International Journal of Social Science (IJSS)
Vol.5 Issue.2 Agustus 2025, pp: 255-264
ISSN: 2798-3463 (Printed) | 2798-4079 (Online)
DOI: https://doi.org/10.53625/ijss.v5i2.11002

THE ROLE OF TEMPERATURE IN REGULATING CHRYSANTHEMUM FLOWER COLORATION FOR THE OPTIMIZATION OF FLORICULTURE PRODUCTION

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Article Info
Article history:
Received Jun 06, 2025
Revised Jul 11, 2025
Accepted Aug 09, 2025

Keywords:
Chrysanthemum,
Temperature,
Flower Color,
Anthocyanin,
Floriculture

ABSTRACT
The coloration of chrysanthemum flowers is strongly affected by ambient temperature, primarily through the biosynthetic and degradative pathways of anthocyanin pigments. This literature review synthesizes findings from 2015 to 2025, focusing on temperature effects under both open-field and controlled-environment (greenhouse) conditions. Elevated temperatures (≥30 °C) have been shown to inhibit anthocyanin biosynthesis and accelerate pigment degradation, leading to faded petal coloration. Conversely, cooler temperatures promote pigment accumulation, resulting in brighter and more persistent floral hues. These temperature-dependent responses vary across cultivars and are influenced by developmental stages and interactions with light intensity, relative humidity, and nutrient status. Greenhouse cultivation offers potential mitigation but demands integrated microclimate regulation. Omics approaches, including transcriptomics and metabolomics, hold promise in uncovering the genetic mechanisms that regulate flower coloration. In parallel, the application of smart technologies such as the Internet of Things (IoT) and big data, driven prediction systems can support precision cultivation practices. These insights provide a scientific foundation for optimizing chrysanthemum-based floriculture production systems that are resilient to climate change.

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1. INTRODUCTION

Chrysanthemum (*Chrysanthemum* spp.) is a high-value floricultural crop with increasing market demand, commonly cultivated for cut flowers, potted ornamentals, and as components of garden and landscape designs (Shi et al., 2022). In Indonesia, chrysanthemum is considered a nationally prioritized ornamental commodity, predominantly grown in highland areas such as Tomohon, Lembang, and Batu, which offer ideal agroclimatic conditions for its development. Cultivation in these regions significantly contributes to the livelihoods of horticultural farmers (Rahmawati et al., 2021). The primary aesthetic and commercial appeal of chrysanthemums lies in the diverse coloration of their petals, ranging from white, yellow, and orange to red and purple. These hues are primarily attributed to flavonoid compounds, especially anthocyanins, which are responsible for red to purple pigmentation (Zhao et al., 2021). Beyond their visual appeal, anthocyanin accumulation is highly sensitive to both biotic and abiotic environmental factors. Among these, temperature plays a crucial role by directly regulating the biosynthetic pathways of these pigments.

Temperature is a critical factor for regulating flavonoid biosynthesis, particularly through its influence on the activity of key enzymes such as chalcone synthase (CHS), chalcone isomerase (CHI), and dihydroflavonol 4-reductase

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ISSN: 2798-3463 (Printed) | 2798-4079 (Online)

(DFR), all of which are essential for anthocyanin formation (Shi et al., 2022; Wang et al., 2024). Chrysanthemum grows optimally and produces high-quality flowers at temperatures ranging from 18 to 25 °C. When ambient temperatures exceed 30–32 °C, anthocyanin synthesis is disrupted while pigment degradation accelerates, resulting in faded petal coloration (Wu et al., 2024). Nevertheless, chrysanthemum is relatively tolerant to low temperatures. Exposure to cooler night temperatures has been shown to enhance anthocyanin accumulation, leading to more bright and visually appealing flowers (Liu et al., 2025). In contrast, high temperatures induce thermal stress that suppresses the expression of pigmentation-related genes, ultimately reducing the visual quality and market value of the flowers.

