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## From petals to patterns: recent advances in breeding for diverse floral forms

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#### Abstract

Floriculture is a dynamic and economically important sector, driven by consumer demand for novelty, aesthetics, and unique floral designs. Among breeding goals, the development of novel flower colours and forms is central, as these traits directly influence market value and consumer preference (Chandler and Sanchez, 2012). This review summarizes the genetic and biochemical bases of floral pigmentation and morphology and examines both traditional approaches, such as hybridization, mutation breeding, and polyploidy, and modern molecular tools, including transgenics, RNA interference, CRISPR-Cas genome editing, and marker-assisted selection. Case studies in rose, chrysanthemum, petunia, gerbera, and carnation illustrate practical achievements in expanding colour diversity and floral forms. Despite these advances, challenges remain in trait stability, regulatory compliance, and consumer acceptance of genetically modified ornamentals. The integration of conventional and advanced breeding strategies offers opportunities for creating unique, visually appealing, and market-ready ornamental varieties.

**Keywords:** Breeding, Anthocyanins, Carotenoid, Mutation breeding, Hybridization, Polyploidy, CRISPR-Cas9, RNA interference (RNAi), Marker-assisted selection (MAS), Genetic engineering.

#### Introduction

Floriculture, an integral branch of horticulture, significantly contributes to the global economy through the production of cut flowers, potted plants, and landscape ornamentals. Its commercial success hinges on visual appeal, where traits such as color, form, fragrance, and vase life determine marketability, with color and form exerting paramount influence on consumer preference and aesthetic value. The expansion of global markets has intensified demand for novelty, including flowers with rare shades, variegated patterns,

unique forms, and extended durability (Datta, 2022). Traditionally, enhancements in flower color and form relied on natural sports, hybridization, and mutation breeding; however, molecular genetics, genomics, and biotechnology have revolutionized ornamental breeding by enabling precise manipulation of pigment biosynthesis and floral development genes (Nishihara and Nakatsuka, 2011). Landmark achievements, such as the blue rose and striped petunias, underscore the efficacy of genetic engineering and RNA interference in achieving previously unattainable traits, while non-GMO approaches like mutation breeding, polyploidy induction, and somaclonal variation continue to generate valuable diversity (Katsumoto *et al.*, 2007). This review synthesizes current insights into the genetic, biochemical, and molecular underpinnings of flower color and form, delineates conventional and modern breeding strategies, and elucidates challenges and opportunities shaping the future of the floriculture industry.

## **Genetic and Biochemical Basis of Flower Colour**

### **Pigment Groups**

Flower colour diversity is a key ornamental trait that strongly influences consumer preference and market demand (Mekapogu *et al.*, 2020). Floral coloration arises mainly from the presence, absence, or relative abundance of three major pigment groups: flavonoids, carotenoids, and betalains (Narbona *et al.*, 2021). Each pigment group is characterized by distinct biochemical pathways, cellular localization, and taxonomic distribution, which together contribute to the wide variation in flower colours observed in nature (Grotewold, 2006; Zhao *et al.*, 2022).

### **Flavonoids**

Flavonoids, particularly anthocyanins, are the most widespread pigments in higher plants, with glycosylated derivatives such as cyanidin, delphinidin, pelargonidin, peonidin, malvidin, and petunidin imparting red, pink, purple, violet, and blue hues (Andersen and Markham, 2006; He and Giusti, 2010). These water soluble pigments are localized in vacuoles of epidermal cells, and floral colour expression is influenced by vacuolar pH, co-pigmentation with flavones and flavanols, and metal ion complexation (e.g., delphinidin–Mg<sup>2+</sup> or Fe<sup>2+</sup> complexes in hydrangea), as exemplified in *Petunia* (purple to blue),

*Chrysanthemum* (pink to purple), and *Rose*, where the absence of the delphinidin pathway restricts true blue flower development (Tanaka and Brugliera, 2013).

