

photochemical quenching in *T. hemsleyanum* decrease, while non-photochemical quenching increases, indicating the occurrence of photoinhibition. Moderate shading, by contrast, can maintain relatively high photochemical efficiency (Dai et al., 2009). Similar patterns have also been reported in other woody and medicinal plants: net photosynthetic rate is relatively high under moderate shading, the functions of photosystem II and photosystem I are more coordinated, whereas strong light or heavy shading may cause photosystem functional imbalance (Barazetti et al., 2021).

However, the effect of shading on photosynthetic efficiency is dual in nature. When shading is too strong, insufficient photosynthetically active radiation becomes the main factor limiting photosynthesis in *T. hemsleyanum*. Under such conditions, even if stomatal conductance does not decline significantly, insufficient light energy received by leaves will restrict both light and dark reactions, resulting in a decrease in net photosynthetic rate. Long-term heavy shading reduces organic matter synthesis, disrupts the balance between respiratory consumption and material accumulation, and further affects robust vine growth, leaf functional maintenance, and underground tuberous root enlargement. Therefore, the key to shading cultivation is not simply to reduce light exposure, but to regulate light intensity rationally so that *T. hemsleyanum* can avoid strong light stress while obtaining sufficient light energy to support biomass accumulation and medicinal quality formation.

4.3 Effects on the antioxidant system and cellular homeostasis

The shading environment also regulates stress resistance and cellular homeostasis in *T. hemsleyanum* by affecting the production and scavenging of reactive oxygen species. Regulation of the antioxidant system is an important mechanism by which plants cope with light stress. Although direct studies on antioxidant enzyme activities in *T. hemsleyanum* remain relatively limited, related studies in model shade-tolerant plants and medicinal plants are more abundant. Under strong light, high temperature, water stress, or other unfavorable light environments, the photosynthetic electron transport chain in leaves is prone to over-reduction, resulting in the accumulation of reactive oxygen species (ROS), which can further induce membrane lipid peroxidation, protein damage, and destruction of photosynthetic structures (García-Caparrós et al., 2020; Mishra et al., 2023). Therefore, plants must rely on enzymatic and non-enzymatic antioxidant systems to remove excess ROS, protect cellular structures, and maintain metabolic stability.

The main enzymatic antioxidant components include superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), glutathione peroxidase (GPX), glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), and dehydroascorbate reductase (DHAR). These enzymes act cooperatively to convert reactive oxygen species such as superoxide anions and hydrogen peroxide into less harmful products. Meanwhile, non-enzymatic antioxidants such as ascorbic acid, glutathione, carotenoids, and flavonoids can also provide additional redox buffering capacity (García-Caparrós et al., 2020; Rajput et al., 2021). Moderate shading can reduce excessive light energy input, alleviate photooxidative pressure, and help maintain coordinated operation of antioxidant enzyme systems, thereby improving the plant's buffering capacity against environmental fluctuations.

Under different light conditions, many plants can maintain ROS homeostasis by upregulating antioxidant-related gene expression and increasing antioxidant enzyme activities. In the shade-tolerant plant *Solidago canadensis*, increased shading can induce high expression of SOD, POD, CAT, APX, and GPX genes, thereby enhancing ROS scavenging capacity under shading stress. In shade-tolerant *Panax notoginseng*, strong light stress increases SOD, POD, and CAT activities, while non-photochemical quenching dissipates excess energy to prevent photooxidative damage (Cun et al., 2023). Jasmine shows rapid changes in SOD, POD, APX, and CAT activities under different shading levels, and these changes are affected by both shading intensity and duration. Moderate shading generally supports more efficient antioxidant responses and reduces membrane lipid peroxidation compared with full sunlight or heavy shading (Deng et al., 2018). Based on these findings, it can be inferred that, in *T. hemsleyanum*, suitable shading environments may reduce excessive ROS production caused by strong light or extreme shading, support balanced antioxidant enzyme activity, and maintain membrane integrity, osmotic regulation capacity, and