endophyte-based inoculants may be developed to improve the production of specialized metabolites (Cheng et al., 2019; Laffon et al., 2024; Liu et al., 2025). On this basis, quality-oriented "substrate-microbe integrated products," such as biofortified composite substrates, mycorrhiza-assisted seedling substrates, and functional microbial slow-release carriers, could provide innovative technological solutions for high-quality *D. officinale* cultivation.

7.3 Establishing high-efficiency cultivation systems for large-scale production

The *D. officinale* industry is gradually transitioning from wild harvesting and small-scale cultivation toward facility-based, large-scale, standardized, and modern production systems. Advances in propagation technologies, substrate improvement, and integrated cultivation practices have enabled the industry to shift from dependence on wild resources to large-scale protected cultivation and environmentally friendly production systems (Liu et al., 2025). Nevertheless, cultivated products still face challenges related to inconsistent quality and efficacy, lack of unified standards, and the need to balance high productivity with resource conservation and environmental sustainability (Cheng et al., 2019). Therefore, the development of high-efficiency cultivation systems suitable for large-scale production should be based on standardized substrate formulations integrated with irrigation and fertilization management, environmental control, pest and disease management, and standardized harvesting and processing protocols.

Future efforts should focus on systematically evaluating the performance of different substrates and identifying standardized formulations suitable for diverse ecological regions, cultivation facilities, and production systems. Simultaneously, substrate production standards, quality inspection protocols, and application guidelines should be established to improve product consistency, reproducibility, and industrial compatibility. Green composite substrates should also be integrated with microbiome-informed management strategies, enabling the transition from empirical substrate selection to precision substrate design. For large-scale commercial production, substrates must not only satisfy the physiological requirements of *D. officinale* roots and support quality formation but also be compatible with mechanized filling systems, automated irrigation, integrated fertigation, disease monitoring, and product traceability systems, thereby enhancing production efficiency and quality stability.

With the advancement of smart agriculture technologies, *D. officinale* cultivation is expected to move toward increasingly digitalized and precision-based management. Studies have shown that PLC-SCADA-based greenhouse systems can accurately monitor and control temperature, moisture, humidity, and light intensity, achieving prediction errors below 2.5% and providing reliable decision support for precision cultivation management. Edge-computing and digital-twin platforms developed for *D. officinale* production can further improve environmental control accuracy, increase yield by more than 20%, and reduce energy consumption by over 40%, thereby providing scalable frameworks for intelligent cultivation systems (Li et al., 2025). In addition, big-data approaches can be applied to identify and manage experimental outliers in digital cultivation datasets, improving the reliability of growth, yield, and quality modeling as well as decision-making processes. In the future, integrating standardized composite substrates, microbiome-based management strategies, intelligent greenhouses, Internet of Things (IoT) monitoring technologies, and digital-twin models is expected to facilitate the establishment of a modern *D. officinale* production system characterized by high yield, superior quality, low production costs, traceability, and long-term sustainability.

8 Conclusions

Existing studies consistently indicate that, under artificial cultivation conditions, cultivation substrates are fundamental factors determining the growth performance and morphogenesis of *Dendrobium officinale*. Differences in substrate physicochemical properties, such as porosity, water-holding capacity, aeration, bulk density, pH, and cation exchange capacity, directly affect the root-zone microenvironment, thereby regulating seedling survival, root architecture, and aboveground biomass accumulation. Natural organic materials, such as sphagnum moss and bark, as well as properly treated agricultural wastes, such as coconut coir, rice husks, and peanut shells, generally provide favorable support and buffering effects. In contrast, unsuitable substrates characterized by excessive compaction, poor drainage, or nutrient imbalance may cause root rot, nutrient