrated pest and disease management (IPM) provides another essential agronomic adaptation. Climate change intensifies pest pressure, making reliance on chemical pesticides both costly and unsustainable. IPM strategies that combine resistant cultivars, biological control agents, and environmentally friendly chemical options offer long-term resilience. For example, predatory mites are increasingly used in European greenhouses to control thrips, reducing pesticide dependence under changing climate conditions [51, 52].

5.3 Technological Innovations

The rapid digital transformation of agriculture is also reaching floriculture. Precision agriculture technologies, enabled by sensors, artificial intelligence, and data analytics, are revolutionising climate adaptation. IoT-based sensor networks measure temperature, humidity, soil moisture, and CO_2 in real time, providing growers with data-driven insights to optimise climate control. Machine learning algorithms can predict flowering times, water requirements, and disease outbreaks based on climatic inputs, enabling proactive management [52, 53].

Controlled environment agriculture (CEA) is gaining attention for floriculture, particularly in regions where outdoor production is becoming less viable. Vertical farming approaches, already established in leafy vegetable production, are being tested for ornamentals such as potted foliage plants and speciality flowers. While challenges remain in scaling to cut flowers, these systems offer insulation from climatic variability [54, 55].

Renewable energy integration is a vital technological frontier. Solar-powered irrigation systems, geothermal heating for greenhouses, and biomass-based energy systems reduce reliance on fossil fuels while lowering production costs. In the Netherlands, research into closed greenhouse systems powered by geothermal energy has shown promise in reducing carbon footprints while maintaining high-quality output [55, 50].

Another innovation is the use of decision support systems (DSS) that integrate weather forecasts with crop simulation models. Such platforms provide growers with tailored recommendations on irrigation scheduling, harvest timing, and pest control. Cloud-based DSS can also be linked to global climate projections, providing exporters with long-term planning tools [41, 42].

5.4 Socio-Economic and Policy Strategies

Adaptation to climate change in floriculture cannot be addressed solely through genetic or technological means. Socio-economic and institutional strategies play an equally critical role. Farmer training and capacity building are fundamental, particularly in developing countries where smallholders dominate production. Extension services must provide updated knowledge on climate-smart practices, greenhouse management, and water-efficient technologies [44, 47].

Financial tools such as crop insurance and credit support are necessary to mitigate risks. Given the high perishability of flowers, even brief disruptions in climate-sensitive supply chains can result in significant losses. Insurance schemes tailored to ornamental crops, though limited, are beginning to emerge. For example, some Kenyan rose farms participate in climate-indexed insurance schemes that compensate growers for losses during droughts [48, 49].

Producer organisations and cooperatives enhance resilience by pooling resources and improving bargaining power in markets. They also facilitate shared investment in infrastructure such as cold chains and irrigation systems. At the policy level, governments need to incentivise sustainable floriculture practices through subsidies for the adoption of renewable energy, water-efficient technologies, and organic certification systems. International certification schemes, including Fairtrade and carbon-neutral labels for flowers, are gaining prominence as consumer demand for environmentally responsible products increases [50, 51].

Trade policies also require attention. As climate change shifts production zones, international regulations governing imports and exports will need to accommodate new realities. Ensuring compliance with phytosanitary standards in response to changing pest and disease regimes will be essential to maintain market access. Policymakers must also consider mechanisms to protect the livelihoods of workers in regions where floriculture may decline due to climate unsuitability [53, 54].

5.5 Integrated Approaches to Adaptation

While each adaptive strategy offers benefits, its true potential lies in integration. Genetic improvement must be combined with agronomic practices, technological innovations, and supportive policies to create resilient floriculture systems. For instance, the development of heat-tolerant rose varieties achieves maximum impact when grown in climate-controlled polyhouses equipped with smart irrigation and supported by insurance schemes that reduce financial risks. Similarly, vertical farming systems for ornamentals will require integration with renewable energy policies and market incentives for sustainably grown flowers [55, 56].

Integrated approaches also extend to research collaborations. Multi-disciplinary platforms that unite plant scientists, climatologists, economists, and industry stakeholders can bridge knowledge gaps and accelerate innovation. International networks, similar to those established for staple food crops, are urgently needed in floriculture to coordinate research on stress physiology, genetic improvement, and socio-economic adaptation [53, 57].