Temperature-induced color changes in chrysanthemum flowers are not uniform across cultivars, as physiological responses are strongly influenced by each cultivar's genetic variability (Guo et al., 2024). Certain cultivars, such as 'Chrystal Regal' and 'Zi Feng Che', exhibit high heat tolerance and are able to maintain petal color intensity under elevated temperatures. In contrast, cultivars like 'Nannong Ziyunying' tend to show noticeable fading when exposed to heat stress (Wu et al., 2024). In Indonesia, Aisyah et al. (2020) reported that nationally recognized cultivars such as 'Tomohon Merah' and 'Darmo Putih' demonstrated relatively stable flower coloration even when cultivated during the dry season, when daytime temperatures are relatively high. These findings highlight the importance of breeding programs focused on enhancing tolerance to temperature extremes, as an adaptive strategy to mitigate the impacts of climate change-induced thermal fluctuations in horticultural environments.

The rise in global temperatures due to climate change poses increasing challenges in maintaining flower color quality in chrysanthemums, particularly under open-field cultivation systems where microclimate conditions cannot be regulated (IPCC, 2023). In this context, greenhouse cultivation emerges as a viable solution, offering more stable and controllable temperature management. Optimized regulation of both daytime and nighttime temperatures within greenhouses has been shown to preserve flower color intensity and extend postharvest vase life (Liu et al., 2025). This article presents a comprehensive review of scientific literature published between 2015 and 2025, focusing on the effects of temperature on chrysanthemum flower coloration under both open-field and controlled-environment conditions. The review aims to provide a scientific basis for developing climate-adaptive cultivation technologies and to support the advancement of sustainable floriculture practices.

2. RESEARCH METHOD

This review employed a literature-based methodology by systematically collecting and analyzing primary data from peer-reviewed national and international journals published between 2015 and 2025.

3. RESULTS AND DISCUSSION

The relationship between temperature and chrysanthemum flower coloration has been the focus of numerous scientific studies over the past decade, due to the critical role of temperature in regulating the anthocyanin biosynthesis pathway. A comprehensive review of literature published between 2015 and 2025 provides in-depth insights into the effects of temperature, under both open-field and greenhouse conditions, on petal color intensity and stability. The variability in responses among cultivars, growth stages, and the interaction between temperature and other environmental factors highlights the complexity of the physiological mechanisms underlying floral pigmentation. To facilitate a structured understanding, this section is organized into several key subtopics: the effects of high and low temperatures on anthocyanin synthesis, cultivar-specific responses to thermal conditions, the role of greenhouse environments, temperature sensitivity at different developmental stages, interactions with other environmental factors, and implications for floriculture production systems and future research directions.

3.1 Effects of High Temperature on Chrysanthemum Flower Color Intensity

Elevated ambient temperatures are a major factor contributing to the decline in the visual quality of chrysanthemum flowers, primarily due to disruptions in the anthocyanin biosynthetic pathway. When air temperatures exceed 30 °C, pigment production in the petals is inhibited, resulting in paler and less attractive flower coloration. Zhang et al. (2021) reported that increasing the temperature from 25 °C to 35 °C significantly suppressed the expression of key structural genes such as *CHS*, *F3H*, and *DFR*, which are essential for anthocyanin synthesis. This reduction was particularly evident in cultivars that are sensitive to heat stress, ultimately reducing the ornamental value of the flowers and potentially affecting their market price.

In addition to inhibiting anthocyanin biosynthesis, high temperatures also accelerate pigment degradation by increasing the activity of oxidative enzymes such as peroxidase (POD) and polyphenol oxidase (PPO). Chen et al. (2017) reported a significant rise in the activity of both enzymes in chrysanthemum petal tissues under high-temperature exposure, which subsequently led to color fading. This enzymatic increase is closely associated with the accumulation of reactive oxygen species (ROS) induced by heat stress, resulting in structural damage to anthocyanin molecules. Such degradation is irreversible, and the original color intensity cannot be restored even if temperature conditions return to normal.

These findings are particularly relevant for chrysanthemum cultivation in tropical and subtropical regions, where high temperatures often prevail during the growing season. To mitigate the adverse effects on flower color quality, several adaptive strategies have been recommended, including partial shading, flexible adjustment of planting schedules, and the selection of cultivars with enhanced heat tolerance (Han et al., 2020). Concurrently, recent advances in molecular research have underscored the importance of analyzing heat-responsive gene expression, such as *HSP70* and *HSFA2*, which hold potential for integration into breeding programs aimed at improving thermal resilience without compromising aesthetic quality. The synergistic application of agronomic and molecular approaches is expected to facilitate the development of chrysanthemum cultivars capable of maintaining stable coloration and productivity under extreme thermal stress.