### **Carotenoids**

Carotenoids are lipid-soluble tetraterpenoid pigments localized in plastids, particularly chromoplasts, and are responsible for yellow, orange, and red flower colours; they include carotenes such as  $\beta$ -carotene and lycopene, as well as xanthophylls including lutein, zeaxanthin, and violaxanthin (Nisar *et al.*, 2015). In floriculture, marigold (*Tagetes* spp.) accumulates high levels of lutein, sunflower petals display bright yellow coloration due to carotenoid deposition, and calendula and daffodil exhibit carotenoid-derived golden-yellow hues. Breeding strategies increasingly target carotenoid biosynthesis and degradation pathways, including the manipulation of carotenoid cleavage dioxygenases, to enhance colour intensity and stability in ornamental crops (Ohmiya, 2020; Yuan *et al.*, 2021).

### **Betalains**

Betalains are a unique class of nitrogen containing, water soluble pigments derived from tyrosine and are mutually exclusive with anthocyanins, such that plants synthesize either betalains or anthocyanins but never both (Timoneda *et al.*, 2019). They are classified into betacyanins, responsible for red to violet hues, and betaxanthins, which produce yellow to orange colours, and are taxonomically restricted to the order Caryophyllales, including ornamentals such as *Bougainvillea*, *Amaranthus*, *Mirabilis*, and *Portulaca* (Khan and Giridhar, 2015). In floriculture, betalains contribute to the vivid pigmentation of *Bougainvillea* bracts and *Celosia* inflorescences, and their distinct biosynthetic pathway presents opportunities for metabolic engineering and transgenic introduction into anthocyanin producing species to expand the ornamental colour spectrum (Polturak and Aharoni, 2018).

### **Interaction of Pigments**

The final visible colour of flowers is not determined by a single pigment class but results from complex interactions among biochemical and structural factors. Combinations of anthocyanins and carotenoids can produce distinctive hues, such as the orange petals of lilies, while variations in vacuolar pH modify colour expression without altering pigment composition, as

observed in the red-to-blue transition in *Hydrangea* (Grotewold, 2006; Davies *et al.*, 2012). Additionally, structural features—including epidermal cell shape, cuticle thickness, and flavanol co-pigments—affect light reflection and perception, collectively contributing to the remarkable diversity of floral coloration (Tanaka *et al.*, 2008).

#### **Factors Influencing Flower Colour Expression**

Flower colour expression is determined not solely by pigment presence but by a complex interplay of biochemical, physiological, and structural determinants that collectively influence how pigments are perceived. This multifactorial regulation includes vacuolar pH and metal ion effects on anthocyanin spectral properties as well as epidermal cell morphology and light scattering, which together modulate the final visible colour of floral tissues (Rezende *et al.*, 2025; Chen *et al.*, 2022). Understanding these integrated mechanisms is critical for breeders and biotechnologists aiming to manipulate and enhance ornamental traits for both aesthetic appeal and commercial success (Timoneda *et al.*, 2019).

#### **Vacuolar pH**

Vacuolar pH is a key determinant of flower colour, as anthocyanins exhibit red–magenta hues under acidic conditions (pH 4–5) and shift toward blue–violet in neutral or alkaline vacuoles (Tanaka *et al.*, 2008). This effect is evident in *Ipomoea* spp., where petals change from reddish to bluish during flower opening, and in *Hydrangea macrophylla*, where aluminium accumulation modifies vacuolar pH to produce blue inflorescences. Breeding strategies targeting tonoplast transporters and pH regulators offer a practical approach for precise colour modification (Ravikumar and Dhatt, 2023).

#### **Co-pigmentation**

Co-pigmentation refers to non-covalent interactions between anthocyanins and colourless flavonoids such as flavones, flavonols, or phenolic acids, which can intensify colour, stabilize anthocyanins, and subtly shift hues (Qi Qin *et al.*, 2024; Trouillas *et al.*, 2016). For instance, intermolecular co-pigmentation between flavonols and anthocyanins has been shown to produce bathochromic shifts in the flower colour of *Ranunculus* cultivars, supporting enhanced colour

expression. From a breeding perspective, promoting co-pigment accumulation or engineering increased flavanol and flavone biosynthesis provides a viable route to novel hues and improved colour stability in ornamental plants (Forkmann and Martens, 2001).

