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Variation in Flower Color and Morphological Traits of *Phalaenopsis* and Its Application in Commercial Horticulture

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Abstract *Phalaenopsis* is an important ornamental crop, and its flower color and morphological traits are key determinants of ornamental value and commercial application. This study systematically analyzes the variation characteristics of flower color (including solid, bicolor, and patterned types) and morphological traits (flower form, inflorescence, and plant architecture) in *Phalaenopsis*, and further elucidates their underlying mechanisms from genetic, environmental, and cultivation management perspectives. The results indicate that variation in flower color is primarily regulated by anthocyanin metabolism and its associated regulatory genes, whereas morphological traits are governed by complex polygenic interactions. Environmental factors such as light, temperature, and nutrient conditions significantly influence trait expression by modulating physiological processes and gene expression. Based on representative cultivar case studies, the study further demonstrates how trait combinations affect ornamental value and market positioning, and discusses their practical applications in cultivar selection and production management. In response to current challenges such as cultivar homogenization and insufficient trait stability, strategies emphasizing germplasm innovation and precise regulation are proposed. This study provides a theoretical basis for trait optimization and the advancement of commercial horticulture applications in *Phalaenopsis*.

Keywords *Phalaenopsis*; Flower color variation; Morphological traits; Commercial horticulture; Market positioning

1 Introduction

Phalaenopsis is one of the most important ornamental plants in the Orchidaceae and occupies a central position in the global floriculture industry, having long dominated the international orchid market (Badriah et al., 2024). Owing to its elegant floral form, extended blooming period, diverse coloration, and strong adaptability, it is widely used in both potted plant and cut-flower production systems, contributing substantial economic value to the floriculture industries of Asia, Europe, and North America (Bidarnamani et al., 2024). With the advancement of protected horticulture technologies and the refinement of tissue culture propagation systems, *Phalaenopsis* has achieved large-scale commercial production and has become a key commodity in greenhouse flower trade (Sevilleno et al., 2023). In China, the industry has developed rapidly in recent years, gradually expanding from festival-oriented consumption to applications in home gardening and landscape decoration.

The commercial value of *Phalaenopsis* is primarily determined by the combined effects of flower color and morphological traits, among which color, pattern, and floral form directly influence visual appeal and market positioning (Gawenda et al., 2012). Flower coloration exhibits a continuous spectrum ranging from white and cream to yellow, pink, and deep purple, often accompanied by complex patterns such as stripes, spots, and multicolored combinations, greatly enhancing product diversity (Badriah et al., 2024). Meanwhile, morphological traits, including flower diameter, floral shape, labellum structure, inflorescence arrangement, and plant architecture, not only determine ornamental quality but also directly affect product grading and application scenarios. For example, large-flowered cultivars with well-organized inflorescences are more suitable for high-end markets, whereas compact and multi-branching types are better adapted to home gardening. In addition, traits such as spike number, inflorescence orientation, and stem strength are closely associated with transport performance and display quality (Pramanik et al., 2022).

At the genetic level, flower color and morphological traits in *Phalaenopsis* are governed by complex molecular regulatory networks. Flower coloration is mainly controlled by the anthocyanin biosynthesis pathway and its regulatory genes, such as MYB and bHLH transcription factors, while floral organ development and inflorescence architecture involve coordinated action of multiple genes (Lou et al., 2023; Wen et al., 2025). In recent years, advances in genome-wide association studies (GWAS) and transcriptomic analyses have progressively elucidated the genetic basis of these traits, providing important support for molecular breeding (Hsu et al., 2022; Iiyama et al., 2024; Mursyidin and Hidayat, 2025). However, existing studies have largely focused on individual traits or molecular mechanisms, and systematic understanding of the interactions between flower color and morphological traits, as well as their integrated phenotypic effects, remains limited.

This study aims to systematically analyze phenotypic variation in *Phalaenopsis* from the perspective of multi-trait integration and coordinated expression. Focusing on variation in flower color and morphological traits, this work explores how different trait combinations influence commercial value and market segmentation, with the objective of revealing the relationships among key traits and their functional roles in cultivar selection and commercialization strategies. In practical production systems, trait expression is jointly influenced by genetic background, environmental conditions, and cultivation practices. Environmental factors such as light, temperature, and nutrient availability can significantly regulate pigment accumulation and floral development, leading to substantial phenotypic variation within the same genotype. Moreover, with increasing diversification of consumer preferences, demand for bicolored flowers, novel plant architectures, and integrated trait performance continues to rise, rendering traditional single-trait evaluation and breeding approaches insufficient for modern ornamental horticulture.

2 Types of Flower Color and Morphological Traits in *Phalaenopsis*

2.1 Flower color types and their characteristics

Flower color is one of the most visually striking and attractive ornamental traits in *Phalaenopsis* and serves as a key phenotypic basis for product differentiation and consumer preference. In general, *Phalaenopsis* exhibits a wide spectrum of flower colors, including white, pink, purple, yellow, and intermediate hues, which can further develop into complex patterns such as bicolored, gradient, spotted, veined, and harlequin types (Figure 1). Based on color composition and spatial distribution, flower color can be broadly classified into three categories: monochromatic, bicolored, and patterned types. Monochromatic flowers exhibit relatively uniform coloration across petals and sepals, such as pure white, pink, purple, or yellow. This type of coloration is simple, stable, and visually consistent, making it highly suitable for standardized commercial production and widely used in high-end gifts, wedding decoration, and large-scale potted plant production. Phenotypic surveys indicate that most commercial hybrids still exhibit relatively uniform color distribution, reflecting high product consistency (Indraloka and Rahayu, 2022). Genetic studies further suggest that flower color traits can be partially independent from quantitative traits such as flower size, and are controlled by relatively distinct genetic mechanisms; genome-wide association studies have identified multiple QTLs associated with anthocyanin biosynthesis, providing a genetic basis for the stable breeding of monochromatic cultivars (Hsu et al., 2022).

