In addition to solid-state fruiting body production, liquid cultivation and bioreactor systems have gradually become important components of facility-based *G. lucidum* production. Liquid facility-based models mainly target mycelial biomass, extracellular polysaccharides (EPS), triterpenoids, and other metabolites, and generally use shake flasks, stirred-tank reactors, or specially designed bioreactors for closed cultivation (Alsaheb et al., 2020). For example, new reactors such as the Air-L-Shaped Bioreactor (ALSB) can reduce mycelial adhesion to the reactor wall and clumping, thereby improving mass transfer efficiency and process economics (Supramani et al., 2023). In addition, two-stage liquid static cultivation and bag-type static bioreactors can be used for efficient accumulation of triterpenoids, indicating that facility-based *G. lucidum* cultivation has expanded from simple fruiting body production to targeted production of mycelia and functional metabolites. Overall, facility-based *G. lucidum* cultivation is forming a diversified system ranging from greenhouse cultivation, intelligent mushroom houses, and multi-layer bag cultivation to liquid fermentation and bioreactor production.

2.3 Development characteristics of large-scale *Ganoderma lucidum* production

In recent years, the *G. lucidum* industry has increasingly shown trends toward scaling-up, intensification, engineering, and standardization. Traditional solid-state cultivation based on logs or beds has a relatively long production cycle and high labor intensity, and is vulnerable to contamination, continuous cropping obstacles, and environmental fluctuations. These limitations make it difficult to meet global market demand for stable supply and quality consistency (Araque et al., 2020; Wu et al., 2024). As *G. lucidum* is increasingly used in dietary supplements, pharmaceuticals, functional foods, and health products, large-scale production requires not only higher yield, but also unified standards for active components, safety, and batch consistency. Through unified strain supply, standardized substrate preparation, centralized cultivation management, and batch-based production processes, production costs per unit can be effectively reduced, production efficiency can be improved, and product quality stability can be enhanced.

During large-scale development, facility-based cultivation and process engineering have become important technical supports. Engineering simulation studies have shown that tools such as SuperPro Designer can be used to simulate industrial-scale submerged cultivation of *G. lucidum*, predict equipment requirements, energy consumption, and operating costs, and evaluate the economic effects of bioreactor scale-up. For example, increasing bioreactor volume from 2 m^3 to 20 m^3 can significantly reduce the unit production cost of extracellular polysaccharides and other products, demonstrating the importance of economies of scale and process optimization (Araque et al., 2020). Semi-industrial and pilot-scale studies have also shown that controlled pH, optimized carbon and nitrogen sources, and appropriate reactor configurations can significantly improve the yields of extracellular polysaccharides and other metabolites (Alsaheb et al., 2020; Supramani et al., 2023). This indicates that large-scale *G. lucidum* production is no longer limited to traditional cultivation experience, but is gradually moving toward process design, parameter optimization, and engineering scale-up.

Standardized management is an important approach to enhancing the competitiveness of the large-scale *G. lucidum* industry. At present, *G. lucidum* production has shifted from merely pursuing yield to placing greater emphasis on quality, safety, traceability, and market standardization. Relevant reviews have indicated that industrial standardization of *G. lucidum* is promoting the standardization of raw material sources, processing procedures, quality control, and product circulation, while emphasizing the importance of active component content, hygiene and safety, and production consistency in industrial development. Meanwhile, facility-based cultivation, non-soil-contact systems, and clean-environment management can help reduce heavy metal contamination and the hazards of competitive fungi, thereby improving production reproducibility and quality stability (Lim et al., 2024; Wu et al., 2024). In the future, with the further application of environmental monitoring, intelligent ventilation, automatic spraying, data analysis platforms, and bioreactor technologies, large-scale *G. lucidum* production will place greater emphasis on precise regulation, green production, brand-oriented operation, and alignment with international quality standards, thereby promoting the industry toward high-quality development.