6. Global Trends in Floriculture under Climate Change

6.1 Shifts in Floriculture Production Zones

One of the most visible consequences of climate change is the shifting geography of floriculture production. As mean annual temperatures rise and rainfall patterns change, traditional production regions are experiencing reduced suitability, while new zones are emerging. In the Netherlands, warming winters pose a threat to the long-term viability of bulb crops, such as tulips and hyacinths, which require extended periods of chilling for uniform flowering. Projections suggest that by mid-century, these crops may need to be cultivated further north or subjected to artificial cold storage, which would raise production costs [11, 12].

In East Africa, where Kenya and Ethiopia dominate global rose exports, the increasing frequency of droughts and higher irrigation demands are reshaping production strategies. Some farms are relocating to higher altitudes where cooler temperatures provide more stable growing conditions. In India, producers are increasingly adopting protected cultivation to offset the risks of erratic monsoons and summer heat, while highland states such as Himachal Pradesh and Uttarakhand are gaining prominence as alternative production zones for temperate ornamentals [13, 17].

In Latin America, Colombia and Ecuador remain major players in rose production for the North American market, but higher rainfall variability is driving investments in disease management and greenhouse technologies. Meanwhile, climate warming opens opportunities in new regions. Northern Europe, Canada, and parts of Central Asia may become suitable for crops that were previously limited to milder climates. These shifts indicate that climate change will not only challenge existing producers but also redistribute global comparative advantages [24, 29].

6.2 Market and Consumer Preference Shifts

Climate change is also influencing consumer demand, both directly and indirectly. Rising awareness of environmental issues has fostered a preference for flowers produced with lower carbon and water footprints. Eco-labelled and sustainably certified flowers are gaining market share in Europe and North America. Consumers are increasingly willing to pay premiums for flowers certified under Fairtrade or carbon-neutral schemes, signalling a shift in value from purely aesthetic qualities to sustainability credentials [12, 17].

Another trend is the growing demand for locally produced flowers. The transportation of cut flowers across continents contributes significantly to greenhouse gas emissions, and climate disruptions exacerbate concerns over supply chain stability. In response, markets such as the United States are experiencing a revival of domestic floriculture, particularly in California and Alaska, where climatic conditions remain favourable. Similarly, in Europe, local seasonal flowers are regaining popularity, aligning with broader movements for sustainable consumption [15, 17].

Consumer preferences are also diversifying toward long-lasting, hardy varieties that can withstand the transport and storage challenges exacerbated by global warming. Crops such as chrysanthemums, alstroemeria, and potted succulents are gaining prominence due to their durability and reduced post-harvest losses. Climate change, therefore, is reshaping demand in terms of both sustainability and the specific traits valued by consumers [18, 19].

6.3 Emerging Markets and Production Regions

Beyond established hubs, new markets and production zones are expanding. Asia is emerging as a significant growth area for floriculture. China has seen rapid increases in both domestic consumption and export capacity, with Yunnan Province becoming a major centre of cut-flower production. India is expanding its presence in domestic markets with marigolds, roses, and chrysanthemums, while also exploring the export potential of tropical orchids and anthuriums. Vietnam and Thailand are strengthening their positions in the orchid trade, catering to both regional and international markets [26, 28].

Africa beyond Kenya and Ethiopia is also beginning to establish itself as a floriculture producer. Countries such as Tanzania, Uganda, and Rwanda are exploring cut-flower production for the European market, benefiting from favourable altitudes and relatively low production costs. In South America, Peru and Bolivia are experimenting with niche floriculture products, diversifying beyond the dominance of Colombia and Ecuador [29, 30].

The growth of these emerging markets reflects both climate-driven opportunities and strategic diversification. As traditional hubs face increasing climate risks, new regions are filling the gaps, reshaping the global distribution of floriculture [31, 32].

6.4 Trade Regulations and International Agreements

Climate change intersects with global trade policies in multiple ways. As production zones shift and sustainability concerns rise, importing countries are tightening standards on carbon footprints, pesticide residues, and phytosanitary compliance. The European Union, a major consumer of imported flowers, is considering carbon border adjustment mechanisms that could penalise imports produced with high emissions. This could significantly affect exporters in Africa and Latin America unless they adopt cleaner energy and production practices [43, 44].

