Review Article

Impact of Climate Change on Flowering Patterns and Productivity in Floriculture- A review

Abstract

The floriculture industry, a vital component of global horticulture, is increasingly threatened by climate change, which disrupts flowering patterns, reduces productivity, and alters the market value of ornamental crops. This review synthesizes current research on how climatic factors—such as temperature fluctuations, altered precipitation, elevated atmospheric CO_2, and extreme weather events—affect key aspects of floricultural crop growth and phenology. Rising temperatures accelerate flowering in many species but can also lead to heat stress, floral bud abortion, and reduced flower quality in sensitive crops like roses (*Rosa hybrida*) and snapdragons (*Antirrhinum majus*). Similarly, changes in precipitation patterns, including drought and waterlogging, further complicate floral development by impairing water and nutrient uptake. Elevated CO_2 generally promotes biomass accumulation and water-use efficiency but may not necessarily translate into improved floral yield or quality. To address these challenges, the adoption of adaptive strategies such as breeding climate-resilient varieties, implementing optimized agronomic practices, and utilizing controlled environment agriculture is critical. Future research must focus on species-specific and long-term studies to identify the differential impacts of climate change on diverse floricultural species. Moreover, multi-stressor impact assessments and exploration of phenotypic plasticity and genetic adaptation are needed to develop cultivars capable of maintaining high performance under complex environmental conditions. Integrating climate models and decision support systems will further enable precise forecasting and strategic planning, supporting growers in mitigating climate-related risks. By advancing understanding in these areas, the floriculture industry can better adapt to changing climates and maintain economic sustainability, ensuring the continued success of this important sector amidst global environmental shifts.

Keywords: *Climate Change, Flowering Patterns, Phenology, Heat Stress, Drought Tolerance, CO_2 Impact*

I. Introduction

A. Significance of Floriculture

Floriculture, a specialized branch of horticulture, is a thriving industry globally, encompassing the cultivation and marketing of flowering plants, cut flowers, and ornamental foliage. This sector significantly contributes to national economies, especially in countries such as the Netherlands, Colombia, Kenya, and India, where it supports both rural livelihoods and export markets [1]. In 2019 alone, the global floriculture market was valued at approximately USD 55 billion, with a projected annual growth rate of 5.2% over the next decade.

The economic value of floriculture is not only confined to the sale of fresh-cut flowers and potted plants but also extends to the associated supply chains, including breeding, tissue culture, and post-harvest management. Additionally, floricultural crops play a critical role in ecological landscaping and environmental management, supporting biodiversity, and enhancing urban aesthetics. The rising demand for ornamental plants has spurred advancements in breeding, with an emphasis on developing cultivars that exhibit unique colors, fragrance, and improved shelf life [2].

B. Overview of Climate Change Effects on Plant Phenology

Climate change, driven by anthropogenic activities, is altering global temperature and precipitation patterns, leading to significant shifts in plant phenology—the timing of developmental events such as flowering, leaf-out, and fruiting. Phenological changes serve as critical indicators of the biological impact of climate change on plant systems. In particular, the flowering patterns of many plant species have been advancing or delaying in response to warming temperatures and altered precipitation regimes. For example, in temperate regions, many spring-flowering plants are now blooming earlier by approximately 2.5 days per decade due to increased spring temperatures [3].

In floriculture, altered phenological patterns can have profound consequences on productivity and market timing. Changes in flowering onset and duration can lead to mismatches in flowering synchronization, affecting pollination success and reducing seed set and fruit formation in flowering crops . Moreover, unpredictable flowering patterns complicate harvest scheduling and post-harvest handling, leading to potential economic losses. Phenological changes may also alter the quality traits of ornamental flowers, such as size, shape, and pigmentation, which are highly sensitive to temperature and light conditions [4].

Additionally, extreme weather events, such as heatwaves and unseasonal frosts, can disrupt flowering by causing floral bud abortion, reduced floral longevity, and abnormal floral morphology. Such events have been documented to cause significant yield losses in sensitive floricultural crops like roses, tulips, and chrysanthemums . The phenological shifts are not uniform across species; thus, the interspecific differences in climate sensitivity further complicate predictions for mixed cropping systems commonly used in floriculture [5].