#### **Metal Ion Chelation**

Metal ion chelation plays a crucial role in flower colour development, as certain anthocyanins form stable metallo-anthocyanin complexes with ions such as Fe<sup>2+</sup>, Mg<sup>2+</sup>, or Al<sup>3+</sup>, producing distinctive hues (Kondo and Yoshida, 2003; Tanaka *et al.*, 2008). In *Hydrangea macrophylla*, blue coloration arises from delphinidin-based anthocyanins chelating aluminium ions in acidic soils, while in *Centaurea cyanus* (cornflower), brilliant blue shades result from anthocyanin–metal ion complexes. From a breeding perspective, manipulating soil mineral availability or enhancing metal ion transporter activity provides a practical strategy for expanding the ornamental colour spectrum.

#### **Cell Shape and Epidermal Structure**

Cell shape and epidermal structure are critical determinants of flower colour perception, as epidermal micromorphology modulates light reflection and intensity independent of pigment content. Specifically, conical-shaped epidermal cells function to concentrate and reflect incident light, thereby enhancing colour saturation and glossiness—a phenomenon well-documented in *Petunia* and *Antirrhinum majus* whereas flat cells tend to diffuse light, resulting in duller phenotypes (Noda *et al.*, 1994). Consequently, breeding strategies that select for favorable epidermal architectures or target cell-shape regulatory genes, such as the MIXTA transcription factor, offer a viable avenue for enhancing floral aesthetic appeal without necessitating alterations to pigment biosynthetic pathways (Reed *et al.*, 2022).

#### **Environmental and Developmental Factors**

Environmental and developmental factors exert a strong influence on flower colour expression, with temperature, light, and growth stage playing key roles. Elevated temperatures often reduce anthocyanin accumulation, resulting in paler flowers, as observed in roses and chrysanthemums, while UV and high-intensity light enhance anthocyanin biosynthesis, deepening pigmentation (Azadi *et al.*, 2016). Colour transitions during blooming, such as in morning glory

and hibiscus, arise from biochemical and pH changes, and shifts during senescence frequently serve as signals to pollinators, thereby supporting reproductive success.

### **Genetic Control of Flower Forms**

Flower form is a key determinant of aesthetic value, consumer preference, and market demand in floricultural crops, representing a complex trait governed by genetic, molecular, and developmental mechanisms, with floral homeotic genes—particularly members of the MADS-box family—playing a central role in specifying organ identity and shaping overall floral architecture (Chen and Li, 2018).

### **Role of MADS-box Genes**

MADS-box genes are a family of transcription factors that regulate floral organ identity across the different whorls of a flower. Their function is elegantly explained by the widely accepted ABC model of flower development, in which specific gene combinations determine organ specification: Class A genes confer sepal identity; Class A together with Class B genes specify petals; Class B combined with Class C genes determine stamens; and Class C genes alone establish carpel identity (Coen and Meyerowitz, 1991). This genetic framework highlights the central role of MADS-box genes in orchestrating floral morphology.

### **Variations in Flower Forms Due to Gene Expression**

Mutations, altered expression, or silencing of floral homeotic genes can produce striking modifications in flower morphology. Suppression of C-class genes (AGAMOUS-like) prevents stamen formation and replaces them with petals, resulting in double flowers—a commercially valuable trait in ornamentals such as roses, carnations, and marigolds (Lönig and Saedler, 2002). Genes regulating floral symmetry, including CYCLOIDEA, DIVARICATA, and RADIALIS, determine whether flowers are zygomorphic or actinomorphic; mutations in these genes can shift symmetry patterns, as observed in snapdragon and orchids. Additionally, regulatory genes and microRNAs influence cell division and elongation, thereby modifying petal shape, size, and serration. For example, variations in petal lobing and serration in chrysanthemum and petunia are linked to changes in transcription factor activity (Luo *et al.*, 1996).

