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.