Bicolored flower types refer to flowers that display two or more colors within a single bloom, such as edge coloration, central shading, and gradient transitions. Compared with monochromatic types, bicolored flowers exhibit stronger visual layering and impact, better meeting the growing market demand for novelty and personalization, and are therefore increasingly represented in modern commercial cultivars. Their formation is primarily associated with differential accumulation of pigments across petals, sepals, and the labellum, with the labellum often displaying a dominant contrasting color and serving as the visual focal point (Indraloka and Rahayu, 2022). At the molecular level, the expression intensity and spatial distribution of structural and regulatory genes in the anthocyanin pathway directly determine the formation of bicolored and gradient patterns. Overexpression of PhCHS5 and PhF3′5′H can significantly intensify flower coloration, particularly in the labellum, indicating that variation in pigment biosynthesis pathway activity is a key molecular basis for bicolored traits.


Figure 1 Different gene expressions result in diverse flower colors in *Phalaenopsis* orchids

Patterned flower types represent the highest level of complexity in the *Phalaenopsis* color system and include stripes, spots, veins, blotches, and harlequin patterns. These highly distinctive color forms are often used in specialty cultivar development and high-end markets. Studies have shown that different red pigmentation patterns are regulated by distinct R2R3-MYB transcription factors: PeMYB2, PeMYB11, and PeMYB12 are associated with background coloration, spot formation, and venation patterns, respectively. In harlequin types, the random distribution of spots and blotches is associated with regulatory disruption involving PeMYB11, insertion of the retrotransposon HORT1, and interactions with miR858 and MYB repressors, leading to diverse pigmentation patterns (Lu et al., 2024a). Therefore, patterned coloration fundamentally arises from uneven pigment deposition under specific spatial and temporal gene expression, rather than simple color combination.

2.2 Flower form and structural variation

In addition to flower color, floral form and structural characteristics are critical criteria for evaluating ornamental value and cultivar classification in *Phalaenopsis*. The flowers exhibit a typical zygomorphic structure, consisting of three sepals, two lateral petals, and a highly specialized labellum, with a central column. This structure forms the basis of the characteristic “butterfly-like” appearance and defines the primary directions of floral variation. At the level of petals and sepals, significant variation exists among cultivars in terms of length, width, thickness, and curvature, resulting in diverse forms such as flat, cup-shaped, and elongated morphologies (Figure 2) (Indraloka and Rahayu, 2022; Hartati and Samanhudi, 2024). Standard cultivars typically exhibit well-spread petals and strong symmetry, whereas improved cultivars may incorporate wavy margins or increased curvature to enhance visual novelty. Quantitative analyses indicate that sepal and petal dimensions vary significantly among cultivars and serve as important indicators for classification and diversity evaluation.

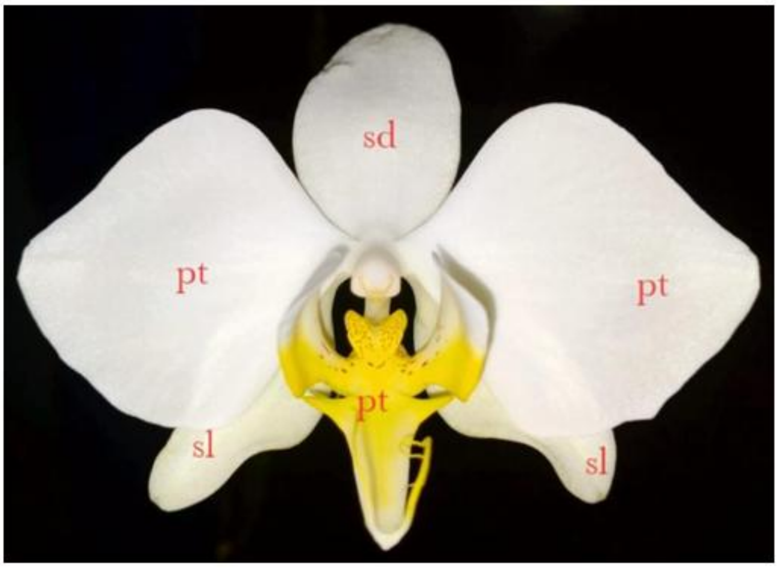

Figure 2 Floral morphology of *Phalaenopsis sp* (Adopted from Indraloka and Rahayu, 2022)
Image caption: sd=sepal dorsal, pt=petal, sl=sepal lateral (Adopted from Indraloka and Rahayu, 2022)

Petal texture represents an important microstructural feature influencing ornamental perception. *Phalaenopsis* petals can generally be categorized into waxy and velvety types: waxy petals have tightly arranged epidermal cells and a thicker cuticle, resulting in a glossy appearance, whereas velvety petals possess conical cells and a thinner cuticle, producing a softer visual effect. This indicates that floral aesthetics are not solely determined by macroscopic shape but are also influenced by microscopic structure, affecting both visual and tactile perception. The labellum is the most variable and diagnostic floral structure, exhibiting substantial variation in size, lobe differentiation, curvature, and color contrast. In some cultivars, a well-developed and vividly colored labellum forms a strong visual focal point, whereas in others, it contributes to overall harmony. Molecular studies have shown that *MADS-box* genes such as *SEPALLATA-like* and *AGL6-like* play key roles in labellum formation, and alterations in their expression can result in petal-to-labellum transformations, producing novel floral forms. Thus, the labellum serves not only as a descriptive trait but also as a key structure for understanding genetic regulation of floral morphology (Indraloka and Rahayu, 2022).

