substrate mainly composed of spent mushroom residues, Chinese herbal residues, and agricultural by-products such as chestnut shells, peanut shells, mulberry branches, corncobs, and wood chips can increase the transplant survival rate of *D. officinale* to more than 98%. After 1.5 years of cultivation, the average plant height reached approximately 78 cm and the stem diameter reached 7.5~8.2 mm, indicating good adaptability and growth vigor under field conditions. A cement-tile bed cultivation system using pine bark as the main substrate can also ensure a transplant survival rate of more than 98%, promote plant growth compared with traditional cultivation methods, advance flowering and stem formation, and increase yield per unit area. In addition, a 50:50 mixture of pine bark and fern fiber achieved a 100% survival rate 12 months after ex vitro transplantation and showed good performance in plant height, root number, fresh weight, and dry weight, suggesting that a rational combination of water retention and aeration is conducive to sustained seedling growth (Luan et al., 2021).

The substrate requirements of *D. officinale* vary among different growth stages. The seedling stage relies more heavily on strong moisture retention and environmental stability, whereas during the rapid growth stage, the requirements for substrate aeration, drainage, and nutrient supply gradually increase. Wood-based substrate combinations such as bark-sawdust mixtures can also support high survival rates and favorable growth. Among them, an alder bark:fine sawdust ratio of 5:1 showed good performance in plant height, stem diameter, root number, and leaf number, and was considered a suitable cultivation substrate. Therefore, rationally selecting or adjusting substrate types according to different growth stages of *D. officinale* is an important measure for improving seedling survival, enhancing plant vigor, and achieving stable production.

3.2 Effects on root development and nutrient uptake

Roots are important organs for water and mineral nutrient uptake in *D. officinale*, and their developmental status directly determines the subsequent growth potential of the plant. Cultivation substrates influence root morphogenesis and physiological activity by regulating rhizosphere moisture, oxygen, and nutrient supply. Substrate porosity, water-holding capacity, drainage, and nutrient status are key factors determining root development in *D. officinale*. Well-aerated substrates are conducive to root apical meristem activity and new root formation, whereas prolonged waterlogging or poor aeration can easily cause root hypoxia, inhibit root growth, and even induce root rot. During the hardening stage, sphagnum moss significantly increases root length, root number per cluster, and root biomass, indicating that a moist, fine-textured, and well-aerated medium facilitates rapid root proliferation and functional root formation in seedlings.

Bark-based substrates and composite substrates supplemented with structural materials such as fern fiber, perlite, and ceramsite are beneficial for increasing root length, root number, and root activity. A pine bark-based mixed substrate combined with fern fiber promoted rooting under greenhouse conditions over 12 months, enabling plants to develop more roots, longer roots, and higher fresh weight than other tested substrates (Luan et al., 2021). Some nutrient solutions and granular substrate formulations also aim to rapidly promote root emergence from stems and improve transplant survival. Reported results indicate that the cultivation period for complete plant formation can be shortened to approximately 25 days, with a high field survival rate, suggesting that nutrient-rich, well-buffered, and structurally suitable substrates can significantly promote root initiation and growth. For *D. officinale*, which has well-developed aerial roots, maintaining an appropriate air-water ratio is essential for healthy root development.

Substrates also serve as reservoirs and exchange interfaces for mineral nutrients and carbon sources. Widely targeted metabolomic studies have shown that pine bark, coconut coir, and their mixed substrates differ significantly in physicochemical properties, including water-holding capacity and nitrogen, phosphorus, and potassium contents, leading to marked changes in the stem metabolite profiles of *D. officinale*. This suggests that nutrient acquisition and metabolic status differ under different substrate conditions (Zuo et al., 2020). Ecophysiological studies have also found that total nitrogen, total phosphorus, pH, and available phosphorus in the soil are closely related to polysaccharide, total alkaloid, and flavonoid contents, and these parameters are all influenced by substrate selection in artificial cultivation systems (Yuan et al., 2020). In addition, mycorrhizal associations formed within or on the surface of substrates can enhance nutrient uptake. The growth-promoting