

plants, short-term shading can promote leaf nitrogen metabolism and increase amino acid accumulation, whereas long-term or high-intensity shading inhibits sugar metabolism and alters flavonoid metabolic pathways (Li et al., 2020). Under shading conditions, protein hydrolysis and nitrogen redistribution can increase free amino acid content, while catechin and other phenolic compound levels decline, reflecting a shift in carbon-nitrogen allocation direction (Shao et al., 2022). Shading experiments in forest plants have shown that, as shading increases, the leaf C:N ratio decreases while the N:P ratio increases, and non-structural carbohydrates are closely associated with C: N: P stoichiometric characteristics, suggesting a dynamic trade-off between carbon storage and nutrient utilization under low-light environments (Liu et al., 2020). For *T. hemsleyanum*, if shading is appropriate, carbon supply and nitrogen utilization can remain relatively coordinated, which is beneficial for protein synthesis, enzymatic reactions, and normal operation of metabolic pathways. If shading is excessive, however, carbon assimilation becomes restricted while nitrogen metabolic demand remains, potentially causing C-N imbalance and affecting plant dry matter accumulation and substrate supply for secondary metabolism.

5.3 Effects on the accumulation of flavonoids, polysaccharides, and phenolic compounds

Flavonoids, polysaccharides, and phenolic acids are important active components for evaluating the medicinal quality of *T. hemsleyanum*, and they are also representative pharmacologically active substances in its tuberous roots and leaves (Hu et al., 2021). The accumulation of these components is jointly regulated by multiple factors, including light intensity, spectral composition, temperature, water availability, nutrient status, and growth stage. The shading environment can influence the operation of secondary metabolic pathways in *T. hemsleyanum* by altering light signal input, photosynthetic product supply, and cellular redox status. Moderate shading can alleviate strong light stress and maintain a relatively stable physiological metabolic state, thereby providing a favorable cellular environment for active component synthesis. Meanwhile, suitable weak light or specific light quality stimulation may also induce plants to adjust phenylpropanoid metabolism and flavonoid biosynthesis, thereby affecting the accumulation of flavonoids and phenolic compounds.

Different active components do not respond uniformly to shading environments. In *T. hemsleyanum* cultivated under different colored films, blue film promoted vegetative growth and soluble amino acid accumulation, whereas red film significantly increased flavonoid content and the activity of key enzymes such as phenylalanine ammonia-lyase (PAL). This indicates that changes in light quality under shading environments may lead plants to exhibit different metabolic orientations between yield and quality (Bai et al., 2021). Long-term low-intensity blue light treatment of *T. hemsleyanum* tuberous roots can simultaneously increase tuberous root yield and total flavonoid content, enhance antioxidant activity, and upregulate genes related to flavanol biosynthesis (Zhao et al., 2024). In addition, seasonal analysis has shown that flavonoid content, as well as the antioxidant activities of major phenolic compounds and polysaccharides in *T. hemsleyanum*, fluctuate with changes in sunshine duration, temperature, and humidity, while suitable shading conditions help enhance the accumulation of medicinally relevant phenolic compounds and polysaccharides (Figure 2) (Shi et al., 2022). These results indicate that the accumulation of active components in *T. hemsleyanum* is sensitive to both light intensity and spectral composition, and shading management affects not only yield but also the intrinsic quality of medicinal materials.

Polysaccharide accumulation is usually closely related to carbohydrate metabolism, tuberous root development, and storage substance formation. Therefore, when excessive shading causes carbon source insufficiency, polysaccharide accumulation may be inhibited. Shading studies on *Bletilla* species have shown that moderate shading or medium light intensity can result in relatively high polysaccharide content, accompanied by increases in precursor substances such as sucrose-6-phosphate and glucose-6-phosphate. In contrast, excessive shading or strong light reduces polysaccharide levels and disrupts carbon metabolism (Xu et al., 2024; Zhu et al., 2024). Flavonoids and phenolic compounds are more strongly affected by light signals, oxidative stress, and secondary metabolic enzyme activities. Studies on tea plants have shown that strong shading generally inhibits flavonoid and catechin biosynthesis while increasing free amino acid content, indicating that reduced light can alter the balance between nitrogen-rich and carbon-rich metabolites (Li et al., 2020; Shao et al., 2022). Therefore, the effects of shading environments on the medicinal quality of *T. hemsleyanum* are component-specific, light quality-sensitive, and intensity-dependent. An ideal shading regime should promote the coordinated accumulation of major active