3.2 The Role of Low Temperature in Enhancing Petal Coloration

Exposure to low temperatures plays a critical role in enhancing petal color intensity in chrysanthemums by activating the anthocyanin biosynthesis pathway. Cool night temperatures, typically ranging between 15–20 °C, have been shown to significantly promote greater pigment accumulation compared to warmer conditions. A study by Zhang et al. (2020) demonstrated that cold temperatures induce the upregulation of flavonoid biosynthetic genes such as *F3H* and *ANS*, which are key components in the anthocyanin synthesis process in cut chrysanthemums. This results in petals with more bright and saturated colors, as well as improved postharvest visual longevity. Such improvements in color quality provide notable agronomic advantages, particularly for chrysanthemum production aimed at aesthetic applications and export markets.

In addition to stimulating anthocyanin biosynthesis, low temperatures also help inhibit the activity of pigment-degrading enzymes, particularly peroxidase (POD), which typically increases under high-temperature conditions. Sun et al. (2019) reported that cold exposure suppresses the expression of POD-encoding genes in chrysanthemum petal tissues, thereby enhancing color stability and extending the visual longevity of the flowers. This effect is most pronounced during the bud development to early flowering stages, when the plants exhibit heightened sensitivity to temperature fluctuations. The study also emphasized that the benefits of low temperatures are not permanent; a rapid increase in temperature may suppress anthocyanin production or even initiate pigment degradation. Therefore, maintaining consistently cool temperatures is essential for optimizing chrysanthemum color quality during the cultivation process.

Low-temperature control in greenhouse-based cultivation represents a promising strategy to enhance flower color quality in chrysanthemums. Xu et al. (2022) reported that maintaining day/night temperatures around 22/16 °C significantly intensified red and purple pigmentation in several ornamental chrysanthemum cultivars, compared to higher temperature regimes. These findings indicate that temperature manipulation in controlled environments can be practically applied to improve visual quality without relying on chemical treatments. However, the effectiveness of this method should be adjusted to the specific characteristics of each cultivar and balanced against the potential risk of growth suppression caused by excessive cooling, which may ultimately affect overall production efficiency.

3.3 Cultivar-Specific Responses to Temperature

The response of chrysanthemums to temperature is highly dependent on the cultivar, as each exhibits distinct genetic traits that influence the biosynthesis and stability of anthocyanin pigments. Some cultivars can maintain intense coloration even under extreme temperature conditions, while others are more prone to significant fading. Putri et al. (2021) reported that local cultivars such as 'Cempaka Ungu' and 'Puspita Nusantara' demonstrated stable flower coloration when cultivated in highland areas with fluctuating temperatures. Importantly, 'Cempaka Ungu' retained its purple pigmentation throughout seasonal transitions, indicating a physiological adaptation to rapid temperature fluctuations.

Research by Apriyani et al. (2022) revealed that two local chrysanthemum cultivars, 'Kalika', 'Kencana', and 'Salsabila', exhibited stable flower coloration even when cultivated in mid-altitude regions with daytime temperatures ranging from 28–30 °C. These findings suggest that certain local cultivars possess adaptive capacity to relatively high temperatures, making them promising candidates for cultivation in tropical environments. Meanwhile, Pradipta et al. (2023) reported differences in temperature tolerance between the 'Mustika Tanjung' and 'Ratih Ayu' varieties. 'Mustika Tanjung' maintained bright yellow pigmentation under moderate temperatures (24–30 °C), whereas 'Ratih Ayu' experienced color fading under heat stress but demonstrated recovery of pigmentation intensity once temperatures decreased, indicating the presence of physiological pigment restoration mechanisms.

Studies on international chrysanthemum cultivars have also demonstrated similar patterns of temperature responses. Kim et al. (2019) reported that several Korean cultivars, such as 'Baekma' and 'Red I', exhibited greater color stability compared to 'Pink Star' and 'Yeonhwa', which were more susceptible to fading under high-temperature conditions. Meanwhile, a study by Zubair et al. (2023) revealed that the Pakistani cultivar 'Purple Queen' maintained anthocyanin content above 70% despite being exposed to daytime temperatures as high as 35 °C. Findings

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from Yoshida et al. (2018) also indicated that the Japanese variety ‘Shuho-no-chikara’ possessed strong color retention when nighttime temperatures remained stable around 22 °C. These differences highlight the importance of varietal selection based on temperature tolerance as a key strategy to mitigate the impacts of climate change on floricultural production systems.