C. Purpose and Scope of the Review

The purpose of this review is to synthesize current knowledge on the impact of climate change on flowering patterns and productivity in floriculture. Although much attention has been paid to the agricultural sector regarding climate change impacts, there is a relative paucity of research focusing specifically on ornamental horticulture. This review aims to bridge this gap by evaluating how various climatic factors—such as temperature fluctuations, altered precipitation, increased atmospheric CO_2, and extreme weather events—affect the phenology and productivity of floricultural crops [6].

The scope of this review encompasses a wide range of floricultural species, including economically significant annuals, perennials, bulbs, and cut flowers. The focus will be on understanding the physiological and ecological mechanisms driving phenological changes and how these changes translate to shifts in productivity, flower quality, and marketability. Furthermore, the review will highlight adaptive strategies, such as breeding climate-resilient cultivars and implementing controlled environment agriculture, to mitigate the adverse effects of climate change [7].

By providing a comprehensive synthesis of existing research, this review seeks to inform breeders, growers, and policymakers on the potential challenges and opportunities presented by a changing climate in the floriculture industry. Ultimately, it aims to contribute to the development of sustainable management practices that can help secure the future of this economically and culturally valuable sector.

II. Flowering Patterns in Floricultural Crops

A. Factors Influencing Flowering

The flowering process in floricultural crops is governed by a complex interplay of genetic, environmental, and physiological factors, making it highly variable among species [8]. Genetic predispositions determine the plant's inherent response to environmental triggers, such as photoperiod and temperature, while physiological signals and hormonal balances further fine-tune the flowering process. For example, the genetic basis for flowering in model systems like *Arabidopsis thaliana* has been well studied, with key flowering time genes such as *FLOWERING LOCUS T* (*FT*) and *CONSTANS* (*CO*) identified as central regulators.

Environmental factors, such as photoperiod and temperature, play a crucial role in the timing of floral induction. Many floricultural species are categorized as short-day, long-day, or day-neutral plants, which dictates their response to the length of day and night [9]. For instance, chrysanthemums (*Chrysanthemum morifolium*) are classic short-day plants, initiating flowering when day length shortens, while petunias (*Petunia hybrida*) are long-day plants that require longer daylight exposure to flower. **Temperature**, on the other hand, acts both independently and in conjunction with photoperiod, with processes such as vernalization in species like tulips and hyacinths requiring a prolonged period of cold to trigger flowering.

Physiological factors include hormonal signals such as gibberellins (GA), cytokinins, and ethylene, which modulate floral induction and development [10]. For example, in *Rosa hybrida*, increased levels of gibberellins can induce flowering, whereas ethylene exposure often causes premature petal senescence in many cut flowers. Similarly, nutrient availability, particularly nitrogen and phosphorus levels, can significantly influence the onset and quality of flowering.

B. Physiological and Environmental Triggers of Flowering

Flowering in floricultural crops is the result of intricate physiological processes that are sensitive to external environmental cues. The integration of these signals is mediated by molecular pathways that respond to photoperiod, temperature, and other environmental factors [11]. Key among these are **photoreceptors** like phytochromes and cryptochromes, which detect changes in light quality and duration, influencing flowering through the activation of the *FT* and *CO* genes.

The **thermosensory pathway** is another critical trigger for flowering, particularly in temperate species. For example, in floricultural species such as *Dianthus caryophyllus* (carnations), high temperatures promote early flowering, while low temperatures are essential for floral initiation in cold-requiring species like lilies (*Lilium spp.*) and daffodils (*Narcissus spp.*). Similarly, **water availability** can act as a stress cue that modulates flowering time, with drought often delaying or inhibiting flowering in sensitive crops like marigolds (*Tagetes spp.*) [12].

In controlled environments, manipulating these physiological triggers can optimize flowering. For instance, by altering day length or providing supplemental lighting, growers can induce flowering at desired times, making crops like poinsettias (*Euphorbia pulcherrima*) and chrysanthemums bloom out of their natural season. Similarly, the use of chemical treatments like growth regulators allows precise control over flowering time and floral morphology.