### **Modern Approaches in Flower Form Breeding**

Traditionally, flower form improvement in floricultural crops relied on hybridization and phenotypic selection. However, advances in molecular biology now allow precise manipulation of floral development through modern biotechnological tools. Functional genomics enables the identification and characterization of key genes regulating flower form, while marker-assisted selection (MAS) facilitates the use of molecular markers linked to desirable traits in breeding programs. Genetic engineering and CRISPR-Cas9 gene editing provide targeted modification of floral homeotic genes to generate novel forms, and RNA interference (RNAi) offers a strategy to silence specific genes, such as C-class genes, to induce commercially valuable traits like double flowers (Kumar *et al.*, 2020).

### **Significance for Floriculture**

Unique flower forms hold significant value in floriculture, contributing to three major dimensions: aesthetic appeal, commercial profitability, and biodiversity. Distinct morphologies enhance ornamental beauty, while traits such as double flowers and novel petal structures command higher prices in the marketplace. Moreover, gene manipulation technologies enable the creation of new cultivars with diverse forms, ensuring both novelty and competitiveness in the global floriculture industry (Teixeira da Silva *et al.*, 2018).

### **Conventional Breeding Approaches**

Despite the rise of modern biotechnology, conventional breeding remains the backbone of the floriculture industry. These time-tested methods continue to generate the vast majority of commercial cultivars, leveraging natural and induced genetic variability to improve aesthetic and agronomic traits.

### **Hybridization**

Hybridization is the primary method for gene introgression and the creation of novel genetic combinations. It exploits sexual recombination to merge desirable traits—such as unique pigmentation, disease resistance, and altered floral morphology—from diverse parental lines. In commercial floriculture, interspecific and intervarietal hybridization have been pivotal. For instance, the vast majority of modern Chrysanthemum morifolium cultivars are complex hexaploids derived from

centuries of interspecific hybridization among elemental species like *C. indicum* and *C. zawadskii* (Datta and Janakiram, 2015). Similarly, in *Rosa*, wide distant hybridization has been instrumental in introducing recurrent blooming and new color breaks from wild species into cultivated lines (Van Huylenbroeck *et al.*, 2020). This approach facilitates the exploitation of heterosis (hybrid vigor), often resulting in progeny with superior growth habits and floral abundance compared to their parents.

### **Mutation Breeding**

Physical mutagens (e.g., gamma rays, X-rays, fast neutrons) and chemical mutagens (e.g., ethyl methanesulfonate [EMS], colchicine) are widely employed to induce point mutations or chromosomal aberrations. Extensive success has been documented in *Chrysanthemum*, *Dianthus caryophyllus* (carnation), and *Dahlia*, where induced mutagenesis has led to hundreds of registered varieties (Chen *et al.*, 2011). For example, gamma irradiation has been successfully used to develop novel flower colors and shapes in *chrysanthemum* by altering anthocyanin biosynthetic pathways (Jain, 2010).

### **Polyploidy Breeding**

This technique has been highly successful in crops like *Tagetes erecta* (African marigold), where tetraploids exhibit significantly larger blooms and improved vase life compared to their diploid counterparts. Furthermore, polyploidy can restore fertility in sterile interspecific hybrids, allowing for further breeding progress in complex genera like *Gladiolus* and *Petunia* (Dhooghe *et al.*, 2011).

### **Selection of Natural Sports**

Spontaneous somatic mutations, commonly known as "bud sports," are a major source of variability in vegetatively propagated ornamentals. These mutations often occur in the meristematic cells and can lead to periclinal chimeras, where a layer of mutated cells overlays a genetically distinct core. This phenomenon is responsible for the origin of many commercially dominant cultivars in *Rosa* and *Chrysanthemum*. Breeders continuously monitor production fields for these sports, which can be stabilized through vegetative propagation to fix novel traits such as variegated petals or distinct colour shifts (Datta, 2022).

