global standard for *G. lucidum* fruiting bodies and an ISO standard for spore powder is under development, providing a basis for harmonized testing, packaging, storage, and trade. At the enterprise level, whole-process standardization should further emphasize purity and contamination control, since wild-imitating collection systems have reported>99.9% purity, while dedicated collecting techniques reported high yield, lower cost, and heavy metals controlled within national standards.

5.2 Application of digital technologies in production management

The next step is to digitize production management so that environmental regulation, disease prevention, and process traceability shift from experience-based control to real-time data-driven control. Across mushroom production systems, IoT platforms have been used to monitor temperature, humidity, light intensity, and substrate moisture in real time through sensors connected to cloud-based mobile and web applications, with autonomous feedback control of the cultivation chamber (Irwanto et al., 2024). This is directly relevant to *G. lucidum* spore powder because mushroom growth is highly sensitive to environmental instability, and digital systems are designed precisely to stabilize those parameters that are otherwise difficult to maintain under traditional management (Irwanto et al., 2024). IoT architectures now also support remote visualization, automated actuation of humidifiers, heaters, lighting, and exhaust fans, and cloud dashboards for continuous decision-making, which reduces dependence on manual inspection and improves consistency between batches (Chong et al., 2023).

Evidence from broader mushroom systems suggests that these digital tools can deliver practical production gains, not only monitoring convenience. A low-cost centralized IoT ecosystem increased controlled-room yield by about 49% over ordinary cultivation while also integrating disease detection, agronomist advisory support, and e-commerce functions (Guragain et al., 2024). Another IoT cultivation study found about 28% higher production and better yield consistency than conventional methods, while TinyML-based monitoring enabled on-device processing of temperature, humidity, CO2, light, soil moisture, pH, and soil temperature with low latency and improved environmental stability (Rukhiran et al., 2023; Adebayo et al., 2025). For *G. lucidum* production specifically, digital management can be extended beyond greenhouse control to process simulation and bioprocess optimization, since industrial-scale modeling showed that reactor scale strongly changes cost, reducing modeled production cost from 6.82 USD/g at 2 m^3 to 0.8 USD/g at 20 m^3, and specialized bioreactor design improved fungal biomass and exopolysaccharide production under optimized pH, glucose, agitation, and aeration conditions (Araque et al., 2020; Supramani et al., 2023).

5.3 Industrial chain extension and product development directions

The industrial application of *G. lucidum* spore powder is moving beyond raw health supplements toward multi-level product development in foods, nutraceuticals, pharmaceuticals, and functional ingredients. Spore powder has already become a new resource for health products and pharmaceuticals, and the broader *G. lucidum* industry is expanding internationally as demand grows for dietary supplements, herbal products, and functional foods (Tang et al., 2023). This industrial extension is scientifically plausible because the spores contain genetic material and active components similar to the fruiting body, and wall-breaking and extraction technologies have substantially expanded their research and application value (Xu and Li, 2019; Chen et al., 2025). Product development should therefore target both direct-use spore powder and processed functional fractions, because bioactive triterpenoids from spore powder can be efficiently extracted by optimized dual-mode sonication and show antioxidant, antibacterial, and potential anticancer activity, while proteoglycans prepared from cracked or uncracked spore powder have shown antioxidant, hypoglycemic, antibacterial, and antitumor functions (Zhu et al., 2019).

Industrial-chain extension should also emphasize high-value by-product utilization and diversified consumer products. Spore powder after oil extraction still retains substantial bioactive substances and improved intestinal barrier dysfunction in mice by enriching beneficial microbiota and increasing tight-junction protein expression, indicating that oil-extracted residues are not waste but candidate secondary raw materials for gut-health products (Zhong et al., 2025). In the food sector, broken spore powder functioned as a feasible raw material for Chinese steamed bread, and 0.5%~1% addition gave the most suitable balance of quality and sensory performance, showing a concrete route for mainstream food incorporation (Chen et al., 2025). At the same time, related