The future direction is to build sensor-based, automated, and model-assisted production systems that reduce reliance on manual regulation. Automated environmental control studies for *G. lucidum* cultivation show that temperature, humidity, light, and $CO_2$ require continuous monitoring, that manual regulation is inconsistent and error-prone, and that sensor-triggered fogger or sprinkler systems can maintain humidity above 80% in mushroom houses. More broadly, bioprocess studies highlight the scale-up challenge of maintaining consistency, contamination control, and productivity when moving from laboratory to industrial systems, and call attention to cost and sustainability constraints that must be addressed simultaneously (Lim et al., 2024). Precision regulation should therefore evolve toward integrated digital management of environmental sensing, spawn quality, contamination risk, nutrient supply, and scale-up modeling, so that production can be optimized not only for yield but also for reproducibility, economic viability, and low-carbon operation (Karunarathna et al., 2025).

### 6.3 Improvement of quality evaluation and standardization systems

A third challenge is that the current quality evaluation framework for *G. lucidum* spore powder is still fragmented across identity, composition, and safety control. Although the Chinese Pharmacopoeia already specifies identification, content determination, and microbial requirements for spore powder, with minimum limits for polysaccharides and triterpenes/sterols, and although GB/T and NY/T standards cover harvesting, processing, wall-breaking rate, ganoderic acid, and total triterpenoid determination, these standards do not fully resolve the large commercial variability seen in real products. Commercial surveys found marked variation in polysaccharides and triterpenes across 84 batches of *Ganoderma* products, with total polysaccharides ranging from 0.22% to 3.31% and total triterpenes from 0.21% to 10.56%, while targeted LC-MS/MS showed triterpene contents of only 0.01% to 0.98% (Liu et al., 2025). Earlier spore-powder studies also found source-dependent differences in ash and triterpene content, and HPLC fingerprinting showed substantial year-to-year variability in Ganoderma chemical profiles (Yeung et al., 2022). These findings show that future quality control cannot rely on one or two bulk indicators alone.

Future standardization should therefore integrate molecular authentication, multi-component quantification, structural characterization, and international harmonization. ITS2 barcoding identified 16 adulterants among 84 commercial Ganoderma samples, while U.S. supplement testing found that only 26.3% of products matched their labels, showing that identity auditing needs to become routine rather than exceptional (Wu et al., 2017). More comprehensive quality systems are already emerging: HPLC-DAD fingerprinting supports simultaneous evaluation of multiple ganoderma acids, saccharide mapping and HPSEC-MALLS-RID provide improved polysaccharide assessment, and single-step extraction with fine structural evaluation can cut preparation time to one-sixth and save 50% of raw material while improving analytical efficiency (Yeung et al., 2022; Zheng et al., 2024). At the standard-system level, ISO 21315:2018 established the first international standard for *G. lucidum* fruiting bodies and an ISO standard for spore powder is under development, so the next step is to link domestic pharmacopoeial methods with internationally harmonized standards that cover authenticity, active components, wall-breaking efficiency, safety limits, packaging, storage, and traceability (Liu et al., 2025).

## 7 Conclusions

Efficient production technologies are the material foundation for improving the market competitiveness of *Ganoderma lucidum* spore powder, because the industry still faces strict growth requirements, unstable batch yield, and limited availability of high-spore-yield, contamination-resistant cultivars. Breeding progress shows that process competitiveness can be improved at the source: UV-mutant strain UV119 increased basidiospore yield by 19.27% over its parent and 20.56% over "Longzhi No.1," while also improving resistance to undesired microorganisms. At the cultivation stage, integrated workflows that link strain selection, substrate preparation, sterilization, inoculation, fruiting management, and dedicated powder collection can produce high-yield, high-purity spores, with one wild-simulating process reporting>99.9% purity and another collection technology reporting>32% higher selling income with heavy metals controlled within national standards. Process competitiveness also depends on rational medium design and cleaner collection schemes, including filter-cloth wrapping and substrate systems intended to reduce resource waste, pesticide residues, heavy metals, and low