C. Methods of Monitoring Flowering Patterns

Accurate monitoring of flowering patterns is essential for understanding the phenological responses of floricultural crops to environmental changes and for optimizing production. Traditional methods include **visual observation** and recording of key phenological stages, such as bud formation, floral opening, and senescence [13]. However, these methods can be labor-intensive and prone to observer bias, particularly when dealing with large-scale plantings.

Modern approaches employ **digital imaging and phenotyping tools** to quantify flowering traits more precisely. High-resolution cameras and automated image analysis software can track the onset, duration, and synchrony of flowering across multiple plants simultaneously. **Time-lapse photography** is increasingly used in research and commercial settings to monitor flower development stages, allowing detailed studies of flowering kinetics in species like roses (*Rosa hybrida*) and lilies (*Lilium spp.*) [14].

Furthermore, **remote sensing technologies**, including **satellite imagery and unmanned aerial vehicles (UAVs)**, are being adapted to assess flowering patterns in large-scale floricultural fields. These technologies enable the detection of phenological shifts due to climate change or stress conditions over broad areas, providing valuable insights into crop performance and health. **Thermal imaging** and **chlorophyll fluorescence** measurements are also utilized to assess the physiological status of flowering plants, detecting stress responses that may affect flowering quality and yield [15].

Another promising development is the use of **genetic markers** and **molecular assays** to monitor the expression of flowering-related genes in response to environmental changes. Such molecular techniques provide early indicators of flowering transitions, enabling more precise management of flowering time and improving the predictability of flowering outcomes in various floricultural species.

III. Impact of Climate Change on Flowering Patterns

A. Temperature Variations

Temperature is a key environmental factor that regulates the timing and quality of flowering in floricultural crops, and even small changes can lead to significant shifts in phenology [16]. As global temperatures rise due to climate change, flowering patterns in numerous species are being disrupted. Studies show that in temperate regions, an increase of just 1°C can advance the flowering time of spring-flowering plants by up to 6 days. This phenomenon has been observed in several floricultural crops, including tulips (*Tulipa spp.*) and daffodils (*Narcissus spp.*), where warming temperatures have led to earlier flowering and shortened flowering duration.

Higher temperatures also affect flowering quality and floral morphology. In heat-sensitive crops like snapdragons (*Antirrhinum majus*) and chrysanthemums (*Chrysanthemum morifolium*), elevated temperatures can cause flower bud abortion, reduced petal size, and discolored blooms. Furthermore, temperature variations can disrupt the physiological processes required for synchronized flowering, leading to irregular blooming patterns and reduced aesthetic appeal [17].

Heat stress can also negatively impact the reproductive success of floricultural species by reducing pollen viability and stigmatic receptivity, as observed in petunias (*Petunia hybrida*) and lilies (*Lilium spp.*). In contrast, cold-sensitive species such as geraniums (*Pelargonium spp.*) may experience frost damage during unexpected cold spells, leading to significant yield losses. Thus, temperature variability, both in the form of heatwaves and unseasonal frosts, poses a major challenge for maintaining consistent flowering patterns and quality in the floriculture industry [18].

B. Changes in Photoperiod and CO_2 Levels

Photoperiod is a critical determinant of flowering time in many floricultural species, influencing the switch from vegetative to reproductive growth based on day length. While photoperiod itself is not directly altered by climate change, shifts in regional climates may push crops to new latitudes, exposing them to unfamiliar photoperiod regimes. For example, in crops like chrysanthemums and poinsettias (*Euphorbia pulcherrima*), changes in day length can disrupt the timing of flowering and affect market scheduling [19]. As such, shifts in growing regions may necessitate new management practices to synchronize flowering with traditional market windows.

In addition to photoperiod, rising atmospheric CO_2 levels, which are projected to reach 550 ppm by 2050, have direct and indirect effects on flowering phenology. Elevated CO_2 generally promotes earlier flowering by accelerating vegetative growth and reducing the time to floral induction in several species. Studies on marigolds (*Tagetes spp.*) and petunias show that increased CO_2 levels can enhance flower number and size, thereby improving market value .However, CO_2-induced changes in flowering time are often coupled with shifts in resource allocation, potentially reducing stem strength and overall plant stability in some crops [20].

