

variation in form or composition but still meet the threshold for medicinal processing or propagation use (Cheng et al., 2023; Liao et al., 2023). Lower-grade rhizomes or younger fractions should be diverted to comprehensive utilization pathways, since young rhizomes still contain substantial polysaccharides and similar biological activity to mature material. To support standardization at scale, rapid non-destructive methods such as NIRS should be incorporated into grading, and the broader quality system should connect variety, environment, metabolite profile, and efficacy so that commercialization standards remain aligned with standardized cultivation and harvesting practice (Pu et al., 2024).

5 Storage and Vigor Maintenance Techniques of Rhizomes

5.1 Key postharvest treatment and sterilization/anti-decay techniques

After harvest, *P. sibiricum* rhizomes should first undergo careful cleaning, wound reduction, and surface disinfection, because rhizome propagules are highly vulnerable to postharvest loss from soil-borne pathogens, pests, and mechanical injury during the storage interval before replanting (Stephen et al., 2023). In stored *P. sibiricum* tubers, a newly reported postharvest rot reached nearly 40% incidence in a storage facility, with lesions expanding from light brown spots to extensive tissue decomposition, confirming that decay control is a central storage problem rather than a secondary one. The causal agent was identified as the *Fusarium solani* species complex, and disease was reproduced after inoculation under 25 °C and 80% relative humidity, indicating that warm and humid storage conditions strongly favor postharvest rot development. For pathogen isolation from diseased *P. sibiricum* tubers, infected tissues were surface-sterilized in 75% alcohol for 90 s followed by 3% hydrogen peroxide for 30 s, providing a directly documented sterilization sequence relevant to rhizome sanitation workflows.

Anti-decay management should also combine biological or physical pretreatments with subsequent low-stress storage. In ginger, seed-rhizome treatment with *Trichoderma harzianum* improved later germination and field performance, especially when paired with a zero-energy cool chamber, showing that pre-storage biocontrol treatment can translate into stronger post-storage vigor. A fungicide treatment also formed part of the tested protection strategies, indicating that both chemical and biological disinfection routes are used for rhizome preservation. Physical pretreatment can also reduce storage injury: ginger rhizomes cleaned, air-dried, and dipped in 45 °C hot water before 5 °C storage showed reduced browning at a 5 min treatment and improved retention of some phytochemical traits, consistent with a preconditioning effect against chilling stress (Shukor et al., 2023). For *P. sibiricum*, this supports a postharvest sequence of sorting out diseased rhizomes, cleaning and drying, minimizing wounds, applying a validated disinfection or biocontrol treatment, and then transferring material promptly into an appropriate storage environment rather than holding it under ambient warm-humid conditions.

5.2 Comparison and applicability of storage methods such as sand storage and cold storage

Different storage methods preserve rhizomes through different mechanisms, so their applicability depends on whether the production goal is short-term sowing viability, delayed sprouting, germplasm conservation, or low-cost farm storage. Traditional matrix-based storage can reduce moisture loss and decay: in ginger, sand, sawdust, and perforated polythene were associated with better sprouting because of lower decay and moisture loss, while pit storage could lose 25%-30% of rhizomes to rot (Stephen et al., 2023). Turmeric studies similarly showed that storage materials significantly reduced postharvest losses relative to no storage material, with straw minimizing weight loss, shrinkage, insect incidence, and rotting, likely by creating an insulated, moisture-retentive microenvironment unfavorable to pests and pathogens (Maharjan and Dhakal, 2025). For field planting material, shade-plus-mulch and tree-shade systems also performed well: turmeric mother rhizomes stored under shade tree plus mulch reached 88.4% sprouting and 94.53% viability, and ginger seed rhizomes stored under tree shade or in mulched pits achieved about 85% viability.

Cold storage is more suitable when the objective is to extend storage duration while maintaining viability, but its success depends on temperature range and rhizome type. In *Miscanthus giganteus*, cold storage had no negative effect on viability, growth, or rhizome carbohydrate and mineral concentrations, and effectively extended planting time. In vitro systems show even stronger conservation potential: encapsulated microrhizomes of *Acorus calamus*