Flower size (flower diameter) is another critical factor influencing market positioning. Large-flowered cultivars are typically used for high-end displays, medium-sized cultivars offer balanced adaptability, and small-flowered types are more suitable for home gardening. Studies have shown that flower diameter is associated with coordinated variation in petal size and labellum proportion, resulting from both cell division and expansion processes, which are regulated by plant hormones such as auxins, cytokinins, and gibberellins (Guan et al., 2025). Therefore, variation in floral form reflects an integrated outcome of developmental regulation and market-oriented selection.

2.3 Inflorescence and whole-plant architecture

Inflorescence structure and overall plant architecture are key traits linking individual flower aesthetics to whole-plant commercial performance. *Phalaenopsis* typically produces racemose inflorescences, but significant variation exists among cultivars in peduncle length, inflorescence orientation, and flower arrangement (Pramanik et al., 2022). Inflorescences may be erect, arching, or pendulous, largely depending on the degree of lignification of the floral axis. Highly lignified inflorescences provide better mechanical support and are suitable for standardized potted plant production, whereas more flexible inflorescences create a dynamic and artistic visual effect, suitable for decorative applications.

Branching ability and spike number directly determine flower quantity and spatial complexity. Highly branched cultivars produce more flowers and achieve a fuller visual effect, while single-spike large-flowered types emphasize individual flower quality. These differences reflect distinct resource allocation strategies, often described as “single-spike large-flower” versus “multi-spike multifloral” commercial types. Inflorescence length and flower number per spike show considerable variation and are key quantitative indicators for distinguishing market types. In addition, flower arrangement patterns, including density and curvature, significantly influence the overall visual presentation.

Whole-plant architecture results from the integration of inflorescence traits and vegetative growth, reflecting plant height, leaf number, and spike distribution. Compact plant types are well suited for home gardening, whereas taller or spreading forms are preferred for landscape and public space applications. Studies have shown that vegetative traits such as biomass and leaf number can predict subsequent flowering performance, indicating that plant architecture reflects cumulative growth status. Notably, structural and metabolic traits may be co-regulated; for example, genes involved in anthocyanin metabolism can also influence branching and floral organ development (Lou et al., 2023). Furthermore, cultivation practices such as paclobutrazol application can modify plant architecture by reducing spike length and improving compactness (Lu et al., 2024b). Therefore, inflorescence and plant architecture are not only outcomes of genetic selection but also important targets for cultivation management.

3 Mechanisms Underlying Trait Variation in *Phalaenopsis*

3.1 Genetic factors

The variation in flower color and morphological traits in *Phalaenopsis* is fundamentally rooted in its genetic background. Significant genetic differentiation exists among species, wild germplasm, and hybrid cultivars in pigment metabolism, floral organ development, and inflorescence formation, collectively determining the diversity of flower color types, floral structures, and plant architecture. Studies based on hybrid populations derived from *Phalaenopsis aphrodite* and *P. equestris* have revealed extensive segregation in traits such as flower color and size. Genome-wide association analyses have identified multiple quantitative trait loci (QTLs) and 35 candidate genes associated with these traits, many of which are involved in anthocyanin biosynthesis (Hsu et al., 2022). These findings indicate that ornamental traits in *Phalaenopsis* are complex quantitative traits controlled by multiple genes and their interactions.

At the molecular level, pigment metabolic networks constitute the core genetic mechanism underlying flower color formation. The accumulation intensity and spatial distribution of anthocyanins, flavonoids, and carotenoids form the basis of monochromatic, bicolored, and patterned phenotypes. Comparative studies of purple and white *P. amabilis* have shown that purple petals accumulate high levels of anthocyanins (mainly cyanidin derivatives), accompanied by upregulation of key structural genes, whereas white petals exhibit restricted metabolic flux and altered flavonoid composition, resulting in pigment deficiency. In *P. pulcherrima*, the transcription factors PpMYB1 and PpbHLH1 form a regulatory complex that activates key genes such as F3H, DFR, and ANS, thereby significantly promoting anthocyanin accumulation (Wen et al., 2025). These results demonstrate that differences in expression intensity and spatial regulation within pigment biosynthesis pathways are the direct genetic basis of flower color diversity.

The formation of complex color patterns is also governed by specific regulatory networks. Members of the R2R3-MYB transcription factor family play differentiated roles in various pigmentation patterns, with distinct genes regulating background coloration, spot formation, and venation. Their differential expression ratios determine the regional distribution of pigments across floral organs. In addition, structural genes such as CHS and F3′5′H not only affect color intensity but also influence branching and floral organ number (Lou et al., 2023), suggesting coordinated regulation between metabolic pathways and morphological development. Therefore, flower color, floral form, and plant architecture are not independent traits but may be interconnected through shared regulatory networks. In breeding practice, hybridization remains the primary approach for expanding trait diversity; however, due to polygenic control and complex genetic backgrounds, progeny often exhibit significant phenotypic segregation and low stability of desirable trait combinations (Hsu et al., 2022). Furthermore, distant hybridization may produce triploid or aneuploid individuals, which can negatively affect fertility and subsequent utilization (Sevilleno et al., 2023).

