

water status, base layout should favor areas with controllable irrigation, rapid drainage after rainfall, and moderated temperature fluctuations. The practical target is a nursery environment that reduces abiotic stress during early establishment while allowing seedlings to develop balanced shoot-root architecture and adequate acclimation capacity before transplanting.

6.2 Substrate formulation and precise water-fertilizer management techniques

Substrate formulation for *P. sibiricum* seedlings should emphasize porosity, moisture buffering, and support for root-system development, because root morphology is a major determinant of seedling quality and later field performance. Across nursery studies, root volume, total root length, root surface area, root dry mass, and the number of first-order lateral roots repeatedly emerged as effective indicators of seedling quality (Robonen et al., 2023). Root restriction or poor substrate structure reduces the seedling's capacity for water and nutrient uptake, while better-developed root systems support higher biomass accumulation under stress (Wu et al., 2022). For this reason, substrate mixtures should be loose, well-aerated, and structurally stable, so that rhizome-derived seedlings can produce fibrous roots and maintain an appropriate shoot-root balance.

Water and fertilizer management should be precise because both deficiency and excess quickly impair photosynthesis, growth, and physiological quality. Nitrogen deficiency in rice seedlings reduced CO₂ assimilation, stomatal conductance, and chlorophyll content, while impairing the photosynthetic electron transport chain and activating oxidative-stress defenses. Excessively severe water stress likewise reduced growth and photosynthetic traits in multiple seedling systems, while moderate control of water status is central to vigor maintenance and stress conditioning (Shin et al., 2021; Wu et al., 2022). In practical nursery management, this supports small-dose, stage-specific fertilization and moisture regulation based on substrate water-holding status, with routine observation of chlorophyll status, biomass allocation, and root growth as feedback indicators (Zhang et al., 2024; Baha et al., 2025). System optimization should favor steady nutrient supply and avoidance of prolonged saturation, because these conditions better preserve root activity and reduce the risk of weak, top-heavy seedlings (Robonen et al., 2023; Lee et al., 2026).

6.3 Shading regulation and integrated green pest and disease control system

Shading regulation should be used to stabilize the microenvironment, but not to the extent that it suppresses biomass formation and physiological performance. Light quality and intensity strongly regulate seedling photosynthetic efficiency, pigment accumulation, oxidative status, and biomass yield. In alfalfa seedlings, combined red and blue light improved Fv/Fm, SPAD, chlorophyll content, and biomass, while single red light increased oxidative stress indicators (Rahman et al., 2025). At the same time, excessive shade can reduce dry-matter accumulation by inhibiting photosynthesis and disturbing agronomic traits (Zhang et al., 2024). For *P. sibiricum* nurseries, this means shading should be dynamically adjusted to reduce heat and water stress in sensitive periods while maintaining sufficient photosynthetic input for robust rhizome and root formation.

Green pest and disease control should combine environmental prevention, substrate hygiene, and beneficial-microbe management. In *Polygonatum*, poor yield and quality are associated with pathogenic rhizosphere microorganisms including *Fusarium*, while better performance is associated with beneficial groups such as *Allorhizobium-Neorhizobium-Pararhizobium-Rhizobium* and *Talaromyces* (Robonen et al., 2023). More generally, beneficial microbial inoculation in nursery substrates improved germination, chlorophyll content, shoot length, root length, and seedling vigor in ornamental crops (Liu et al., 2023). Compost-based and bioinoculant-based systems can also contribute pathogen suppression, nutrient solubilization, and biostimulation, making them suitable components of an integrated green management system (Yu et al., 2025). A standardized *P. sibiricum* seedling base should therefore use healthy propagation material, sanitized substrates, rational shading and irrigation, and biologically oriented disease prevention to reduce dependence on high-intensity chemical control while maintaining uniform, vigorous seedlings for release.

7 Seedling Quality Evaluation and System Optimization

7.1 Evaluation system for morphological and root-related indicators

The morphological evaluation system for *P. sibiricum* seedlings should use easily measured nursery traits as the first screening layer, with seedling height, root-collar diameter, shoot biomass, root biomass, total biomass, and