and composition: red light inhibited fruiting body differentiation, while green light increased fruiting body weight by 21.4%, raised pileus triterpenes by 28.1%, and enhanced multiple extracellular enzyme activities, indicating that optimized spectral management can improve both yield formation and metabolite accumulation (Liu et al., 2024). Air supply is also a critical control variable, because in static culture systems it significantly increased triterpenoid accumulation, supporting the broader principle that oxygen availability and ventilation influence secondary metabolism and probably later sporulation performance (Hu et al., 2018). At the production-house scale, sanitation management is equally important: repeated cultivation can favor antagonistic fungi such as *Trichoderma* and *Mucor*, whereas waterlogging-based sanitation sharply reduced their colonization, restored fruiting body development to about 90%, and enabled spore yields of about 5 kg per house where the untreated control failed (Tong et al., 2020). Taken together, efficient environmental regulation for spore production should integrate temperature-humidity coordination, pH adjustment, spectral light management, adequate aeration, and strict sanitary control to stabilize fruiting and maximize subsequent spore formation.

3.2 Optimization of high-yield spore production cultivation models

High-yield spore production also requires choosing cultivation models that shorten the cropping cycle, reduce contamination, and improve substrate conversion efficiency. Reviews and cultivation studies show that *G. lucidum* can be produced by bottle procedures, sawdust bags, short wood segments, tree stumps, wood logs, and liquid-state culture, but for fruiting bodies and spores the dominant industrial direction has shifted from natural logs toward sawdust-based bag or synthetic log systems (Jeewanthi et al., 2017; Zhou, 2017). Earlier wood-log cultivation required a long cropping cycle of roughly 6~24 months and generally lower yield, whereas lignocellulosic bag substrates permit more controlled and efficient biomass transformation (Thiribhuvanamala and Krishnamoorthy, 2021). Direct comparisons in Cambodia found higher contamination in log culture than bag culture for *G. lucidum*, and sawdust substrates gave higher yield and biological efficiency, supporting the superiority of bag cultivation where cleanliness and standardization are priorities (Chanshorphea, 2019). This shift is consistent with the broader ecological advantage of *G. lucidum* cultivation, namely the conversion of agricultural and forestry residues into medicinal biomass using relatively low-cost solid substrates (Thakur et al., 2024).

Within sawdust-based systems, substrate design and strain-model matching are decisive for high spore yield. Substrates of 70% rice straw and 30% sawdust shortened the fructification period to 17.33 days, coconut wood log sawdust with wheat bran produced 77.5 g per 175 g substrate and 44.3% bioefficiency, and indigenous Pakistani material performed best on sawdust+wheat straw, showing that optimized lignocellulosic combinations can substantially improve production efficiency (Thiribhuvanamala and Krishnamoorthy, 2021). Other local evaluations similarly found that rubber sawdust, mango sawdust, or their mixtures maintained relatively high yield and biological efficiency, while sawdust outperformed paddy straw, sugarcane bagasse, maize stalk, and coir pith for total yield in another recent comparison (Sethi and Chinara, 2025). Spawn medium optimization matters as well: corn grit produced rapid mycelial growth in one study, while barley grains were the most appropriate spawn medium in another, indicating that cultivation models should be regionally adapted rather than fixed to one recipe (Ghafoor et al., 2025). Finally, high-yield models depend on elite strains; the 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 microbial invasion, so the most effective cultivation model is an integrated system that combines superior germplasm, low-contamination bag culture, and substrate formulas tailored for rapid colonization and sustained sporulation (Figure 1) (Tang et al., 2023).

3.3 Optimization of spore powder collection and processing technologies

After sporulation, efficient production depends on standardized collection and processing technologies that preserve bioactive components while improving release from the hard sporoderm. *G. lucidum* spores are rich in polysaccharides and triterpenoids, but their wall is composed mainly of chitin, cellulose, and lignin, making the contents difficult to digest and absorb unless wall disruption is performed (Qi et al., 2024). Mechanical rolling, room-temperature milling, ultrafine grinding at low temperature, ball milling, and combined chemicophysical