Soil-borne diseases such as Verticillium wilt, Phytophthora crown rot, root rot, and complex root disease syndromes can seriously reduce plant vigor and yield. At the same time, control methods like soil fumigation face economic, regulatory, and environmental constraints (Rathod et al., 2021). Soil heterogeneity, salt accumulation, and poor drainage and aeration can also disrupt the uniform distribution of water and nutrients, leading to uneven plant growth and unstable fruit quality. Soilless cultivation systems—including solid substrates (such as peat, coco peat, coconut fiber, perlite, and rockwool) and hydroponic systems—provide a more controlled root environment and can effectively address these problems. They allow production in areas where soil is unsuitable, contaminated, or unavailable, and enable precise control of water supply, nutrient delivery, root aeration, and electrical conductivity (Wanas and Khamis, 2022).

This study evaluates different combinations of soilless substrates and nutrient supply strategies to optimize yield and fruit quality in greenhouse strawberry production, with a focus on resource use efficiency and practical applicability. Specifically, the study aims to: (i) compare different substrate types or their mixtures with conventional soil cultivation in terms of plant growth, yield, and fruit quality; (ii) assess the effects of different nutrient solution management strategies on productivity and key quality traits; and (iii) identify substrate–nutrient combinations that improve water and nutrient use efficiency while maintaining or enhancing fruit quality. By clarifying these relationships, this study provides both scientific support and practical guidance for substrate selection and nutrient management in greenhouse strawberry production.

2 Characteristics of Ideal Substrates for Strawberry Cultivation

2.1 Physical properties

From a physical perspective, an ideal substrate should have a balanced pore structure, good aeration, sufficient water-holding capacity, and stable root-zone temperature. Organic substrates such as coir, peat-based mixes, bark, sawdust mixtures, and polyester fiber generally hold more water than mineral soils under saturated conditions and after free drainage. With proper irrigation management, this feature is usually associated with larger canopy size, higher biomass, and increased marketable yield (Zahid et al., 2021).

However, if the proportion of fine particles is too high, or the substrate becomes compacted over time, leading to increased bulk density and electrical conductivity (EC), it will result in poor aeration, salt accumulation, and reduced yield. For example, this occurs in organic substrates where the proportion of particles smaller than 0.25 mm is high and the EC exceeds 2.0 $mS \cdot cm^{-1}$ (Guerrero-Guerrero et al., 2021).

Substrates with moderate bulk density and good water retention can buffer day–night temperature fluctuations. Together with ambient and substrate temperatures, they affect fruit firmness, acidity, vitamin C content, and volatile flavor composition. Compared with soil cultivation, substrate-based systems generally improve fruit quality (Buragienė et al., 2024; Xu et al., 2025).

2.2 Chemical properties

From a chemical perspective, an ideal substrate should maintain a slightly acidic pH, moderate EC, and relatively high cation exchange capacity (CEC), so that it has good nutrient buffering capacity under intensive water and fertilizer management. Studies on potting soils and soilless substrates show that slightly acidic conditions, high CEC, and low background salinity are favorable for strawberry growth. In contrast, too low EC limits plant vigor, while EC above about 2.0 $mS \cdot cm^{-1}$ can cause salt stress and substrate compaction (Guerrero-Guerrero et al., 2021).

In practical greenhouse production, nutrient solutions and substrates are usually controlled within pH 5.5~6.5 and EC below about 1.5~1.8 $mS \cdot cm^{-1}$. This range is associated with better vegetative growth, yield, and fruit quality in coir-perlite-vermicompost mixtures, peat-based substrates, coir, and bark–sawdust formulations (Schafer and Lerner, 2022).

Substrates with higher CEC, especially those rich in organic matter (such as coir, peat, vermicompost, or livestock manure-based substrates), can adsorb and slowly release K^+, Ca^{2+}, and Mg^{2+}. This helps buffer rapid changes in