### **Mutation Breeding: Achievements and Prospects**

Mutation breeding has proven particularly successful in floriculture, where flower color—often governed by a few genes sensitive to mutagenic agents—has enabled the development of novel cultivars in species such as *chrysanthemum* (with hundreds of gamma ray-induced varieties featuring altered shades of pink, purple, yellow, and white, plus compact, dwarf, and early-flowering mutants), *gerbera* (novel ray floret patterns, enhanced color intensity, and improved petal shapes), *carnation* (striped petals, bicolors, better fragrance, and vase life), *rose* (rare color tones difficult via conventional breeding), and *gladiolus*, *lilium*, and *petunia* (compact dwarfs for pot culture, plus gains in floral longevity and abiotic stress resistance) (Onozaki, 2019; Schum, 2003).

### **Prospects of Mutation Breeding**

With the growing global demand for novelty in ornamental plants, mutation breeding holds strong prospects, including its integration with molecular tools like TILLING for precise screening of mutant populations to enhance efficiency, synergy with CRISPR-Cas systems for improved precision while maintaining non-GMO consumer acceptance, sustainability as a low-cost and eco-friendly alternative to transgenic methods, and alignment with ongoing market needs for unique flower colors, patterns, and shapes in floriculture (Kumar and Kumar, 2018).

### **Biotechnological Approaches**

The advancement of biotechnology has revolutionized floriculture breeding, particularly in modifying flower color and form, where conventional methods are often constrained by species barriers and protracted generation times, whereas biotechnological tools facilitate targeted, efficient, and innovative trait development (Tanaka *et al.*, 2009).

### **Genetic Engineering**

Genetic engineering has revolutionized flower colour modification by enabling direct gene transfer across species to manipulate pigment biosynthetic pathways. A major focus has been the anthocyanin biosynthesis pathway, which governs red, purple, and blue pigmentation. A landmark achievement was the creation of blue roses and blue carnations—long considered unattainable through conventional breeding—by introducing delphinidin biosynthesis

genes from *Petunia* and *Viola* (pansy) (Holton and Tanaka, 1994). These transgenic flowers not only achieved commercial success but also opened new avenues for expanding the ornamental palette, demonstrating the potential of biotechnology to overcome natural limitations in floral pigmentation (Davies *et al.*, 2008).

#### **RNA Interference (RNAi)**

RNA interference (RNAi) is a powerful tool for modifying flower colour by silencing specific genes within pigment biosynthetic pathways. In *Petunia*, suppression of the chalcone synthase gene disrupted anthocyanin accumulation, producing striking white-striped flowers against purple backgrounds (van Houwelingen *et al.*, 1998). Beyond this, RNAi has been applied to block competing pigment branches, thereby enhancing the accumulation of desired pigments and generating novel bicolours and floral patterns. Importantly, this approach enables fine-tuned colour manipulation without the need to introduce foreign pigment genes, making it a precise and versatile strategy for ornamental plant improvement (Nishihara and Nakatsuka, 2011).

#### **CRISPR-Cas Genome Editing**

The CRISPR-Cas9 system represents the next generation of precision breeding, enabling highly specific edits to genes involved in pigment biosynthesis. Current research in *Petunia* and *Chrysanthemum* focuses on modifying key anthocyanin pathway genes, such as flavonoid 3-hydroxylase and dihydro-flavonol reductase, to generate novel colour shades, altered pigment intensity, or stable bicolours (Kishi-Kaboshi *et al.*, 2017). Importantly, this approach may be considered non-GMO in certain jurisdictions if no foreign DNA is introduced. Beyond coloration, CRISPR is also being explored to engineer traits such as floral longevity, fragrance, and stress tolerance, further expanding its potential in ornamental plant improvement.

#### **Marker-Assisted Selection (MAS)**

Marker-assisted selection (MAS) integrates traditional breeding with molecular tools to accelerate the development of new flower varieties. DNA markers linked to pigment biosynthetic genes allow breeders to identify seedlings carrying desirable alleles without waiting for flowering. For instance, markers associated

with anthocyanin and carotenoid pathway genes in *Petunia*, *Chrysanthemum*, and *Marigold* have been successfully applied to screen populations for targeted colour traits. By reducing breeding cycles and improving efficiency, MAS enables the rapid development of cultivars with stable and predictable flower colours, strengthening both ornamental appeal and commercial value (Debener and Linde, 2009).