The interaction between elevated CO_2 and temperature can lead to unpredictable outcomes. For instance, while higher CO_2 can mitigate some of the negative effects of heat stress by improving water-use efficiency, it may also exacerbate the impact of drought on flowering by accelerating water depletion. These complex interactions underscore the need for species-specific studies to fully understand how combined environmental changes will affect flowering patterns in diverse floricultural crops.

C. Precipitation Changes and Extreme Weather Events

Climate change is expected to alter global precipitation patterns, leading to increased frequency and intensity of droughts, heavy rainfall, and extreme weather events [21]. These changes have significant implications for the flowering patterns of floricultural species, particularly those sensitive to water availability.

Drought stress can delay flowering, reduce flower size, and decrease the number of blooms in many floricultural crops, such as marigolds (*Tagetes spp.*) and zinnias (*Zinnia spp.*). This effect is primarily due to the disruption of hormone levels (e.g., abscisic acid and gibberellins) that are crucial for floral development. Moreover, prolonged drought conditions can lead to the cessation of flowering altogether, as seen in impatiens (*Impatiens walleriana*), where severe water stress can prevent floral bud formation.

Conversely, excessive rainfall and waterlogging can be equally detrimental, causing root hypoxia and nutrient leaching, which negatively affect flowering and overall plant health [22]. In species like roses (*Rosa spp.*) and carnations (*Dianthus caryophyllus*), waterlogged conditions have been linked to increased bud drop, poor flower quality, and heightened vulnerability to root pathogens. Flooding events can result in complete crop failure, especially in low-lying floricultural fields, where extended periods of soil saturation lead to root death and reduced plant vigor.

Extreme weather events, such as storms, hail, and unseasonal frosts, pose an additional threat to floricultural crops by causing physical damage to flowers and disrupting normal flowering cycles. Hailstorms, for example, can destroy delicate petals and stems, rendering cut flowers unsellable, while high winds can break flower stalks and reduce overall yield [23]. Heatwaves, on the other hand, can lead to thermal stress, resulting in flower bud abortion and poor bloom quality in sensitive crops like snapdragons and gerberas (*Gerbera jamesonii*).

V. Impact of Climate Change on Productivity in Floriculture

The productivity of floricultural crops is highly dependent on environmental conditions, making the industry particularly vulnerable to the impacts of climate change. Rising temperatures, altered precipitation patterns, and increased atmospheric CO_2 concentrations are altering the growth, quality, and yield of ornamental plants in various ways [24]. These changes have significant implications not only for crop performance but also for the economic viability of floriculture, which relies heavily on maintaining consistent quality and market schedules. This section discusses how climate change is affecting flower quality and yield, growth dynamics and resource allocation, and the economic stability of the floriculture industry.

A. Effects on Flower Quality and Yield

Flower quality is one of the most critical attributes in floriculture, as it directly influences market value and consumer preferences. Climate change is affecting various aspects of flower quality, including size, shape, color, fragrance, and post-harvest longevity, which are highly sensitive to environmental conditions [25]. For instance, elevated temperatures during the flowering period can lead to reduced flower size and altered pigmentation in heat-sensitive crops like roses (*Rosa hybrida*) and carnations (*Dianthus caryophyllus*). In roses, heat stress has been associated with a reduction in petal number and increased susceptibility to petal scorching, both of which diminish visual appeal.

Temperature extremes also affect flower yield by disrupting normal developmental processes. In chrysanthemums (*Chrysanthemum morifolium*), elevated temperatures during bud initiation can result in premature floral differentiation, leading to incomplete or deformed blooms. Similarly, in lilies (*Lilium spp.*), high temperatures during early growth stages can induce stem elongation and reduce flower bud formation, negatively impacting yield and stem strength [26]. Additionally, prolonged exposure to suboptimal temperatures can increase the incidence of physiological disorders, such as leaf and flower discoloration, bud blasting, and tip burn, as observed in poinsettias (*Euphorbia pulcherrima*) and snapdragons (*Antirrhinum majus*).

Changes in precipitation patterns also influence flower yield and quality by affecting soil moisture availability and plant water status. Drought stress during critical growth stages can reduce flower size, decrease the number of flower buds, and shorten the blooming period in marigolds (*Tagetes spp.*) and zinnias (*Zinnia spp.*). On the other hand, excessive rainfall can lead to waterlogging, which negatively affects root health and nutrient uptake, resulting in poor-quality flowers and reduced yield in roses and carnations [27]. These changes highlight the sensitivity of floricultural crops to even slight deviations in moisture availability, making water management a crucial aspect of climate adaptation in floriculture.