3.2 Environmental factors

Beyond genetic control, environmental factors significantly influence the expression of *Phalaenopsis* traits by regulating physiological metabolism and developmental processes, with light and temperature being the most critical variables. Light conditions directly affect vegetative growth, thereby influencing flowering potential. Higher light intensity promotes biomass accumulation and leaf development, which are positively correlated with subsequent spike number and flower production. Moreover, appropriate light conditions enhance anthocyanin synthesis and improve color saturation, whereas insufficient light leads to paler coloration, and excessive light may cause tissue damage. Therefore, shading systems are commonly used in greenhouse production to optimize light conditions.

Temperature plays a decisive role in flowering regulation. Moderate low-temperature treatment is typically required to break floral bud dormancy and induce inflorescence initiation, whereas higher temperatures tend to maintain vegetative growth and delay flowering. In addition, temperature affects cell division and expansion processes, thereby influencing flower size and the degree of floral opening, ultimately impacting commercial quality. Thus, temperature not only determines the timing of flowering but also shapes floral morphology and inflorescence characteristics.

Environmental regulation of flower color also involves changes in cellular microenvironment and physiological status. For example, in blue-purple *Phalaenopsis*, flower coloration is influenced not only by pigment composition but also by vacuolar pH and the relative proportions of metal ions. Elevated pH and specific ion combinations can shift flower color from purple toward blue-purple hues (Zhao et al., 2024; Narbona et al., 2025). Furthermore, regulatory genes associated with pigmentation, such as MYB and bHLH, respond to environmental signals including light, low temperature, and hormonal cues (Wang et al., 2025b), indicating that environmental factors can modulate pigment accumulation through transcriptional regulation. Overall, environmental factors interact with genetic regulatory networks to produce substantial phenotypic plasticity, offering opportunities for production control while posing challenges for quality consistency.

3.3 Cultivation management factors

Cultivation management serves as a critical link between genetic potential and environmental conditions, directly influencing trait expression in *Phalaenopsis*. Nutrient supply is one of the most fundamental factors, as macronutrients such as nitrogen, phosphorus, potassium, and calcium not only affect vegetative growth but also play key roles in floral induction and inflorescence development. Appropriate nitrogen levels support normal growth, whereas excessive nitrogen may delay flowering and insufficient nitrogen may reduce flower number. Calcium supplementation has been shown to significantly increase leaf area, flower number, and dry weight while improving overall plant nutritional status (Alves et al., 2024), highlighting its importance in structural stability and flowering quality.

In controlled production systems, CO_2 concentration and nutrient solution management also significantly influence commercial traits. Elevated CO_2 levels can promote spike elongation, increase branching, and accelerate flowering, although flower number does not respond linearly to nutrient solution electrical conductivity, indicating the need for precise fertilization management. Additionally, practices such as shading, foliar fertilization, and temperature regulation can improve plant vigor and synchronize flowering, thereby enhancing product quality (Mubarok et al., 2024). These findings reflect a transition from conventional management to precision cultivation systems.

Furthermore, cultivation practices can indirectly affect trait formation by modulating gene expression. Regulation of genes such as CHS and F3′5′H not only influences flower color but may also affect branching and floral organ development (Figure 3) (Lou et al., 2023), while transcription factors such as MYB and bHLH respond to environmental and hormonal signals (Wang et al., 2025b). This indicates that cultivation management operates by influencing physiological signaling and gene regulatory networks to optimize phenotypic outcomes. Overall, well-designed management strategies are essential for improving trait stability, ensuring product uniformity, and maximizing economic value, serving as a crucial bridge between genetic potential and commercial production.

