

root-shoot balance as core indicators. Among these traits, root-collar diameter is the most consistently useful single index, because it correlates strongly with destructive quality traits and with composite indices such as Dickson quality index across multiple species (Guimarães et al., 2024). Height should not be used alone, because its interpretive value improves only when combined with diameter and biomass-allocation traits (Robonen et al., 2023). Accordingly, a practical nursery standard for *P. sibiricum* should record seedling height, basal diameter, shoot fresh and dry weight, root fresh and dry weight, total dry matter, and shoot-root ratio, and then calculate integrated indices such as H/D, S/R, and DQI to reduce misclassification caused by any single trait (Lee et al., 2026).

Root-related traits should form the second core module of the evaluation system, because aboveground morphology alone is often an incomplete predictor of later establishment. The most informative root indicators are total root length, root surface area, root volume, root dry mass, fibrosity, and the number of first-order lateral roots, all of which reflect absorptive capacity and establishment potential (Robonen et al., 2023). Diameter remains useful here as well, since initial stem diameter predicted later root volume, root area, and root dry mass better than shoot length or lateral-root number in red oak seedlings. For operational detection, root systems can be scanned and quantified by image-analysis platforms such as WinRHIZO, which have been used to measure root length, surface area, volume, average diameter, root tips, forks, and crossings under seedling stress and quality studies (Wu et al., 2022; Mahmood et al., 2022). Because nursery morphology does not always translate directly into field growth, especially across different sites or species, the morphological system for *P. sibiricum* should be calibrated as a target seedling standard linked to local planting conditions rather than treated as a universal threshold (De Melo et al., 2018; Guimarães et al., 2024).

7.2 Physiological and biochemical indicators and vigor detection methods

Morphological indices should be complemented by physiological and biochemical indicators, because seedling quality also depends on physiological readiness, water relations, nutrient status, carbohydrate reserves, and photosynthetic function. Among rapid vigor indicators, chlorophyll-related indices, SPAD value, photosynthetic rate, stomatal conductance, and chlorophyll fluorescence are especially useful because they respond sensitively to nutrient deficiency and environmental stress (Liu et al., 2023). The maximum quantum efficiency of PSII, Fv/Fm, is a particularly valuable indicator: it declined under chilling stress in corn, under nitrogen deficiency in rice, and was incorporated into recent integrated morphophysiological seedling quality indices (Wu et al., 2022; Lee et al., 2026). SPAD and chlorophyll content also track vigor well, since they were identified among key indicators in drought-resistance evaluation and multimodal seedling grading models (Liu et al., 2023; Yu et al., 2025).

Biochemical vigor detection should focus on reserve and stress-metabolism indicators, especially carbohydrates, proline, malondialdehyde, and antioxidant-enzyme activities such as SOD, CAT, POD, and APX. Under drought or chilling, vigorous seedlings typically maintain better growth and photosynthesis while activating osmotic adjustment and antioxidant defense, whereas sensitive seedlings show stronger membrane peroxidation and growth suppression (Wu et al., 2022). Proline accumulation, SOD activity, and controlled MDA response were useful discriminators between drought-resistant and drought-sensitive cotton lines, and MDA plus soluble sugars were principal predictors in *Gleditsia* drought-response analysis (Baha et al., 2025). For direct vigor testing before transplanting, root growth potential, electrolyte leakage, budbreak response, carbohydrate concentration, and cold-hardiness tests remain informative because they integrate multiple seedling subsystems rather than measuring one material trait in isolation. In system optimization, these physiological and biochemical measures should be used to verify or correct morphology-based grading, not to replace it, because performance tests are often more predictive but also more laborious.

7.3 Stress resistance evaluation and grading standards for seedling release from nursery

Seedlings released from the nursery should meet explicit stress-resistance standards, because seedling quality is ultimately defined by the ability to survive environmental stress and sustain subsequent growth. Stress-resistance evaluation for *P. sibiricum* should therefore include low-temperature, drought, and transplanting-related tolerance, assessed through a combination of growth retention, leaf morphology, photosynthetic traits, water status,