emphasize short-term biological effects while giving insufficient consideration to economic costs, resource-use efficiency, operational convenience, supply-chain stability, and compatibility with certification standards. As a result, a gap remains between research outcomes and industrial demands.

Experiences from soilless cultivation and protected agriculture indicate that substrates intended for commercial application must be compatible with mechanized production systems, integrated fertigation technologies, pest management programs, and standardized production workflows. However, many experimental studies do not adequately simulate such practical conditions and often fail to provide management details necessary for large-scale implementation (Barrett et al., 2016). Research has shown that conventional substrates such as rockwool remain widely used in certain crops largely because of their high uniformity and compatibility with fertigation systems. In contrast, more sustainable materials, including coconut coir, biochar, compost, and wood fiber, although demonstrating promising agronomic performance in experimental trials, still face challenges related to supply stability, salinity control, substrate standardization, and compatibility with automated production systems (Atzori et al., 2021; Fussy and Papenbrock, 2022).

For medicinal orchids such as *D. officinale*, the insufficient integration of substrate formulations with industrial production is also reflected in the limited translation of research findings into quality standards. Current commercial production still relies primarily on traditional substrates such as sphagnum moss and bark. Although some composite substrates have shown superior effects on growth promotion and quality improvement, standardized formulations, technical production specifications, and long-term validation remain lacking. Agricultural and agro-industrial residues, including coconut fiber, carbonized rice husks, coffee husks, and sugarcane bagasse, offer ecological and economic advantages as orchid cultivation substrates. However, their application is constrained by issues such as pathogen contamination risks, fluctuations in salinity, nutrient immobilization, difficulties in controlling root-zone biological activity, and unstable supply chains (Atzori et al., 2021; Cacini et al., 2021). Therefore, future research should place greater emphasis on aligning substrate development with industrial requirements. While maintaining favorable growth performance and quality enhancement, efforts should focus on establishing standardized substrate production processes, quality control systems, and application protocols. Such measures will facilitate the transformation of research achievements into scalable, certifiable production systems that comply with pharmaceutical and functional food standards, thereby supporting the sustainable development of the *D. officinale* industry.

## 7 Future Perspectives and Development Trends

### 7.1 Development of green and environmentally friendly composite cultivation substrates

With the increasing emphasis on ecological agriculture, green production, and resource recycling, the development of resource-efficient and environmentally friendly composite cultivation substrates has become an important direction for the *Dendrobium officinale* industry. Future substrate design should focus not only on growth-promoting effects but also on sustainability, cost-effectiveness, raw material availability, and ecological safety. Research on soilless cultivation media indicates that the global trend is shifting from traditional materials such as peat and rockwool toward renewable resources and agricultural waste utilization, following the principles of “reduce-reuse-recycle” while maintaining suitable physical, chemical, and biological properties for root growth (Barrett et al., 2016). For *D. officinale*, although traditional substrates such as sphagnum moss exhibit excellent moisture retention and root-promoting properties, concerns regarding resource availability, environmental conservation, and long-term costs have increased. Therefore, developing alternative composite substrates based on coconut coir, rice husks, peanut shells, wood fibers, green compost, and biochar is of considerable practical significance (Gruda, 2019; Atzori et al., 2021).

Future research on composite substrates should place greater emphasis on functional optimization and resource integration. Different substrate materials possess distinct advantages in water retention, aeration, nutrient-holding capacity, structural stability, and microecological regulation. Through scientific formulation, complementary properties can be combined to improve overall substrate performance. For example, combining bark-based materials with coconut coir, perlite, expanded clay, or biochar can simultaneously satisfy the requirements for root