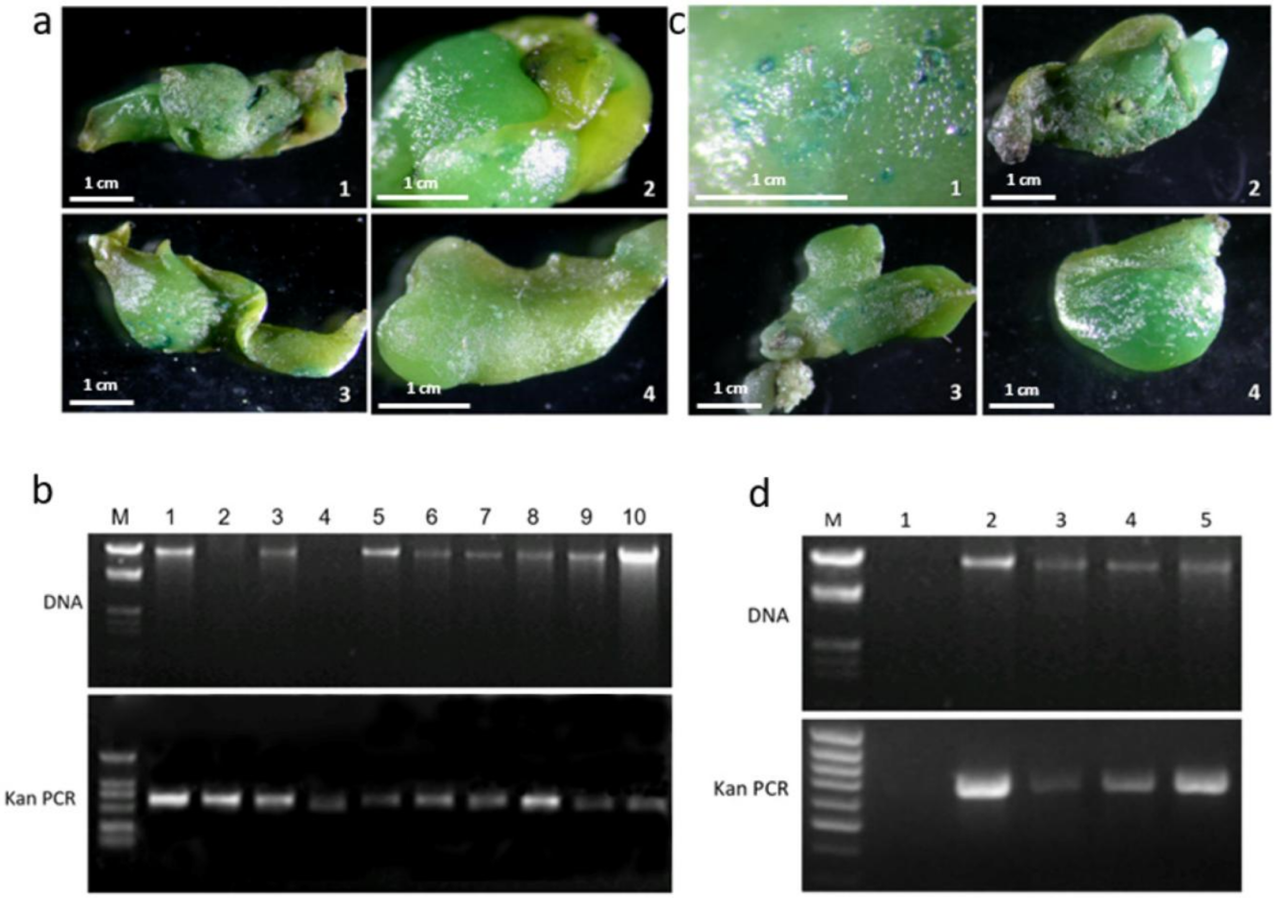

Figure 3 Screening of *Phalaenopsis* protocorms carrying PhCHS5 and PhF3′5′H after transformations (Adopted from Lou et al., 2023)

Image caption: (a) PhCHS5-transgenic *Phalaenopsis* protocorms; The image on the right is a close-focus image of the image on the left (b) Confirmation of the transformation of *Phalaenopsis* protocorms with PhCHS5 by PCR for Kan gene; M stands for marker, 1–10 stands for transformation seedlings; (c) PhF3′5′H-transgenic *Phalaenopsis* protocorms (Adopted from Lou et al., 2023)

4 Case Analysis of *Phalaenopsis*

4.1 Comparison of flower color and morphological traits among typical cultivars

In commercial *Phalaenopsis* production, significant variation exists among cultivars in flower color, pattern, floral morphology, and plant architecture. These differences collectively form the basis of varietal diversity and serve as key criteria for product grading and market segmentation (Hsu et al., 2022; Iiyama et al., 2024). Comparative analyses of representative commercial cultivars indicate that flower color and morphological traits are typically expressed as relatively stable trait combinations, which together define the ornamental style and commercial attributes of each cultivar. Standard large-flowered white cultivars are generally characterized by broad petals, symmetrical arrangement, and pure coloration, conveying a sense of elegance and formality suitable for high-end gift and wedding markets. *Phalaenopsis* Sogo Yukidian ‘V3’ is a representative example, featuring large flowers, a pure white perianth, strong structural integrity, and velvety petals, reflecting a classic and refined aesthetic.

In contrast, pink and purple-red cultivars often exhibit higher color saturation and stronger visual impact, making them more suitable for festive retail markets and prominent display settings. Bicolored and patterned cultivars further enhance individuality. For instance, ‘Frigdaas Oxford’ displays a yellow base color with red-purple patterns, and its thick, waxy petals not only enhance pattern visibility but also improve durability during transport and display (Han et al., 2025). In hybrid populations such as *P. intermedia* (*P. aphrodite*×*P. equestris*), offspring exhibit wide segregation in both flower size and color, ranging from small, vividly colored flowers to medium-sized pure white flowers (Hsu et al., 2022; Iiyama et al., 2024). This demonstrates that the diversity observed in commercial cultivars fundamentally arises from recombination and directional selection of parental traits.

In terms of morphological traits, cultivars also differ significantly in flower diameter, peduncle length, inflorescence orientation, and flower number per spike. Analysis of 19 quantitative traits across 15 hybrid *Phalaenopsis* genotypes revealed distinct morphological groupings (Hartati and Samanhudi, 2024). Further studies on six species and 17 horticultural hybrids showed that inflorescence orientation varies from erect to semi-erect, arching, and pendant, and is closely associated with the degree of lignification in the inflorescence axis (Pramanik et al., 2022). The Indonesian cultivar Puspita Devi Agrihorti, for example, exhibits relatively large flowers (approximately 8.7-8.9×8.2-8.5 cm), long peduncles (50.6-88.2 cm), and 9-20 flowers per spike, showing clear differences from comparison cultivars such as Ayu Pujiastuty and Indu Pramesi (Figure 4) (Nurmalinda et al., 2023).

Figure 4 Candidate Varieties of *Phalaenopsis* 1 (Puspita Devi Agrihorti) (Adopted from Nurmalinda et al., 2023)

4.2 Influence of trait differences on ornamental value

The ornamental value of *Phalaenopsis* arises from the integrated expression of flower color, morphology, and overall plant structure. Among these, flower color is the primary factor influencing first visual impression. Bright or highly contrasting colors tend to attract immediate attention, whereas soft and uniform color tones provide a more stable and enduring aesthetic appeal (Han et al., 2025). Consumer preference studies indicate that cultivars with harmonious combinations of color and pattern are more likely to be favored. For example, Puspita Devi Agrihorti achieved a first-choice preference rate of 35.9% in surveys, highlighting the importance of integrated color design in determining ornamental value (Nurmalinda et al., 2023).