#### **Breeding for Novel Flower Forms**

Flower form is a key ornamental trait that strongly shapes both aesthetic appeal and marketability in floricultural crops. Novel morphologies such as double flowers, star-shaped petals, compact inflorescences, and altered symmetries are highly prized in the industry. Their development relies on integrated breeding strategies that combine conventional selection with modern molecular approaches, enabling the creation of unique and commercially valuable floral architectures (Azadi *et al.*, 2016).

#### **Hybridization and Introgression**

Hybridization and introgression remain cornerstone strategies in ornamental breeding, as they generate variability in floral form traits such as petal number, arrangement, size, and symmetry. Interspecific and intergeneric hybridization allow rare and desirable floral traits to be introgressed into elite commercial backgrounds. Classic successes include the development of double-flowered roses and carnations, as well as star-shaped petunias achieved through hybridization. Despite their effectiveness, these approaches are often limited by reproductive barriers and hybrid sterility, which can restrict the transfer of traits. To overcome these challenges, breeders increasingly complement hybridization with advanced molecular and biotechnological interventions, ensuring greater success in creating novel and marketable floral forms (Van Huylbroeck *et al.*, 2020).

#### **Polyploidy**

Polyploidy, whether spontaneous or induced through antimitotic agents like colchicine or oryzalin, plays a transformative role in shaping floral traits. By altering cell size, gene expression, and developmental pathways, polyploidization often results in petal doubling, thicker floral tissues, and enhanced structural durability—features that contribute to fuller, more robust blooms. It can also generate novel

morphologies, including changes in symmetry and petal texture. In floriculture, polyploid cultivars of *Chrysanthemum*, *Gladiolus*, and *Lily* are widely cultivated, prized for their superior ornamental value, resilience, and adaptability, making polyploidy a powerful tool for both aesthetic enhancement and crop improvement (Dhooghe *et al.*, 2011).

#### **Mutation and Somaclonal Variation**

Mutation breeding and somaclonal variation are both highly effective approaches for generating novel flower forms in ornamental crops. Physical mutagens such as gamma rays, X-rays, and chemical mutagens like ethyl methanesulfonate (EMS) or sodium azide have been widely used to induce heritable mutations, producing unique floral phenotypes—for example, spoon-shaped petals in *Chrysanthemum*. In parallel, somaclonal variation arising during plant tissue culture provides a rich source of morphological diversity. Regenerants of *Gerbera* and *Orchid* frequently exhibit altered petal arrangement, symmetry, or flower doubling (Jain, 2010). Together, these methods offer breeders rapid and cost-effective avenues for developing new ornamental variants, expanding both aesthetic diversity and commercial opportunities in floriculture.

#### **Molecular Approaches**

Molecular approaches have greatly advanced the breeding of novel flower forms by enabling precise manipulation of floral development genes. Key regulators such as *APETALA1*, *APETALA3*, and *PISTILLATA* govern sepal and petal identity, while *AGAMOUS* (*AG*) controls stamen and carpel development—its suppression often producing double-flowered phenotypes. In *Antirrhinum*, the B-class gene *DEFICIENS* plays a central role in petal and stamen formation. These genes have been targeted through transgenic strategies, including overexpression and silencing, as well as CRISPR–Cas genome editing, which allows accurate modification of flower form genes without introducing foreign DNA. Such molecular interventions in ornamentals like *Petunia* and *Orchid* have successfully generated novel petal shapes and altered floral symmetries, expanding both aesthetic diversity and commercial potential in floriculture (Shinoyama *et al.*, 2012).