Table 1. Chrysanthemum Flower Color Response to Temperature Based on Cultivar

No.	Chrysanthemum Cultivar	Origin	Temperature Response	Color Stability	Reference
1	Puspita Nusantara	Indonesia	Color remains stable under moderate temperatures (highland); slightly fades under fluctuating temperatures	Moderate	Putri et al., 2021
2	Cempaka Ungu	Indonesia	High color retention during transitional seasons	High	Putri et al., 2021
3	Kalika Kencana	Indonesia	Stable color expression under relatively high daytime temperatures (~28°C)	High	Apriyani et al., 2022
4	Salsabila	Indonesia	Tolerant to moderately high temperatures; color remains bright	Moderate	Apriyani et al., 2022
5	Sakura Asri	Indonesia	Slight color fading in warmer cultivation areas	Moderate	Putri et al., 2021
6	Mustika Tanjung	Indonesia	Intense yellow coloration remains stable at 24–30°C in mid-altitude regions	High	Pradipta et al., 2023
7	Ratih Ayu	Indonesia	Slight fading at temperatures >32°C; color recovers as temperature drops	Moderate	Pradipta et al., 2023
8	Baekma	Korea Selatan	Resistant to fading; consistent anthocyanin gene expression at moderate temperatures	High	Kim et al., 2019
9	Pink Star	Korea Selatan	Rapid fading observed; unstable pigment expression	Low	Kim et al., 2019
10	Shuho-no-chikara	Jepang	Stable maroon color at night temperatures around ~22°C	High	Yoshida et al., 2018
11	Purple Queen	Pakistan	Maintains anthocyanin levels >70% even at daily temperatures up to 35°C	Very High	Zubair et al., 2023
12	Yeonhwa	Korea Selatan	Prone to fading under high temperatures; reduced flavonoid gene expression	Low	Kim et al., 2019

3.4 Comparison Between Open-Field and Greenhouse Cultivation Environments

The growing environment plays a critical role in determining the physiological quality and visual appearance of chrysanthemum flowers, particularly in relation to petal color intensity and stability. Greenhouse cultivation enables optimal control of microclimatic conditions, including temperature, humidity, and light exposure. This regulation is essential, as chrysanthemums require an ideal temperature range of 18–25 °C to support maximum pigment biosynthesis. Excessively high or unstable temperatures can trigger plant stress and lead to reduced color quality (Liu et al., 2025). In contrast, open-field cultivation faces challenges due to greater fluctuations in microclimatic conditions, making it difficult to maintain consistent flower color quality throughout the growing season.

Various international studies have demonstrated that chrysanthemum cultivation in greenhouse environments offers significant advantages in producing more intense and uniform flower coloration. Wang et al. (2024) reported that consistent temperature regulation within controlled systems enhances the expression of key anthocyanin biosynthesis genes, such as *CHS* and *DFR*, while also slowing pigment degradation during the late flowering stage. Research conducted in Korea by Kim and Jang (2020) further indicated that stable nighttime temperatures in greenhouses significantly contribute to increased cyanidin content in purple chrysanthemum petals. In addition, the use of supplemental lighting in controlled environments has proven effective in extending the pigment formation period and preventing the appearance of uneven flower coloration, particularly during short flowering seasons.

In Indonesia, the application of greenhouse systems for chrysanthemum cultivation remains limited, although its adoption is gradually increasing. Wibowo et al. (2020) reported that farmers in the Lembang region who cultivated local cultivars such as 'Puspita Nusantara' and 'Mustika Cipta' in plastic-covered greenhouses achieved improved flower color quality and extended postharvest longevity by up to 30% compared to open-field cultivation. However, widespread implementation of greenhouse systems is still constrained by high initial investment costs, the lack of active cooling systems, and limited energy and clean water infrastructure in many highland chrysanthemum production centers. To address these challenges, several energy-efficient tropical greenhouse technologies have been tested, including passive ventilation, micro-fogging systems, and reflective roofing materials tailored to local climatic conditions (Aisyah et al., 2020).