B. Shifts in Growth Dynamics and Resource Allocation

Climate change is also altering the growth dynamics and resource allocation patterns in floricultural crops, with implications for both vegetative and reproductive development. Elevated atmospheric CO_2, for instance, generally promotes increased biomass production due to enhanced photosynthetic rates and improved water-use efficiency. However, this increase in vegetative growth does not necessarily translate to improved floral yields, as resource allocation between vegetative and reproductive organs may be skewed [28].

In some floricultural species, such as petunias (*Petunia hybrida*) and geraniums (*Pelargonium spp.*), elevated CO_2 has been shown to increase vegetative growth at the expense of reproductive output, leading to delayed flowering and reduced flower number. This shift in resource allocation can reduce the aesthetic quality of potted plants and cut flowers, which rely on a balanced display of foliage and blooms for maximum visual impact. Similarly, in carnations, increased CO_2 levels can enhance stem elongation and leaf area, but this growth response often results in thinner stems and lower bud formation, compromising both yield and structural integrity [29].

Temperature also influences growth dynamics by affecting the partitioning of assimilates between leaves, stems, and flowers. In heat-sensitive crops like snapdragons, elevated temperatures promote excessive vegetative growth and lead to a reduction in flower bud initiation, causing a shift in the plant's growth strategy that favorsleaf production over flowering. Conversely, in species that require vernalization, such as tulips and hyacinths, insufficient chilling results in stunted growth and poor bud development, as carbohydrates are not adequately translocated to the floral meristems [30].

Water availability further modulates growth dynamics and resource allocation, with drought stress leading to a reduction in shoot biomass and a reallocation of resources to root development in many floricultural crops. This shift is a survival strategy to enhance water uptake under limited moisture conditions, but it comes at the cost of reduced flowering and lower aesthetic value. Thus, climate-induced changes in growth patterns and resource distribution can have profound effects on both the productivity and market quality of floricultural species.

C. Economic Consequences for the Floriculture Industry

The economic consequences of climate change for the floriculture industry are substantial, as changes in productivity, quality, and market timing directly impact profitability [31]. Reduced flower yields and inconsistent quality can lead to lower prices and diminished consumer confidence, especially in high-value crops like orchids (*Orchidaceae*) and roses. For instance, a study on rose production in the Netherlands estimated that heat stress during the flowering period could reduce marketable yield by up to 20%, resulting in significant financial losses.

Climate variability also affects the timing of flowering, leading to mismatches between production and peak market demand, particularly for seasonal crops like poinsettias and chrysanthemums, which are highly sensitive to day length and temperature. Such mismatches can disrupt supply chains and reduce the profitability of growers, as unsold flowers have limited shelf life and cannot be stored for long periods [32]. The increased costs associated with implementing climate adaptation strategies, such as controlled environment agriculture and improved irrigation systems, further strain the financial stability of small-scale and resource-poor floricultural producers.

Moreover, the floriculture industry is vulnerable to the impact of extreme weather events, which can cause sudden and severe damage to crops, infrastructure, and distribution networks. For example, hailstorms, floods, and heatwaves can destroy entire fields of cut flowers, resulting in catastrophic losses that are often not covered by traditional crop insurance schemes. This increased risk necessitates the development of more resilient cultivars and the adoption of innovative risk management practices to safeguard the economic sustainability of the floriculture sector [33].

V. Adaptation Strategies for Sustainable Floriculture

Climate change poses significant challenges to the floriculture industry, impacting flowering patterns, growth dynamics, and overall productivity. To sustain floriculture in the face of these challenges, adaptation strategies need to be implemented to enhance the resilience of crops and optimize production systems. Key strategies include breeding climate-resilient varieties, adopting improved agronomic practices and controlled environment technologies, and using climate models for effective planning and decision-making. Each of these approaches plays a crucial role in mitigating the adverse effects of climate change and ensuring the sustainable development of the floriculture sector [34].

