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.