Studies that systematically compare the effectiveness of greenhouse and open-field cultivation in mitigating the impact of temperature on chrysanthemum flower coloration remain relatively limited. Prasetya et al. (2023) evaluated the use of reflective mulch and shade netting (paranet) on the growth and color quality of chrysanthemums during the dry season in Bali. The findings indicated that these simple protective techniques were able to stabilize soil temperature and buffer daily thermal fluctuations. However, their effectiveness was still inferior to that of enclosed greenhouse systems, which provide more precise temperature regulation. Therefore, adaptive strategies remain essential in open-field cultivation, such as adjusting planting schedules to avoid peak flowering during the hottest months and selecting cultivars with greater physiological tolerance to environmental stress.

Overall, greenhouse systems offer clear advantages in maintaining the stability of chrysanthemum flower coloration. However, their implementation continues to face various challenges. Further studies are needed to directly compare open-field and greenhouse cultivation not only in terms of visual attributes but also through molecular analysis and metabolite profiling to gain a more comprehensive understanding. In terms of technological advancement, the integration of automated temperature sensors and the application of the Internet of Things (IoT) in greenhouse environments are increasingly being adopted as innovative approaches, with strong potential to support precision agriculture practices in the floriculture sector across tropical regions.

3.5 Temperature Effects Across Different Growth Stages of Chrysanthemum

Chrysanthemum responses to environmental temperature vary depending on the growth stage, with the bud initiation phase being the most critical for determining petal color quality. During this phase, cellular differentiation occurs alongside the activation of pigment biosynthesis-related regulatory genes. Lee et al. (2021) reported that exposure to high temperatures during early bud development can cause irreversible disruption in anthocyanin biosynthetic pathways, resulting in faded or uneven flower coloration, even if optimal temperatures are restored in later stages. Furthermore, temperature fluctuations may affect petal development, influencing floral shape, size, and overall color stability.

A study conducted by Yulianti et al. (2020) in Indonesia revealed that local chrysanthemum cultivars, such as 'Dahlia Ungu' and 'Lembang Ceria', exhibited a marked reduction in petal color intensity when bud development occurred under high temperatures exceeding 30 °C, compared to stable temperatures between 24–26 °C. This decline in coloration was associated with the downregulation of key biosynthetic genes, CHS and DFR, during the early stages of floral formation disrupted by heat stress. In contrast, exposure to low temperatures during the vegetative phase, although slowing plant growth, contributed to enhanced color quality during flowering. These findings suggest that the effect of temperature on flower pigmentation is cumulative, beginning from the vegetative stage through to full bloom.

The final stage of flowering, or senescence, is also significantly influenced by ambient temperature. Although petal coloration has reached its final expression, high temperatures can accelerate the aging process and hasten anthocyanin degradation, thereby reducing the flower's vase life. A study by Nasution et al. (2021) reported that cut chrysanthemum cultivars such as 'Mustika Kenanga' and 'Puspita Merah' exhibited better color retention when stored at 20 °C compared to 28 °C, both during postharvest and in-field conditions. These findings highlight that temperature regulation is crucial not only during the flowering stage but also in the postharvest phase, particularly in floriculture distribution systems, to maintain optimal flower quality until it reaches consumers.

A recent study by Rahman et al. (2023) in Bangladesh emphasizes the importance of temperature regulation during the transition phase from vegetative to generative growth in chrysanthemum. The research revealed that temperature fluctuations during this critical period can suppress the expression of MYB transcription factors, which are key regulatory genes in the anthocyanin biosynthesis pathway. This results in an imbalance between morphological development and flower color formation. These findings underscore that optimal temperature management is not only

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Vol.5 Issue.2 Agustus 2025, pp: 255-264
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essential during the flowering stage, but also critically important throughout the growth transition phase to ensure consistent coloration and overall visual quality of the blooms.

Therefore, to produce high-quality chrysanthemums, stable and optimal temperature management must be implemented comprehensively throughout all stages of plant growth, not solely during the flowering phase. Strategies such as appropriate adjustment of planting schedules, selection of cultivars tolerant to extreme temperature fluctuations, and the early application of microclimate control technologies constitute key approaches in addressing increasingly unpredictable thermal conditions driven by global climate change.

