

each bud (Stephen et al., 2023). Annual rhizome segments in *Polygonatum* differ in bud morphology, and some latent buds are long and stout while others are short, thin, or underdeveloped, so division should preferentially use robust, clearly differentiated buds rather than inconspicuous or weak bud positions. In practice, whole-rhizome or large-division propagation is more suitable for conserving elite germplasm and establishing mother-stock nurseries, whereas smaller division is more appropriate when the objective is to expand planting material rapidly under controlled nursery management.

3.2 Technical key points and optimization of segment and bud-section propagation

The technical core of segment and bud-section propagation is balancing multiplication rate against bud survival and reserve sufficiency. Structural studies show that *Polygonatum* annual rhizomes contain latent buds with unequal developmental strength, and underdeveloped buds are less suitable as independent propagules (Stephen et al., 2023). Physiological studies further show that the rhizome is a major storage organ rich in polysaccharides and total sugars, while young rhizomes already retain substantial polysaccharide levels close to mature rhizomes, which supports the use of appropriately developed young bud-bearing segments as nursery material rather than discarding them (Khan et al., 2025). This means optimized segmentation should retain both one effective bud and enough surrounding rhizome tissue to support early sprouting, rooting, and post-cut recovery.

Environmental and hormonal regulation strongly affects the success of these smaller propagules. Cold stratification at 4 °C for more than 70 days alleviated dormancy in *P. sibiricum*, and exogenous GA3 promoted germination and corm growth, indicating that temperature conditioning and hormone-assisted bud activation can improve the performance of bud sections after cutting (Khan et al., 2025). More broadly, temperature, water, and light act as key signals controlling dormancy release and germination, and dark conditions, low-temperature sand treatment, and warm-water soaking improved *P. sibiricum* germination in seed studies, which supports the same general principle of pre-plant conditioning for vegetative propagules (Lubbe et al., 2023). Because rhizome performance also declines under unfavorable soil biotic conditions, nursery substrates for bud sections should avoid acidic, pathogen-prone environments; in *Polygonatum*, rhizome fresh weight and polysaccharide content were highest at soil pH 7.48-7.95, while poor yield and quality were associated with pathogens such as *Fusarium* in the rhizosphere (Meucci et al., 2024). Accordingly, optimization of segment and bud-section propagation should integrate propagule grading, sanitation, temperature pretreatment, and a clean substrate environment rather than relying on cutting strategy alone.

3.3 Application of tissue culture rapid propagation in large-scale production

Tissue culture is the most scalable propagation route for *P. sibiricum* because it can generate large numbers of genetically uniform, pathogen-reduced propagules in limited space and throughout the year (Khan et al., 2025; Nawaz et al., 2025). Existing *P. sibiricum* patents and experimental studies already show that buds from current-year subterranean stems and tuber parts with hidden bud points can be used for cluster-bud induction, callus culture, multiplication, rooting, seedling hardening, and transplanting, with the explicit aim of rapid reproduction and large-area industrialized planting (Stephen et al., 2023). An earlier asexual line system for *P. sibiricum* identified suitable media for growing-point development, adventitious bud differentiation, and rooting, and field planting showed that tube seedlings grew well and increased rhizome yield by 50%. Another rapid-propagation method based on disinfected budded root tubers used cyclic enrichment and bud proliferation for 3–6 generations and was described as applicable to scale production (Marsh et al., 2023).

The key technical challenge is not whether micropropagation works, but whether it can be made simple, reproducible, and economical at production scale. Reviews of commercial micropropagation identify contamination, low multiplication rate, media cost, and acclimatization losses as the main barriers, and they emphasize the need for protocols with high reproducibility and high ex vitro survival (Nawaz et al., 2025). Practical scaling strategies include liquid culture systems, simplified media, and conservation-compatible slow-growth storage systems that reduce labor and maintain viable propagules between production cycles. Related rhizomatous species also show that cold-stored encapsulated microrhizomes or slow-growth cultures can survive for months to a year, supporting the feasibility of integrating storage, transport, and staged nursery supply into a