Differences in floral morphology further enhance the viewing experience. Cultivars with large, symmetrical petals often present a fuller and higher-quality visual impression, while more elongated or loosely arranged floral forms convey a natural and dynamic aesthetic. The labellum (lip) plays a particularly important role in visual focus, with its structure and color contrast contributing to increased depth and complexity (Figure 5). Petal texture also influences perception; velvety petals enhance softness and elegance, whereas waxy petals increase glossiness and durability (Han et al., 2025).

In addition, the combination of flower size and flower number determines the mode of visual presentation. Cultivars with fewer but larger flowers emphasize individual floral refinement, whereas those with numerous smaller flowers create a fuller overall display. At the whole-plant level, the coordination between inflorescence structure and plant architecture is equally critical. Cultivars with erect, self-supporting inflorescences provide better display quality and a more orderly appearance (Pramanik et al., 2022). Therefore, ornamental value is not determined by a single trait, but by the synergistic interaction of color, floral form, and plant structure.

Figure 5 Different flower shapes of the *Phalaenopsis* orchid

4.3 Impact of trait variation on market positioning

Variation in *Phalaenopsis* traits directly determines market positioning and product stratification. Different combinations of flower color, morphology, and plant architecture correspond to specific consumption scenarios and price segments, forming the basis for effective market segmentation (Gabellini and Scaramuzzi, 2022). In high-end gift markets, cultivars with large flowers, pure colors, and well-structured forms are preferred, particularly white or light-colored *Phalaenopsis*, which are widely used in weddings and formal occasions due to their strong cultural symbolism (Han et al., 2025).

In mass consumer and home gardening markets, trait preferences emphasize practicality and cost-effectiveness. Small-flowered, highly branched, and high-flower-number cultivars are more suitable for household display due to their compact form and abundant visual effect. At the same time, cultivars with self-supporting inflorescences and stable flowering performance are better suited for supermarkets and retail chains, where product uniformity and transport durability are critical (Pramanik et al., 2022).

Bicolored, patterned, and novelty cultivars are primarily targeted at differentiated and high-value markets. These products exhibit strong visual identity in both color and structural traits, catering to collectors and consumers seeking unique or personalized products (Badriah et al., 2024). For example, the strong consumer performance of Puspita Devi Agrihorti demonstrates that the combination of rich coloration and high flower number can establish competitive advantages in regional markets (Nurmalinda et al., 2023). Under current consumption trends, *Phalaenopsis* product development is shifting from single-trait optimization to the integration of trait combinations with market positioning, which has become a key strategy for enhancing industry competitiveness.

5 Application in Commercial Horticulture

5.1 Cultivar selection and market matching

In commercial horticulture systems, the selection of *Phalaenopsis* cultivars must be precisely aligned with target consumer markets. Different consumer groups exhibit significant variation in aesthetic preferences, usage scenarios, and price sensitivity, thereby imposing distinct requirements on flower color, floral morphology, and plant architecture (Nurmalinda et al., 2023). Consequently, the commercial application of color and morphological traits is not merely an aesthetic decision, but a strategic configuration based on market segmentation and consumer behavior. With the development of data-driven marketing, cultivar selection is gradually shifting from experience-based approaches to more precise matching grounded in consumer preference data and channel-specific demand.

In high-end gift and interior decoration markets, consumers tend to prefer cultivars with pure colors, well-structured flower forms, and clear visual focal points. Such products emphasize ceremonial value and spatial aesthetics, making large-flowered white or light pink *Phalaenopsis* particularly advantageous (Nurmalinda et al., 2023). In contrast, mass-market consumers prioritize cost-effectiveness and spatial adaptability, favoring multifloral, highly branched, and compact cultivars that provide higher visual density within limited space (Gabellini and Scaramuzzi, 2022; Han et al., 2025). These differences highlight the distinct trait combinations required across market segments.

With increasing consumption upgrading and diversification of aesthetic preferences, demand for personalized products continues to grow. Younger consumers and horticultural enthusiasts are more inclined to select cultivars with complex color patterns, such as bicolored, spotted, or harlequin types, which enhance visual distinctiveness and command premium prices in niche markets (Badriah et al., 2024; Chen et al., 2024). As a result, modern cultivar selection has evolved from simple visual evaluation to a multidimensional decision-making process that integrates consumer demand, market positioning, and distribution channel characteristics (Gabellini and Scaramuzzi, 2022; Wei et al., 2022).

5.2 Production management and commercialization strategies

Production management is the key process through which the genetic potential of *Phalaenopsis* cultivars is translated into stable commercial value. The inherent advantages of a cultivar can only be fully realized under appropriate production systems that ensure uniformity and marketable quality (Han et al., 2025). Therefore, modern production management focuses on regulating plant development throughout the entire growth cycle—from vegetative growth to flowering—by controlling standards, uniformity, and floral quality.

Different cultivars require differentiated management strategies. Large-flowered cultivars typically demand enhanced nutrient supply and structural support to ensure flower size and integrity, whereas multifloral or highly branched cultivars require careful regulation of branching and flowering synchronization to maintain visual balance. Precise control of light, temperature, and nutrient conditions can significantly influence spike number, flower count, and plant uniformity. Additionally, leaf number and plant biomass can serve as reliable predictors of flowering performance, indicating that production management is not only a cultivation practice but also a tool for targeted optimization of trait expression.