3.6 Interaction Between Temperature and Other Environmental Factors

While temperature plays a significant role, changes in chrysanthemum petal coloration result from complex interactions with other environmental factors, including light intensity, nutrient availability, and relative humidity. An imbalance in any of these factors can trigger physiological stress, which directly disrupts the accumulation and stability of anthocyanin pigments, the primary compounds responsible for red, purple, and blue coloration in petals. Tanaka and Shibata (2020) reported that high temperatures combined with high-intensity light accelerate anthocyanin degradation through photo-oxidative processes, further compromising pigment stability (Kumar et al., 2023). Such conditions are often observed in open-field cultivation during the dry season, where excessive solar radiation intensifies the effects of high temperatures, particularly in red and purple cultivars that are more susceptible to color fading. Conversely, moderate lighting can stimulate the expression of biosynthetic genes such as *CHS* and *F3H*, which play crucial roles in pigment formation. In a study conducted by Siregar et al. (2020) in Indonesia, the cultivar 'Mustika Ungu' exhibited the most intense petal coloration when grown under 30% shade, compared to full sun or excessive shading. These findings highlight that regulating light intensity is a key strategy for enhancing flower color quality, especially within tropical cultivation systems.

In addition to light intensity, the availability of nutrients such as nitrogen (N) and phosphorus (P) plays a critical role in the pigment biosynthesis of chrysanthemum flowers. Nitrogen deficiency, particularly under high-temperature conditions, can exacerbate metabolic disturbances and suppress the expression of key genes such as *CHS* and *DFR*, which are central to the anthocyanin biosynthesis pathway. Aisyah et al. (2020) reported that local cultivars such as 'Darma' and 'Pesona Ungu' exhibited more optimal floral coloration when treated with moderate nitrogen application (100 kg N/ha), especially under daytime temperatures exceeding 30 °C, compared to those receiving lower doses. Similar findings were presented by Irawan and Mulyati (2019), who found that nitrogen fertilization at an optimal dose of 120 kg N/ha enhanced anthocyanin accumulation and maintained color stability in the 'Citra Pesona' cultivar grown in the highlands of West Java. Conversely, excessive nitrogen application may lead to hormonal imbalances, inhibit flowering, and accelerate color fading. The relationship between nitrogen levels and temperature was further emphasized by Lin et al. (2022), who observed that nitrogen deficiency at 32 °C significantly reduced color index and downregulated *ANS* gene expression in the potted chrysanthemum cultivar 'Kohana'. These findings underscore the importance of precise nutrient management as a strategic approach to mitigate the negative effects of high temperatures on flower visual quality.

Relative humidity is one of the key components of the microclimate that significantly affects the stability of chrysanthemum flower coloration. Under low humidity conditions, the rate of evapotranspiration from leaf surfaces increases, leading to higher leaf temperatures and more rapid dehydration of petal tissues. Conversely, excessive humidity can trigger pathogen infestation and reduce the respiration efficiency of flowers. Rodriguez et al. (2018) reported that cultivating cut-flower chrysanthemums under relative humidity levels below 50% resulted in reduced cell turgor and accelerated anthocyanin degradation, particularly in red and purple cultivars. This is supported by findings from Marpaung et al. (2021), who observed that relative humidity below 55% adversely affected the postharvest longevity and color intensity of locally grown cut chrysanthemums in North Sumatra. Follow-up research by Marpaung et al. (2020) demonstrated that chrysanthemums cultivated in highland areas with optimal humidity levels of 60–70% produced brighter and more uniform petal coloration compared to those grown in mid-altitude regions with humidity below 50%. In fact, maintaining stable humidity levels above 70% was found to suppress pigment degradation and significantly extend floral display duration. Therefore, to preserve color quality in both open-field and controlled-environment cultivation systems, humidity management strategies are essential. These may include the application of misting systems and reflective mulching to create optimal microclimatic conditions.

