

identified and compared with wild plants bearing single or multiple buds, showing that bud number is a relevant structural trait in cultivation and germplasm evaluation (Cheng et al., 2023). Across *Polygonatum*, rhizomes retain typical monocotyledonous anatomical organization, but species-level differences occur in vascular bundle type, and in *Polygonatum* rhizomes collateral, amphivasal, and incomplete amphivasal bundles have all been observed (Cantürk and Özhatay, 2021).

Bud formation on the rhizome is not random, but follows a recognizable developmental pattern associated with annual segment formation and latent bud differentiation. In some *Polygonatum* germplasm, annual rhizomes carry two developed latent buds with unequal vigor, one long and stout and the other short and thin, suggesting a built-in hierarchy among buds that can influence which propagules dominate subsequent growth. By contrast, other rhizome types show short, small, or underdeveloped latent buds, indicating that the regenerative potential of different rhizome segments is partly constrained by bud morphology itself (Hu et al., 2022). Developmental anatomy further shows that, during seed-derived establishment, the hypocotyl swells into a newborn rhizome and becomes the site on which the germ and radicle differentiate, demonstrating that rhizome formation is an early organizing event in the plant's life cycle rather than merely a later storage response. Because the first rhizome links emerging organs with nutrient transfer tissues, its structural integrity and bud-bearing capacity directly determine the material basis for subsequent vegetative multiplication.

2.2 Physiological basis

The regenerative capacity of *P. sibiricum* rhizomes depends on their strong reserve accumulation function. Histochemical evidence shows that polysaccharides are localized in mucilage cells of *Polygonatum* rhizomes, while saponins and volatile oils are mainly distributed in the ground tissue, indicating spatial differentiation of storage and defense-related metabolites within the underground stem. Chemical studies further confirm that the rhizome is rich in carbohydrates and polysaccharides, which are major bioactive and nutritional components of the species. Detailed carbohydrate profiling suggests that *P. sibiricum* rhizome does not rely mainly on starch; instead, fructo-oligosaccharides are a major component and account for about 28.95% of the rhizome, with higher-degree polymers particularly abundant. This reserve composition implies that nutrient storage in the rhizome is based largely on soluble and structurally diverse carbohydrate pools that can support both medicinal quality formation and regrowth after segment division.

Age-related comparisons show that young rhizomes already possess substantial reserve value: the polysaccharide extraction rate of young rhizomes reached 33.88%, close to 45.08% in mature rhizomes, and their main polysaccharide fractions showed similar structural features and biological activity. This finding supports the physiological feasibility of using younger rhizome material as propagation stock, because immature segments are not nutritionally empty organs but already contain considerable carbohydrate reserves. Regeneration also depends on efficient reserve mobilization. During germination, the haustorium absorbs nutrients from the endosperm and transfers them through the cotyledonary structure to the newborn rhizome, providing the material basis for differentiation of the germ and radicle. At the molecular level, dormancy release and seedling establishment involve broad changes in hormone metabolism genes, cell-wall-related genes, endosperm weakening, carbohydrate metabolism, and amino acid synthesis, indicating that regenerative growth arises from coordinated reserve remobilization rather than passive bud swelling alone (Liao et al., 2021; Gou et al., 2026).

2.3 Environmental regulation

Environmental regulation is a decisive factor controlling rhizome germination and early growth in *P. sibiricum*. Under natural conditions, seeds are dispersed in autumn, produce radicle and corm structures only after warm conditions in the following growing season, and often do not complete shoot emergence until after a second winter, reflecting deep epicotyl morphophysiological dormancy (Liao et al., 2021). Controlled sequential temperature treatment markedly shortens this cycle: warm stratification at 25 °C for 4~6 weeks promotes radicle extrusion and cormlet formation, followed by cold stratification at 4 °C for 8 weeks, after which return to 25 °C induces seedling emergence. Additional studies similarly found that 0 °C sand storage for 120 days favors germination, and recent optimization experiments predicted about 89.31% germination under a combined regime