At the commercialization level, efficient tissue culture systems ensure large-scale propagation and genetic uniformity of elite cultivars (Han et al., 2025), while flowering control technologies determine whether products can meet seasonal and festive market demands. Meanwhile, commercialization strategies increasingly depend on channel differentiation, with different distribution channels imposing varying requirements on plant uniformity, transport stability, and visual quality (Gabellini and Scaramuzzi, 2022; Wei et al., 2022). Therefore, production systems must be closely aligned with marketing and distribution systems to enhance supply chain efficiency and market responsiveness.

5.3 Branding and product combination applications

In an increasingly competitive floriculture market, branding strategies and product combination approaches have become essential tools for enhancing the added value of *Phalaenopsis*. Flower color and morphological traits not only determine ornamental quality but also form the basis of brand identity and product differentiation (Gabellini and Scaramuzzi, 2022). As consumer demand shifts from functional to experiential consumption, *Phalaenopsis* products are transitioning from single potted plants to more design-oriented, scenario-based, and product-line-driven offerings.

Different combinations of traits support differentiated brand positioning. For example, white, round, and multifloral cultivars are well suited for "classic elegance" product lines targeting mainstream and premium decoration markets, whereas cultivars with rare colors or distinctive patterns can be positioned as premium or collector's editions, emphasizing uniqueness and exclusivity (Badriah et al., 2024; Chen et al., 2024). In addition, the cultural symbolism associated with flower colors can be incorporated into brand narratives to enhance emotional value and consumer identification (Nurmalinda et al., 2023).

Product combination strategies further expand the application potential of *Phalaenopsis*. Miniature and multifloral cultivars can be integrated into mixed-planter designs to meet the demands of home decoration and lifestyle-oriented consumption (Gabellini and Scaramuzzi, 2022; Han et al., 2025). Moreover, *Phalaenopsis* can be combined with other ornamental plants or decorative materials to create ready-to-display products that require minimal consumer effort (Fauzia et al., 2023). By integrating trait advantages with branding strategies and product design, producers can significantly enhance product value and broaden application scenarios in the market.

6 Existing Problems and Development Trends

6.1 Current issues

Despite the rapid development of the *Phalaenopsis* industry, significant constraints remain in cultivar innovation and structural optimization, among which the homogenization of commercial cultivars is particularly prominent. Although the number of cultivars on the market continues to increase, most are derived from a limited set of core parental lines. Repeated complex hybridization within similar genetic backgrounds has led to convergence in flower color, flower form, and inflorescence types, resulting in a lack of truly novel trait combinations (Wang et al., 2025a). This phenomenon of "increased quantity but limited innovation" leads to visually similar products in the market, weak differentiation, and reduced attractiveness and competitiveness of new cultivars. In addition, the inefficient utilization of core germplasm resources, characterized by repeated use of favorable traits without systematic integration, further restricts the depth and breadth of cultivar innovation.

At the same time, insufficient trait stability has become a key factor limiting product quality improvement. Flower color and morphological traits in *Phalaenopsis* are highly sensitive to environmental variation, and fluctuations in light, temperature, and cultivation conditions can easily result in unstable coloration, morphological variation, and uneven flowering. In particular, high-value traits such as rare colors and complex patterns often exhibit unstable genetic expression, with segregation, degradation, or weakening occurring across different environments or propagation generations (Wu et al., 2022; Lou et al., 2023; Chen et al., 2024). Furthermore, genetic linkage effects hinder the independent selection of desirable traits, while ploidy abnormalities and cytogenetic instability arising from distant hybridization further complicate trait fixation and large-scale application (Sevilleno et al., 2023; Wang et al., 2025a).

At the production and industry chain levels, issues related to consistency control and supply-demand matching are also evident. Current cultivation practices largely rely on generalized management systems and lack precise, cultivar-specific optimization, resulting in considerable variation in plant growth and flowering performance. Meanwhile, the absence of unified grading standards across the industry leads to inconsistencies in quality evaluation among producers, thereby affecting market efficiency and brand recognition. In addition, while production systems emphasize standardization and scale, consumer demand is increasingly oriented toward personalization and differentiation, creating a structural mismatch that constrains value chain coordination and value enhancement (Gabellini and Scaramuzzi, 2022).

6.2 Changes in market demand and consumer preferences

With consumption upgrading and accelerating urbanization, the *Phalaenopsis* market is shifting from traditional single potted plant consumption toward more diversified and scenario-based applications. Classic large-flowered white or pastel cultivars still dominate the mainstream market, but consumer interest in novel flower colors, compact combinations, and locally bred cultivars is steadily increasing (Nurmalinda et al., 2023). This trend indicates that the market is transitioning from a primarily standardized model to a dual structure combining standardization and differentiation, thereby placing higher demands on cultivar innovation.

Consumer behavior exhibits clear segmentation. Mass-market consumers tend to prioritize price, flower number, and ease of maintenance, with a strong emphasis on product stability and cost-effectiveness. In contrast, high-end consumers and hobbyists place greater value on rarity, uniqueness of flower color, and morphological novelty, and are willing to pay premium prices for distinctive traits. In gift-giving and emotional consumption contexts, *Phalaenopsis* has evolved from a purely ornamental plant into a product carrying cultural symbolism and emotional value, significantly enhancing its added value. This stratification of consumer demand is driving the market toward more refined and multi-tiered structures.

Meanwhile, application scenarios and sales channels continue to expand. *Phalaenopsis* has extended from traditional festive gifts to broader uses such as home decoration, commercial space design, and cultural–creative products. The rapid development of e-commerce and new retail models has increased the importance of visual presentation and packaging design, while also imposing higher requirements on product uniformity and logistics performance. In addition, green consumption concepts and cultural value recognition are gradually becoming important factors influencing consumer choices, promoting the industry toward sustainability and cultural integration (Gabellini and Scaramuzzi, 2022).