A. Breeding Climate-Resilient Varieties

Breeding climate-resilient floricultural varieties is one of the most effective long-term strategies to cope with the impacts of climate change. Conventional breeding, as well as modern molecular techniques, are being employed to develop cultivars that can tolerate abiotic stresses such as heat, drought, and salinity, which are becoming increasingly common under changing climate conditions. For example, marker-assisted selection (MAS) and genomic selection have been successfully used in developing heat-tolerant cultivars of petunias (*Petunia hybrida*) and drought-resistant varieties of marigolds (*Tagetes spp.*) [35].

Heat tolerance is a critical trait in floricultural breeding programs, as rising temperatures can lead to reduced floral quality and altered flowering schedules. In roses (*Rosa hybrida*), breeding for heat tolerance has focused on selecting genotypes that maintain flower size, color, and scent under high-temperature conditions. Recent advances in transcriptomics have identified heat-shock proteins (HSPs) and other stress-responsive genes that can be targeted for genetic improvement [36]. For chrysanthemums (*Chrysanthemum morifolium*), transgenic approaches have been used to enhance heat and drought tolerance by overexpressing stress-inducible genes such as *DREB1A* and *HSP70*, resulting in cultivars that exhibit stable flowering under fluctuating temperatures.

Drought tolerance is another key focus, given that water scarcity is expected to become a more pressing issue in many floriculture-growing regions. Conventional breeding methods, such as hybridization and selection, have been used to introduce drought-resistant traits in species like geraniums (*Pelargonium spp.*) and zinnias (*Zinnia spp.*). In addition, biotechnology approaches, such as the use of CRISPR/Cas9 for gene editing, have enabled precise modifications to improve water-use efficiency and root architecture in floricultural crops.

Salinity tolerance is another trait of interest, especially for coastal regions where saltwater intrusion is a concern [37]. Breeding efforts in floricultural species like lilies (*Lilium spp.*) and gladioli (*Gladiolus spp.*) have focused on enhancing ion transport and osmotic adjustment mechanisms to maintain growth and flowering under saline conditions. These climate-resilient varieties can help stabilize production and reduce the economic losses associated with salinity stress.

B. Agronomic Practices and Controlled Environments

Optimizing agronomic practices and implementing controlled environment technologies are essential for mitigating the impacts of climate variability on floricultural crops. Precision agriculture techniques, such as site-specific irrigation, nutrient management, and stress monitoring, can enhance crop resilience and reduce resource use [38]. For example, the adoption of **drip irrigation** and **subsurface watering systems** has been shown to improve water-use efficiency in floricultural crops like carnations (*Dianthus caryophyllus*) and marigolds (*Tagetes spp.*) under drought conditions.

Mulching and shading are effective agronomic strategies for moderating soil temperature and moisture levels, thereby protecting plants from heat and drought stress. In roses, the use of organic mulches has been associated with reduced soil evaporation and improved flower quality under high-temperature conditions. Similarly, **shading nets** can reduce leaf temperature and prevent sunscald in sensitive species like gerberas (*Gerbera jamesonii*), enhancing both aesthetic quality and yield [39].

Controlled environment agriculture (CEA), which includes greenhouses, polyhouses, and indoor farming systems, provides a more stable environment for floriculture by regulating temperature, light, humidity, and CO_2 levels. Greenhouses equipped with automated climate control systems can mitigate the impact of extreme weather events and ensure year-round production. In poinsettia production, for instance, CEA has been used to optimize flowering time and color development, resulting in higher market value during the holiday season. Similarly, **hydroponic and aeroponic systems** are being explored to reduce water and nutrient use, while maintaining high flower quality in crops like orchids (*Orchidaceae*) and chrysanthemums [40].

The use of **supplemental lighting** is another important strategy in controlled environments, particularly for photoperiod-sensitive crops like chrysanthemums and snapdragons (*Antirrhinum majus*). Light-emitting diode (LED) technology allows precise manipulation of light spectra and intensity, which can be used to optimize flowering time, improve color intensity, and reduce energy costs. For example, studies have shown that red and blue LED lights can enhance the flowering of petunias and geraniums while maintaining compact plant morphology.

