

applications, while also pointing to the need for extraction and purification equipment in the midstream segment. The same analysis suggests further expansion into medical, cosmetic, and oral-care products, including immune regulation, skin repair, whitening, and tooth-protection applications. Because current industry assessments still identify weak innovation capability, low brand competence, and limited market cognition, future industrial upgrading should combine standardized raw-material supply with deep processing, brand development, and diversified consumer products (Hong et al., 2016). For *A. roxburghii*, the most viable industrial development pathway is therefore to use artificial replacement cultivation as the upstream base, and then extend toward high-value extracts, functional foods, pharmaceutical products, and other differentiated applications that increase output value while supporting conservation.

6 Problems and Optimization Strategies

6.1 Utilization efficiency of superior germplasm resources of *Anoectochilus roxburghii* still needs improvement

Current artificial replacement cultivation has reduced dependence on wild resources, but the efficient use of elite germplasm remains limited by slow variety breeding, insufficient protection of breeding resources, and weak integration between germplasm evaluation and industrial propagation (Wei et al., 2022). Existing evidence shows that polyploid breeding is a promising route to superior germplasm utilization, because tetraploid plants generally show higher major secondary metabolite production, stronger photosynthetic performance, larger roots and stomata, and better adaptation to unstable environments than diploid materials (Su et al., 2017; Huang et al., 2022; Zhang et al., 2025). Artificial induction methods have already provided a practical basis for this direction: mutagenic tetraploid breeding reported frequencies above 75% and improved medicinal yield, while optimized in vitro propagation protocols for tetraploid materials achieved high shoot induction, rooting, and transplant survival, making elite-line expansion technically feasible (Zhang et al., 2025). At the same time, utilization efficiency is still constrained by incomplete molecular characterization of germplasm, although the recent chromosome-level autotetraploid genome now offers a reference for functional genomics, marker development, and precise molecular breeding (Fang et al., 2025).

Optimization should therefore focus on building a coordinated “collection-evaluation-breeding-propagation” system for elite germplasm. First, wild, local, and cultivated resources should be systematically collected and conserved, while superior chemotypes and stress-tolerant lines are identified through combined phenotypic, phytochemical, and molecular screening (Ye et al., 2020). Second, molecular breeding should be accelerated by using genomic resources and drought-resistance candidate genes such as the ArWRKY57-ArWRKY70-ArLEA5 module to develop elite cultivars with both stable quality and stronger environmental resilience (Jiang et al., 2025; Fang et al., 2025). Third, rapid propagation systems should be matched to elite germplasm deployment, including PLB-based regeneration, nodal culture, and tetraploid micropropagation, so that breeding gains can be translated quickly into industrial seedling supply (Zhang et al., 2025). In short, the key problem is not the absence of superior germplasm, but the low efficiency with which conserved, identified, bred, and propagated elite materials are converted into standardized cultivation resources (Su et al., 2017; Huang et al., 2022).

6.2 Quality stability of artificially cultivated *Anoectochilus roxburghii* still needs enhancement

The main quality problem in cultivated *A. roxburghii* is that active constituents vary substantially with cultivation mode, light regime, microbial association, habitat conditions, harvest stage, and post-harvest handling, so cultivated material often lacks the consistency required for medicinal use (Luo et al., 2025). Environmental regulation is especially important: blue light improves growth, flavonoids, and polysaccharides, red-blue combinations can markedly increase phenolic acids, flavonoids, and kinsenoside, and optimized orthogonal light protocols differentially favor polysaccharides or flavonoids depending on light intensity, red:blue ratio, and photoperiod (Chen et al., 2021; Luo et al., 2025). Biological regulation is similarly influential, because wild-imitated cultivation shifts the endophytic community toward wild-type structure and is associated with higher kinsenoside, while endophytic fungi, mycorrhizal fungi, AM fungi, and beneficial bacteria all improve biomass and promote accumulation of flavonoids, polysaccharides, or kinsenoside (Ye et al., 2020; Zhang et al.,