transpiration, free radical scavenging activity, fruit firmness, and yield. This indicates that adding 20% perlite can significantly improve the physical properties of coir or peat (Alsmairat et al., 2018).

Perlite-vermiculite-coir (50:25:25) and coir-vermiculite (25:75) substrates resulted in higher plant height, longer roots, larger canopy size, bigger fruits, and higher TSS compared with sand culture or single-component treatments (Raja et al., 2018). Perlite-vermiculite (3:2) and perlite-peat (1:1) mixtures, used in greenhouse and closed hydroponic systems, supported better vegetative growth, higher fruit number, earlier and higher total yield, and improved leaf nutrient status compared to other mineral-organic combinations (El-Sayed et al., 2016; Ahmed and Gad, 2022).

3.4 Comparative analysis of substrate performance

Substrate composition has a significant impact on strawberry growth, flowering, fruit set, yield, and fruit quality. In terrace cultivation and greenhouse systems, a mixture of soil, vermicompost or farmyard manure, and coir at a 1:1:1 ratio resulted in higher plant height, leaf number, runner length, fruit number, and yield per plant than soil alone, highlighting the advantage of coir-rich organic substrates (Kumar et al., 2022).

Soilless substrates composed of coir, perlite, and vermicompost improved leaf area, chlorophyll index, root biomass, and overall vegetative growth compared with soil. Among these, the coir-perlite-vermicompost ratio of 4:1:2 achieved the highest TSS/acid ratio, total sugar, and reducing sugar content, indicating improved fruit flavor quality (Sharma and Godara, 2017; Sharma et al., 2025).

Peat-vermiculite-perlite (1:1:1) and other ternary mixtures (peat:vermiculite, peat:perlite, vermiculite:perlite) outperformed single mineral substrates or pure peat in terms of fruit size, fruit number per plant, early yield, and total yield (Hassan et al., 2021). Rockwool promoted earlier reproductive development and produced more fruits and higher total yield than coir, although coir supported stronger vegetative growth. Quality traits such as sugar content and fruit firmness showed no significant differences between the two substrates (An et al., 2025).

In open-field trough cultivation systems, coir or peat-perlite substrates produced marketable yields comparable to fumigated soil, while offering better control of root-zone moisture (Wang et al., 2016).

4 Nutrient Requirements of Greenhouse Strawberries

4.1 Macronutrient requirements

Nitrogen (N), phosphorus (P), and potassium (K) are the main nutrients regulating strawberry growth and yield. Nitrogen is essential for vegetative growth, runner formation, and flower bud differentiation. Insufficient nitrogen reduces aboveground biomass, alters the balance between shoots and roots, and restricts canopy development. In contrast, appropriate nitrogen uptake is closely related to plant height, dry matter accumulation, and fresh fruit yield.

Phosphorus plays an important role in root development, energy transfer, photosynthesis, and the conversion and transport of sugars. Phosphorus deficiency not only inhibits plant growth but also affects the uptake of nitrogen and potassium, and significantly influences fruit quality traits such as total soluble solids (TSS) and sugar content.

Potassium is crucial for cell expansion, osmotic regulation, carbohydrate synthesis, nutrient transport, and fruit coloration. Potassium deficiency leads to poor fruit coloring and affects the formation of high-quality marketable fruits (Jiang et al., 2023).

Seasonal nutrient uptake patterns show that, under fertilization conditions, the total uptake of N, P, and K by plants can reach 78~91, 12~17, and 92~125 kg·hm^{-2}, respectively. The highest net uptake occurs from flowering to fruit development, while nutrient absorption is relatively low in autumn and during dormancy (Bayram and Elmacı, 2021).

4.2 Importance of micronutrients

Calcium (Ca), magnesium (Mg), iron (Fe), and other micronutrients (such as Zn, Mn, Cu, B, and Mo) play important roles in yield potential and fruit quality. Calcium stabilizes cell walls and membranes, improving fruit