C. Use of Climate Models for Planning

Climate models are increasingly being used in floriculture to predict the potential impacts of climate change and to develop adaptive strategies [41]. These models incorporate data on temperature, precipitation, CO_2 levels, and extreme weather events to forecast changes in crop phenology, growth, and productivity. For floricultural crops, which are highly sensitive to environmental cues, climate models can help in scheduling planting dates, adjusting production timelines, and planning for potential risks.

Phenological models are particularly useful for predicting flowering times under different climate scenarios. In crops like tulips and hyacinths, where precise flowering timing is critical for market success, phenological models have been used to forecast bloom periods and adjust production practices accordingly. These models can also help identify regions that are likely to become unsuitable for traditional floriculture due to shifts in temperature and precipitation patterns, allowing growers to make informed decisions about relocation or crop diversification [42].

Decision support systems (DSS), which integrate climate models with real-time environmental data, are being developed to assist growers in making proactive management decisions. For example, DSS tools that incorporate weather forecasts and crop-specific growth models can optimize irrigation scheduling, pest management, and nutrient application, reducing the risk of yield loss under variable climate conditions. In greenhouse production, DSS can automate climate control, ensuring that temperature and humidity levels remain within optimal ranges for specific crops.

The use of **regional climate projections** and **risk assessment models** is also crucial for understanding the long-term impacts of climate change on floriculture at both local and global scales [43]. These models can help policymakers and industry stakeholders develop targeted adaptation strategies, such as breeding programs, infrastructure investments, and economic policies, to support the sustainable development of the floriculture sector in the face of climate change.

VI. Future Research Directions

Climate change presents unprecedented challenges for the floriculture industry, impacting plant phenology, growth, and market value. While current research has identified broad trends and physiological responses, there remains a critical need for more targeted studies that address species-specific sensitivities, assess the combined effects of multiple stressors, and explore the genetic and phenotypic mechanisms of adaptation [44]. Future research must take a more nuanced approach to understanding how diverse floricultural species will respond to evolving climatic conditions to ensure the sustainability and economic viability of this important industry. This section outlines key areas where further research is needed.

A. Need for Species-Specific and Long-Term Studies

Despite the economic importance and ecological value of many floricultural crops, the majority of climate change studies have focused on a limited number of model species, leaving significant gaps in our understanding of climate sensitivity across the diverse array of ornamental plants [45]. Each species has unique physiological traits and genetic makeups that influence its response to environmental changes, making species-specific research essential for developing targeted adaptation strategies. For instance, while the responses of common bedding plants like petunias (*Petunia hybrida*) and marigolds (*Tagetes spp.*) to heat and drought have been relatively well studied, there is a lack of comparable data for other economically significant crops, such as orchids (*Orchidaceae*) and tropical foliage plants [46].

Species-specific studies should include detailed phenological observations under controlled and field conditions to capture how each plant species responds to variations in temperature, photoperiod, CO_2 levels, and precipitation patterns. For example, long-term monitoring of phenological changes in roses (*Rosa hybrida*) and chrysanthemums (*Chrysanthemum morifolium*) could help predict how shifts in flowering time will impact market dynamics and crop scheduling .Similarly, studies on less common ornamental species, such as anthuriums (*Anthurium spp.*) and heliconias (*Heliconia spp.*), which are often grown in tropical and subtropical regions, are needed to understand their responses to increasing temperatures and altered humidity patterns [47].

Long-term studies are crucial for capturing the cumulative effects of climate change, which may not be apparent in short-term experiments. Climate impacts on floricultural crops often involve subtle changes in growth rates, resource allocation, and reproductive success that unfold over multiple growing seasons. For example, long-term experiments tracking the flowering patterns of tulips (*Tulipa spp.*) in response to warming trends have revealed that even minor increases in temperature over several years can significantly alter bloom timing and reduce flower quality. Therefore, future research should prioritize establishing long-term field trials and phenological databases to better understand and anticipate the impacts of climate change on a wide range of floricultural species.

B. Multi-Stressor Impact Assessment

While most studies have focused on the effects of individual stressors, such as temperature or water availability, plants in natural and managed ecosystems are often exposed to multiple concurrent stressors that can have synergistic or antagonistic effects [48]. For floricultural crops, interactions between heat, drought, elevated CO_2, and other stress factors can produce complex responses that are difficult to predict based on single-stressor experiments. Therefore, there is an urgent need for multi-stressor studies that investigate the combined impact of multiple environmental factors on plant growth, flowering patterns, and quality attributes.