#### **Case Studies**

Several ornamental crops have become model

systems for exploring and applying diverse breeding strategies to modify flower colour and form. These case studies illustrate how conventional methods, mutation breeding, and modern biotechnological approaches have delivered practical advances in floriculture:

#### **Rose (*Rosa spp.*)**

Rose (*Rosa spp.*) has served as a prominent model for flower colour modification in ornamental breeding. Traditionally, roses lacked the delphinidin biosynthetic pathway, rendering true blue coloration unattainable through conventional breeding. This limitation was overcome in 2004 when Suntory and Florigene successfully introduced delphinidin biosynthesis genes from *Petunia* and *Pansy*, leading to the development of the world's first commercially recognized “blue rose” (Katsumoto *et al.*, 2007). In addition to transgenic colour modification, mutation breeding has been extensively employed to generate striped petals and stable bicolour phenotypes, which have gained significant popularity in the modern cut-flower market.

#### **Chrysanthemum (*Chrysanthemum morifolium*)**

*Chrysanthemum* (*Chrysanthemum morifolium*) is a leading model in ornamental breeding for flower colour and form improvement. Gamma irradiation has been widely used to induce mutations, producing numerous colour variants in shades of pink, purple, yellow, and white (Datta, 2022). Induced polyploidy has further contributed to double-flowered types, larger blooms, and thicker floral tissues, enhancing both ornamental value and vase life.

#### **Petunia (*Petunia hybrida*)**

*Petunia* (*Petunia hybrida*) has emerged as a key model system for genetic manipulation of flower colour and patterning. RNA interference (RNAi)–mediated silencing of chalcone synthase led to the development of flowers with white stripes on purple backgrounds, representing a landmark achievement in engineered floral patterning. Furthermore, transgenic approaches have enabled targeted modification of anthocyanin biosynthetic genes to generate a wide spectrum of flower colours and designs. More recently, CRISPR–Cas genome editing is being explored to precisely alter pigment biosynthesis genes, aiming to produce novel colour shades and stable bicolour phenotypes in *petunia* (Subburaj *et al.*, 2016).

#### **Gerbera (*Gerbera jamesonii*)**

Gerbera (*Gerbera jamesonii*) is a widely cultivated ornamental prized for its diverse floral forms and colours. Mutation breeding has produced novel petal morphologies such as spoon-shaped and fringed ray florets, while hybridization between cultivars has introduced new colour combinations and improved symmetry. These strategies have established gerbera as one of the most morphologically and chromatically diverse cut-flower ornamentals (Bhatia *et al.*, 2009).

#### **Carnation (*Dianthus caryophyllus*)**

Carnation (*Dianthus caryophyllus*) has been a model for both flower colour and form modification. The introduction of delphinidin biosynthesis genes through genetic engineering enabled the development of true blue carnations, which were subsequently commercialized. In addition, somaclonal variation arising from tissue culture has produced a range of floral forms, including serrated petals, fringed edges, and altered symmetry, thereby broadening the diversity of commercially available designs (Onozaki, 2019).

#### **Challenges**

Despite significant progress in conventional, mutation, and molecular breeding, the development and commercialization of novel flower colours and forms remain constrained by several biological, technical, and regulatory limitations.

#### **Consumer Acceptance**

Consumer acceptance is a decisive factor in the success of novel ornamental varieties. While genetically modified (GM) flowers such as blue roses and carnations are admired for their uniqueness, public perception remains mixed due to safety and ethical concerns. In contrast, non-GMO methods—including mutation breeding, polyploidy induction, and marker-assisted selection—tend to enjoy broader acceptance, making them more readily adopted in the global floriculture industry. This distinction strongly influences which innovations reach widespread commercial success (Ishizaka, 2012).

#### **Regulatory Hurdles**

Regulatory approval of transgenic and genome-edited ornamental varieties remains a major challenge, as biosafety evaluation processes are time-consuming, costly, and vary substantially among countries. Although ornamentals are generally perceived as lower risk than food crops, stringent regulatory frameworks

continue to cause significant delays in their commercialization (Boutigny *et al.*, 2020).

