

stored in darkness at 10 °C had 100% survival after 1, 3, or 6 months and 80% survival after 12 months, while *Iris pallida* plantlets could be cold-preserved at 4 °C for up to 90 days without significant damage (Meucci et al., 2024). However, refrigeration is not universally superior for fresh seed rhizomes. In ginger, refrigerator storage produced the lowest sprouting and highest weight loss, while pit-sawdust or clay-pot storage performed better over three months (Stephen et al., 2023). For *P. sibiricum*, this implies that sand or mulch-based storage is more practical for short-term nursery use under farm conditions, whereas controlled low-temperature storage is more appropriate for elite propagules, staggered planting, or in vitro conservation, provided temperature and humidity are tightly regulated (De Vitis et al., 2020).

5.3 Environmental regulation and mechanisms for maintaining rhizome vigor

The maintenance of rhizome vigor depends on regulating temperature, moisture, gas exchange, and storage duration so that reserve depletion and pathogen growth are both minimized. Rhizomes remain physiologically active during storage, and temperature strongly affects reserve consumption: in switchgrass, storage at 25 °C for 14 days increased rhizome respiration 5.3-fold relative to 5 °C and depleted starch by 30% (Tejera-Nieves and Walker, 2023). This shows why warm storage rapidly consumes stored carbohydrates that are needed for later regrowth. At the same time, moisture must not be allowed to fall excessively. In small white ginger, storage in an air-conditioned room gave the best 4-month performance, and viability declined when rhizome moisture dropped below 80% (Melati and Rusmin, 2019). Moisture-retentive coverings also help: weekly wetting kept switchgrass rhizomes moist without visible fungal infection during storage, and straw-based turmeric storage reduced physiological weight loss and shrinkage (Maharjan and Dhakal, 2025).

The physiological basis of vigor maintenance is the conservation of non-structural carbohydrate reserves and the suppression of stress injury without triggering uncontrolled growth. Rhizomes function as essential storage organs whose carbohydrates support regrowth after stress, and drought experiments showed that plants conserved rhizomes and maintained carbohydrate concentrations rather than sacrificing them (Lubbe et al., 2023). In cold in vitro conservation, slow-growth storage works by preserving tissue maintenance while suppressing energy-intensive organogenesis, and additives such as sucrose, antioxidants, sorbitol, mannitol, spermidine, and calcium pantothenate improved viability and stress tolerance during storage (Meucci et al., 2024; Khan et al., 2025). Storage duration remains a hard limit, because prolonged storage generally lowers phytochemical and antioxidant quality in rhizomes even when low temperature extends shelf life (Nawaz et al., 2025). Therefore, maintaining *P. sibiricum* rhizome vigor requires a storage environment that is cool but not injurious, humid but not saturated, ventilated yet protected, and short enough to limit reserve decline and pathogen buildup while preserving the bud's capacity for rapid post-storage sprouting (Maharjan and Dhakal, 2025).

6 Key Technologies for Standardized Seedling Production

6.1 Site selection and environmental optimization of seedling production bases

Seedling production bases for *Polygonatum sibiricum* should be located in areas where soil reaction, microbial environment, and local climate jointly support rhizome growth and quality. In *Polygonatum*, genotype adaptability is closely related to rhizosphere conditions, especially soil pH, and the highest rhizome fresh weight and polysaccharide content were associated with soils at pH 7.48-7.95, whereas poor yield and quality were linked with pathogenic microorganisms such as *Pseudomonas*, *Fusarium*, *Neocosmospora*, and *Tausonia* (Shi et al., 2024). This indicates that site selection should avoid acidic, poorly drained, pathogen-prone soils and instead prioritize plots with neutral to slightly alkaline reaction, good aeration, and a stable beneficial microbial community. More broadly, seedling quality depends on matching nursery stock to future site conditions, because defining and producing seedlings according to site-specific requirements improves establishment success (Guimarães et al., 2024).

Environmental optimization within the base should therefore integrate topography, drainage, and local microclimate rather than focusing on a single factor. Nursery stock quality is shaped by both morphology and physiology, and inappropriate cultural or environmental management can produce inferior seedlings that later perform poorly in the field. Because root growth and stress resistance are highly sensitive to temperature and