Multi-stressor impact assessments should address how simultaneous changes in temperature, water availability, and CO_2 affect key physiological processes, such as photosynthesis, nutrient uptake, and hormone regulation, which are critical for flowering and biomass production [49]. For example, research has shown that while elevated CO_2 can enhance photosynthetic rates and water-use efficiency, these benefits are often offset by heat stress, which impairs pollen viability and reduces flower yield in heat-sensitive species like snapdragons (*Antirrhinum majus*). Similarly, drought and salinity can interact to exacerbate osmotic stress, leading to increased floral bud abortion and poor-quality blooms in carnations (*Dianthus caryophyllus*) and geraniums (*Pelargonium spp.*).

The complexity of multi-stressor interactions underscores the need for experimental designs that incorporate multiple environmental variables and use realistic climate scenarios [50]. This approach can help identify critical thresholds and tipping points beyond which plant performance declines sharply, providing valuable insights for breeders and growers. Moreover, integrating multi-stressor studies with physiological and molecular analyses can reveal the underlying mechanisms of stress tolerance and resilience, facilitating the development of cultivars that can withstand complex environmental conditions.

C. Exploring Phenotypic Plasticity and Genetic Adaptation

Phenotypic plasticity—the ability of a single genotype to produce different phenotypes under varying environmental conditions—is a key mechanism by which plants cope with environmental variability [51]. In the context of climate change, phenotypic plasticity allows floricultural crops to maintain stable growth and flowering patterns despite fluctuations in temperature, water availability, and other climatic factors. However, the extent and limits of phenotypic plasticity vary widely among species, and understanding these differences is critical for predicting which crops are most vulnerable to climate change and which are likely to adapt.

Research should focus on quantifying phenotypic plasticity in key traits, such as flowering time, floral morphology, and resource allocation, across a range of environmental conditions. For example, studies on day-neutral and photoperiod-sensitive varieties of petunias and chrysanthemums could help elucidate how plasticity in flowering responses contributes to resilience under shifting photoperiods and temperature regimes. Furthermore, experiments using reciprocal transplant designs—where plants are grown in different environments—can reveal the degree to which phenotypic changes are driven by genetic adaptation versus plastic responses [52].

In addition to phenotypic plasticity, genetic adaptation through natural or artificial selection will be essential for long-term resilience to climate change. Advances in genomics and biotechnology offer new tools for accelerating the development of climate-resilient floricultural crops. Genomic selection, CRISPR/Cas9-based gene editing, and transcriptome profiling can be used to identify and manipulate key genes involved in stress tolerance, flowering regulation, and resource use efficiency [53]. For example, targeted editing of genes related to heat-shock response and flowering time in roses and snapdragons could produce cultivars that maintain flower quality and timing under fluctuating temperatures .

Future research should also explore the potential for **epigenetic modifications**—heritable changes in gene expression that do not involve alterations in DNA sequence—to enhance climate adaptation. Epigenetic mechanisms, such as DNA methylation and histone modifications, can regulate flowering time and stress responses in floricultural species, offering an additional layer of phenotypic plasticity that can be harnessed for crop improvement. Understanding the role of epigenetics in climate adaptation could lead to novel strategies for breeding resilient floricultural crops capable of thriving in a rapidly changing environment [54].

VII. Conclusion

Climate change presents multifaceted challenges to the floriculture industry, impacting flowering patterns, productivity, and market stability. As floricultural crops are highly sensitive to environmental changes, targeted adaptation strategies are essential for ensuring their sustainability. Breeding climate-resilient varieties, optimizing agronomic practices, and employing controlled environment technologies will help mitigate these impacts. Additionally, integrating climate models and decision support systems can enhance planning and risk management. Future research should focus on species-specific responses, multi-stressor interactions, and the role of phenotypic plasticity and genetic adaptation in resilience. Addressing these research gaps will be crucial for developing innovative solutions and safeguarding the economic viability of floriculture in the face of ongoing climatic changes, ultimately supporting both growers and the broader horticultural industry.

VIII. References

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