#### **Trait Stability**

Maintaining consistent expression of key floral characteristics such as colour intensity, petal doubling, and symmetry remains a major challenge in ornamental breeding, as these traits are strongly influenced by environmental factors including light, temperature, and soil nutrition across diverse growing conditions (Azadi *et al.*, 2016).

#### **Breeding Complexity**

Flower form and pigmentation are complex, polygenic traits regulated by multiple interacting genes and regulatory networks, and their strong gene–environment interactions make reliable prediction of trait expression challenging; this complexity is further compounded in many ornamental species by limited genomic resources and large, highly complex genomes, such as in chrysanthemum, which collectively slow breeding progress (Mekapogu *et al.*, 2020).

#### **Future Prospects**

The future of flower colour and form improvement in floriculture is expected to rely on the synergistic integration of advanced biotechnological tools with conventional breeding approaches, driven by growing consumer demand for novelty, sustainability, and environmentally friendly practices, thereby promoting the development of precision-based, resilient, and market-oriented breeding strategies.

#### **Integration of Omics Technologies**

Genomics, transcriptomics, proteomics, and metabolomics together provide comprehensive insights into the molecular mechanisms underlying flower pigmentation and floral development, facilitating the identification of candidate genes, regulatory networks, and metabolic pathways; when integrated with bioinformatics and systems biology approaches, these omics-driven strategies significantly accelerate trait discovery and enable precision-guided breeding in ornamental crops (Nakamura *et al.*, 2021).

#### **Expansion of Genome Editing**

Genome editing technologies such as CRISPR–Cas9 and base editors provide precise, efficient, and cost-effective tools for modifying floral traits. Unlike conventional transgenic methods, these approaches

can create non-GMO cultivars by introducing targeted mutations without foreign DNA, improving consumer acceptance. Future applications are expected to focus on fine-tuning anthocyanin pathways, petal-doubling genes, and floral symmetry regulators, paving the way for custom-designed flowers with novel colours and forms (Kishi-Kaboshi *et al.*, 2017).

### **Synthetic Biology for Novel Pigments**

Synthetic biology offers transformative potential in ornamental breeding by enabling the design and assembly of artificial pigment biosynthetic pathways that do not exist in nature. This approach allows the creation of entirely novel flower colours, including shades beyond the natural spectrum, such as turquoise and metallic hues. Additionally, pathway engineering in microorganisms presents opportunities for the eco-friendly production of floral pigments, providing sustainable alternatives for the dye and ornamental industries.

### **Climate-Resilient Breeding**

Novel floral traits are often unstable under variable climatic conditions, which can compromise flower colour and form. Future breeding programs are expected to emphasize climate-resilient ornamentals by incorporating traits such as heat tolerance, UV protection, and stress-stable pigment expression. These strategies will help maintain the consistent expression of desirable flower forms and colours across diverse global cultivation environments (Kumar *et al.*, 2020).

### **Consumer-Driven Innovations**

Future ornamental breeding will increasingly align with consumer demand for sustainability, eco-labelling, and natural/non-GMO flowers. Breeding programs are expected to emphasize eco-friendly methods such as mutation breeding, marker-assisted selection, and genome editing without transgene integration. Branding and certification of “eco-ornamentals” could further enhance market appeal, strengthening consumer trust and driving growth in the global floriculture industry.

### **Conclusion**

The breeding of floricultural crops for novel flower colours and forms has advanced considerably through the integration of traditional and modern molecular approaches. Conventional strategies such as hybridization, mutation breeding, and polyploidy

remain crucial for generating genetic variability and producing market-acceptable non-GMO cultivars. Meanwhile, biotechnological tools—including genetic engineering, RNA interference, CRISPR–Cas genome editing, and marker-assisted selection—enable precise manipulation of pigment pathways and floral development genes. Case studies in major ornamentals illustrate how these approaches have expanded the colour palette and diversified flower forms, yet challenges persist in ensuring trait stability, navigating regulatory frameworks, and achieving consumer acceptance of genetically modified varieties.

### **Conflict of Interest**

The authors declare that they have no conflict of interest.

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