Collectively, the successful maintenance of optimal flower color intensity in chrysanthemums largely depends on cultivation strategies that holistically integrate all environmental factors. The interactions among temperature, light, nutrient availability, and relative humidity must be simultaneously considered when designing production systems, whether through careful selection of planting time and site, or the use of greenhouses equipped with integrated microclimate control systems. Recent studies have emphasized that the effect of temperature cannot be isolated from other environmental variables, rendering partial approaches less effective. Strategic combinations, such as appropriate light regulation, nutrient management based on the plant's physiological requirements, and balanced humidity control, are essential to ensure consistent and vibrant flower coloration. In the context of precision agriculture, the application of microclimate management technologies, including shade nets, reflective mulches, misting systems, and data-driven microclimate modeling, becomes increasingly critical in response to ongoing climate variability. Therefore, further research examining the synergistic interactions between temperature, light intensity, and nutrient status on pigment-regulating gene expression is vital for supporting the development of more climate-resilient chrysanthemum cultivars and stress-adaptive cultivation technologies.

3.7 Implications for Floriculture Systems and Future Research Directions

Temperature control is a crucial aspect of efficient chrysanthemum cultivation, especially in tropical and subtropical regions that are vulnerable to extreme thermal fluctuations. In Indonesia, the increasing trend of daily temperatures due to climate change has been shown to reduce flower visual quality, shorten shelf life, and diminish the commercial value of cut chrysanthemums in major production centers such as Cipanas and Tomohon (Rahmawati et al., 2021; Yulianingsih et al., 2022). As adaptive measures, the integration of temperature control technologies in greenhouses, selection of cultivation sites with more stable microclimates, and adjustment of planting schedules to cooler seasons are key strategies that must be optimized to support the development of sustainable floriculture systems in tropical regions.

Alongside scientific advancements, floriculture research is increasingly shifting toward multi-omics approaches to uncover the molecular mechanisms underlying plant responses to heat stress. A study by Wang et al. (2023), using transcriptomic analysis, successfully identified several key genes such as *CmDFR* and *CmANS*, which are involved in enhancing heat tolerance in chrysanthemums. Meanwhile, metabolomic approaches have been employed to identify secondary metabolites that contribute to petal color stability even under extreme temperature conditions (Kim et al., 2020). These findings provide a scientific foundation for the development of precision-based breeding programs aimed at producing superior chrysanthemum cultivars with improved heat stress tolerance without compromising floral aesthetic quality.

As a complement to biologically driven innovations, the adoption of digital technologies has become an integral component of modernizing floriculture production systems. In Indonesia, the gradual introduction of automated temperature sensors, Internet of Things (IoT) integration, and artificial intelligence (AI)-based decision support systems is underway (Putra et al., 2023). The integration of real-time temperature data with predictive models for flower color quality is expected to enhance cultivation efficiency while minimizing potential losses caused by climatic anomalies. In line with this, the development of predictive models based on big data and machine learning algorithms has emerged as a strategic research priority in supporting precision chrysanthemum cultivation practices. Cross-disciplinary collaboration, encompassing plant physiology, biotechnology, and digital technology, serves as a foundational framework for building resilient and sustainable tropical floriculture systems.

4. CONCLUSION

Ambient temperature plays a critical role in determining the color quality of chrysanthemum flowers by regulating the biosynthesis and degradation of anthocyanins. Elevated temperatures suppress the expression of biosynthetic genes and accelerate pigment degradation, leading to faded floral hues, whereas cooler temperatures enhance pigment accumulation and improve color intensity. These temperature-related responses are highly dependent on genetic factors, developmental stages, and their interactions with environmental elements such as light intensity, relative humidity, and nutrient availability. The observed variability among cultivars highlights the necessity of appropriate varietal selection and site-specific cultivation strategies. Controlled-environment systems, such as greenhouses, offer advantages in maintaining stable flower coloration, particularly when integrated with energy-efficient technologies and microclimate regulation. Moreover, a multidisciplinary approach, incorporating omics-based breeding for thermal resilience and the integration of Internet of Things (IoT) and artificial intelligence, emerges as a strategic pathway toward the development of precision, adaptive, and sustainable floriculture production systems in the era of climate change.

ACKNOWLEDGEMENTS

Deepest gratitude is extended to Agung Harwanto, S.P., for his unwavering support, guidance, and encouragement throughout the preparation of this review.

International Journal of Social Science (IJSS)
Vol.5 Issue.2 Agustus 2025, pp: 255-264
ISSN: 2798-3463 (Printed) | 2798-4079 (Online)

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International Journal of Social Science (IJSS)
Vol.5 Issue.2 Agustus 2025, pp: 255-264
ISSN: 2798-3463 (Printed) | 2798-4079 (Online)

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