Phytosanitary regulations are also evolving. Climate-driven pest and disease outbreaks increase the risk of non-compliance at borders. Exporters must adopt stricter monitoring and treatment protocols, which increase costs but are necessary to maintain access to high-value markets. International trade agreements will increasingly need to incorporate climate resilience considerations, ensuring that producers in vulnerable regions are not disproportionately excluded from global markets [45, 46].

At the same time, certification systems are gaining strength. Fairtrade, Rainforest Alliance, and carbon-neutral certifications not only provide market access but also help producers invest in sustainable practices. However, certification often requires upfront costs that smallholder producers struggle to meet, highlighting the need for supportive policies and international cooperation [47, 48].

6.5 Floriculture in Urban Greening and Ecosystem Services

Climate change is also altering the role of floriculture in society beyond trade. Urbanisation and the need for climate-resilient cities are increasing the importance of ornamental plants in urban landscapes. Flowers and ornamental greenery play a crucial role in regulating the microclimate, sequestering carbon, and enhancing air quality. They also improve human well-being by reducing stress, promoting social interaction, and contributing to a sense of cultural identity [31, 33].

In many cities, floriculture is being integrated into climate adaptation strategies through urban parks, rooftop gardens, and vertical greening systems. These functions extend the significance of floriculture from a market commodity to a component of ecosystem services and urban resilience. The growing recognition of these contributions is influencing policy and consumer demand, aligning floriculture more closely with sustainability agendas [34, 35].

7. Research Gaps and Future Directions

7.1 Limited Modelling Frameworks for Ornamental Crops

Despite the rapid progress in modelling staple crops such as wheat, rice, and maize, ornamental species remain underrepresented in climate modelling research. Existing models are often borrowed from food crops and fail to adequately capture ornamental-specific traits, such as flower size, fragrance, petal morphology, and vase life. These traits are central to marketability but difficult to quantify [44, 45]. The absence of standardised quality indices hampers the ability to integrate ornamental traits into process-based or machine learning models. There is an urgent need to develop floriculture-specific modelling frameworks that incorporate physiological, biochemical, and aesthetic attributes, ensuring that predictions are meaningful for both growers and markets [42, 56].

7.2 Lack of Long-Term and Multi-Site Experimental Data

Most experimental studies on climate impacts in floriculture are short-term and confined to controlled environments. While these studies provide insights into physiological responses, they rarely capture the cumulative effects of long-term exposure to climate variability. Multi-year and multi-location trials are scarce, particularly in developing countries where floriculture is expanding. Without long-term datasets, it is challenging to validate models or design breeding programs that promote resilience. Collaborative field networks, similar to those established for staple crops, would help generate robust data on temperature responses, water stress tolerance, and disease dynamics in ornamentals [43, 44].

7.3 Integration of Genomics, Physiology, and Climate Science

The intersection of genomics, physiology, and climate science remains poorly developed in floriculture research. While genomic tools are increasingly available, they are rarely linked with climate adaptation studies. Similarly, physiological research often operates in isolation from molecular studies. Bridging these disciplines could enable the identification of climate-resilient genes and their functional validation under field conditions. For example, integrating transcriptome data on heat shock proteins with phenological observations across climate gradients could accelerate the breeding of resilient ornamentals. Developing such interdisciplinary frameworks will be essential for creating cultivars that combine resilience with ornamental quality [34, 35].

7.4 Sustainability Challenges in Floriculture Systems

Sustainability remains a significant challenge in adapting floriculture to climate change. Controlled environment systems, while effective, are highly energy-intensive and often rely on fossil fuels. The use of plastic in polyhouses, mulching, and packaging contributes to environmental waste. Water footprints are another concern, particularly in water-scarce regions such as Kenya's Naivasha Basin, where intensive rose cultivation competes with community water needs. Future research should address these sustainability challenges by exploring the integration of renewable energy, the development of biodegradable materials, and the implementation of water recycling systems. Life-cycle assessments that quantify the carbon and water footprints of various production systems will be crucial in guiding both policy and consumer choices [55, 56].

