Sucrose-metabolizing enzymes provide the second major mechanistic layer. Abiotic stress induced the transcriptional activation of *DoSUS* genes, and *DoSUS2* responded strongly to drought and ABA; heterologous expression of *DoSUS2* increased soluble sugar accumulation and stress tolerance, while the DobHLH14-DoSUS2 module was linked to a broader saccharometabolism network involving *DoSUS1, DoGT5, DoUGE2, DoUGE3,* and *DoVIN2* (Liu et al., 2025). Acid invertases act in parallel: cold and dehydration increased soluble sugar content in leaves and stems, and the associated upregulation of *DoAINV* genes likely enhanced sucrose hydrolysis into glucose and fructose, thereby supporting osmotic homeostasis and polysaccharide accumulation (Liu et al., 2024). Diurnal temperature difference further altered expression of *SUS, SUT, HKL1, HGL, AMY1,* and *SS3*, indicating that environmental control acts on transport, sucrose turnover, starch breakdown, and hexose metabolism simultaneously (Chen et al., 2024). Related *Dendrobium* evidence is mechanistically consistent: cell wall invertase activity rises with sink activation and sucrose feeding stimulates hexose accumulation, supporting a general model in which increased sink-side sucrose cleavage promotes downstream carbohydrate deposition.

6.3 Regulation of carbon allocation and polysaccharide accumulation through environmental stress responses and multifactor interactions

Controlled environments also regulate polysaccharide accumulation by redistributing carbon under stress and by integrating multiple environmental signals. In *D. officinale*, seasonal sugar accumulation depends on temperature and humidity variation, and related genes are enriched in abiotic-stress, photosynthesis, and starch-sucrose metabolism pathways, showing that carbon allocation is embedded in a stress-response framework. Drought and cold often increase soluble sugar pools rather than depleting them, because carbon is redirected toward osmotic adjustment and protective metabolism; under dehydration or cold, soluble sugars rose and AINV-related sucrose cleavage increased, while long-term dehydration changed genes involved in stress response, photosynthesis, phytohormone signaling, carbon metabolism, and fructose/mannose pathways (Liu et al., 2024). This stress-buffering role is consistent with the biology of the species: *D. officinale* can survive prolonged water deficit and rapidly resume growth after rehydration, and its thick, polysaccharide-rich organs are part of that drought-adaptive system (Yu et al., 2025). Moderate stress can therefore favor accumulation, but the response is conditional. In *Dendrobium nobile*, 0℃ for 4 d increased polysaccharides by 56.18%, whereas -4℃ caused severe damage, indicating that beneficial accumulation occurs within a stress window rather than under unlimited stress intensity (Fan et al., 2024).

The mechanism becomes more complex under combined stresses, because light, temperature, humidity, and water supply interact rather than acting additively. In *D. officinale*, combined high temperature and drought caused genotype-dependent differences in morphology, antioxidative capacity, polysaccharide accumulation, and gene expression, and dual stress markedly upregulated glycosyltransferase genes, linking multifactor stress directly to polysaccharide-related biosynthetic capacity (Gao et al., 2026). Broader plant evidence supports the same carbon-allocation principle: drought under elevated temperature tends to reduce starch more than soluble sugars, implying that stored carbon is degraded to maintain osmotic regulation and defense demands when current photosynthesis cannot fully meet metabolic need (Wang and Wang, 2023). At the cultivation scale, ecological analyses identified maximum temperature, humidity, sunshine duration, pH, and soil nitrogen and phosphorus as key variables affecting medicinal quality, confirming that polysaccharide accumulation emerges from multifactor coordination rather than single-factor control.

7 Current Challenges and Future Directions

A central challenge is that the environmental determinants of polysaccharide accumulation are clearly multifactorial, but their optimal thresholds and interaction patterns are still not resolved. Ecological analysis identified eight key factors affecting medicinal quality-maximum and minimum relative humidity, maximum temperature, sunshine duration, soil pH, soil total nitrogen, soil total phosphorus, and available phosphorus-showing that polysaccharide formation depends on a coupled environmental network rather than any single variable. Seasonal work further showed that stem sugar accumulation follows a nonlinear annual pattern and is jointly shaped by temperature and humidity, with rapid accumulation from October to February and transcriptomic enrichment in photosynthesis, abiotic stress, and starch-sucrose metabolism pathways. At the