6.3 Future development directions

The future development of the *Phalaenopsis* industry will center on breeding innovation, with a focus on expanding the genetic base and alleviating cultivar homogenization. Interspecific and intergeneric hybridization to introduce rare flower colors, complex patterns, and desirable plant architectures represents an important pathway for achieving trait breakthroughs (Wu et al., 2022). Meanwhile, advances in genomics and molecular marker technologies, including QTL mapping and core germplasm resource development, are providing a solid foundation for marker-assisted breeding and precision selection (Hsu et al., 2022; Lai et al., 2024). Future breeding strategies are expected to shift from experience-based approaches toward data-driven and goal-oriented frameworks, thereby improving breeding efficiency and trait controllability.

At the technological level, the integration of conventional breeding with modern biotechnologies will become a major trend. Genome editing technologies such as CRISPR/Cas9 offer new opportunities for precise trait improvement, although they are still constrained by limitations in transformation efficiency and regeneration systems (Lou et al., 2023). At the same time, precision production systems based on environmental control and data analysis will contribute to improving flowering synchronization and quality stability (Cembrowska-Lech et al., 2023; Kaya, 2025). The application of high-throughput phenotyping and data modeling is also expected to provide more scientific decision support for production management.

From an industrial perspective, intelligent production and sustainable development will be key future directions. The application of the Internet of Things (IoT) and automated systems can enable precise environmental control, improve production efficiency, and reduce resource consumption. The integration of genomic, phenotypic, and environmental data will further promote the development of intelligent breeding and precision management systems (Xu et al., 2022; Farooq et al., 2024). In addition, optimizing resource use efficiency, developing circular agriculture models, and expanding cultural-creative and design-oriented horticultural products can enhance industry value and facilitate the transition of the *Phalaenopsis* sector from traditional production toward a high-value, innovation-driven industry.

7 Conclusion

Flower color and morphological traits jointly determine the ornamental value, consumer preference, and market competitiveness of Phalaenopsis. On the one hand, the wide spectrum of flower colors—from pure white and soft pastel tones to highly saturated red, purple, and yellow, as well as complex bicolor or spotted patterns—provides diverse visual choices and emotional expressions for consumers, directly influencing first impressions and purchase intention. On the other hand, morphological traits—including flower size and fullness, petal and sepal morphology, labellum structure and pattern, inflorescence length and curvature, branching ability, flower number and arrangement, and overall plant architecture—not only affect aesthetic perception but also determine display performance, transportability, and application scenarios (e.g., potted plants, cut flowers, and long-term indoor decoration). In modern commercial horticulture, these traits are no longer merely static ornamental attributes; instead, they function as integrative indicators linking genetics, environment, and cultivation management, and serve as key tools for branding, product differentiation, and value enhancement. Overall, flower color and morphology constitute the core phenotypic basis for *Phalaenopsis* breeding, production planning, and marketing strategies, and are essential for sustaining industry vitality and innovation capacity.

Variation in flower color and morphological traits provides the foundation for market segmentation and diversified product development in *Phalaenopsis*. Differences in hue, brightness, and pattern enable breeders and enterprises to target specific consumer groups and cultural contexts—for example, white and light-colored cultivars are preferred in minimalist or Nordic-style settings, whereas bright red, purple, or golden cultivars are favored in festive and gift markets. Morphological variation further refines product positioning: large, round flowers with pendulous inflorescences are suitable for high-end display environments (e.g., hotel lobbies); compact plants with multiple spikes and medium-sized flowers are ideal for home and office decoration; while miniature and multifloral cultivars meet the preferences of younger consumers for small, refined, and easily arranged plants. At the production level, trait variation is also closely associated with cost control and supply chain efficiency. Cultivars with stable color expression, uniform morphology, and strong adaptability can reduce production risks and losses, whereas those with extended flowering duration and superior postharvest performance improve inventory turnover and facilitate long-distance distribution. Therefore, effective identification, utilization, and regulation of trait variation not only support the development of distinctive products and brands, but also promote deeper integration of the *Phalaenopsis* industry with diverse consumption scenarios such as home gardening, urban greening, and cultural–creative horticulture.

To fully exploit trait variation and promote the sustainable development of the *Phalaenopsis* industry, future efforts should focus on the coordinated advancement of breeding innovation, standardized production, and market-oriented strategies. In breeding, it is essential to integrate conventional hybridization with molecular-assisted selection and genomic technologies, systematically incorporating elite germplasm with novel colors, patterns, and morphologies while simultaneously improving stress tolerance, flowering stability, and postharvest longevity, thereby achieving the coordinated optimization of ornamental and production traits. In cultivation management, standardized and digitalized systems for regulating light, temperature, nutrition, and plant growth regulators should be established, alongside the adoption of intelligent production technologies (e.g., environmental control, phenotyping, and decision-support systems) to stabilize trait expression, reduce quality variation, and enhance production efficiency. From a market and industry perspective, stronger collaboration among breeders, propagators, producers, distributors, and retailers is required to design product portfolios based on seasons, holidays, and application scenarios, and to develop recognizable product lines and brands centered on clear trait profiles. Meanwhile, incorporating consumer preference research and aesthetic trends into breeding objectives, expanding applications in cultural, educational, and therapeutic contexts, and strengthening international cooperation and intellectual property protection for new cultivars will further enhance the global competitiveness, cultural influence, and long-term resilience of the *Phalaenopsis* industry.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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