7.5 Socio-Economic and Institutional Gaps

Adaptation strategies in floriculture often focus on technological or genetic solutions, but socio-economic and institutional dimensions receive less attention. Smallholder farmers, who dominate production in countries such as India, face barriers to adopting climate-smart practices due to limited access to credit, extension services, and markets. Research is needed to design inclusive adaptation frameworks that address these inequalities. Policies must consider not only export-oriented enterprises but also domestic markets and small-scale producers. Institutional innovations, such as cooperatives, climate-indexed insurance schemes, and digital platforms for market access, require further exploration [57, 58].

7.6 Policy Frameworks for Climate-Resilient Floriculture

Current policies governing floriculture are fragmented, often treating it as a sub-sector of horticulture without dedicated climate adaptation strategies. Few countries have specific policies in place to promote climate-resilient floriculture, despite its significant economic and cultural value. Future policy frameworks should incentivise renewable energy adoption in greenhouses, subsidise water-efficient irrigation, and support certification schemes for sustainable flowers. International policies must also evolve to ensure that producers in vulnerable regions are not excluded from global markets due to rising compliance costs. Collaborative policy initiatives, perhaps under the framework of climate-smart agriculture programs, could provide global coherence in addressing climate challenges in floriculture [44, 45].

7.7 Opportunities for Multi-Disciplinary Research

Floriculture research has traditionally been discipline-specific, with limited interaction between plant science, economics, and social sciences. Yet the complexity of climate change impacts demands multi-disciplinary approaches. Collaborative research platforms that bring together plant breeders, climatologists, economists, and sociologists could generate more comprehensive adaptation strategies. For instance, integrating trade modelling with climate projections would allow forecasting of not just crop suitability but also global market shifts. Similarly, linking urban planning with floriculture research could expand the role of ornamental plants in ecosystem services and climate adaptation strategies in cities [51, 59].

7.8 Pathways for Future Research

Future directions should prioritise the creation of integrated datasets combining climatic, genomic, and socio-economic variables. These datasets can support the development of hybrid models that predict both biological and market responses. Investment in phenotyping technologies, such as imaging systems for flower quality, will provide standardised measures to feed into models. On the policy side, coordinated international research initiatives, similar to those established for staple food crops under CGIAR, could be established for ornamentals, ensuring resource sharing and data harmonisation across countries [21, 38].

Another important pathway is the exploration of alternative production systems. Controlled environment agriculture, vertical farming, and urban floriculture offer insulation from climate variability, but require further research on energy efficiency and consumer acceptance. Research should also address the potential of ornamentals in contributing to climate mitigation through carbon sequestration, biodiversity enhancement, and urban greening. These ecosystem services are often overlooked but could redefine the role of floriculture in a world constrained by climate change [39, 41].

8. Conclusion

Climate change is reshaping the floriculture sector through rising temperatures, irregular rainfall patterns, elevated CO_2 levels, and more frequent extreme weather events. These shifts disrupt flowering cycles, reduce quality attributes such as size, colour, and fragrance, and increase pest and disease pressure. Because floriculture relies on strict quality standards and fast international logistics, even minor climatic disturbances can translate into significant market and livelihood risks. Evidence from major hubs such as the Netherlands, Kenya, India, and Colombia shows that climate impacts are already affecting production, while projections suggest further geographic shifts in suitability. Traditional regions may lose competitiveness, while new areas in higher latitudes and altitudes gain prominence, altering global trade flows. Adaptation is possible through multiple pathways. Breeding for stress-tolerant cultivars, efficient water and nutrient management, protected cultivation, and integrated pest control offer immediate resilience. Technological innovations in sensing, modelling, and renewable energy integration enhance long-term sustainability. At the same time, socio-economic measures, including insurance schemes, certification systems, and supportive trade regulations, are essential to ensure equitable adaptation.

Research gaps remain significant. Floriculture lacks robust long-term datasets, modelling tools tailored to ornamental traits, and integrated studies combining genomics, physiology, and climate science. Addressing sustainability challenges, energy demand, plastic use, and water footprints requires targeted innovation and policy support. The future of floriculture will depend on coordinated efforts by researchers, growers, policymakers, and consumers. If resilience and sustainability are prioritised, floriculture can continue to thrive, contribute to livelihoods, and support urban and cultural landscapes. If adaptation lags, the sector risks severe disruption. The path forward requires aligning scientific innovation with socio-economic inclusion and global sustainability goals.

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