large amounts of phosphorus, potassium, magnesium, and calcium and is difficult to recycle (Vandecasteele et al., 2023b). In contrast, organic spent substrates (such as reduced-peat mixtures, compost-based substrates, and biochar composites) contain higher levels of carbon and nutrients and can be reused as carbon-rich soil amendments. However, this requires well-developed systems for collection, blending, and safe utilization, including pathogen control and salinity management.

8.2 Precision nutrient management

Precision water and nutrient management is a key direction for future optimization, as substrate cultivation systems are highly sensitive to water and nutrient conditions. Currently, both wireless and wired sensor systems are capable of real-time monitoring of substrate moisture content and electrical conductivity, achieving promising results.

In intensive production systems in Western Europe, automation and data-driven control have become standard. Computer-controlled fertigation systems can precisely formulate nutrient solutions based on water quality, cultivar requirements, and the EU “zero discharge” policy. Drainage water is collected, filtered, disinfected (e.g., ultraviolet treatment, slow sand filtration), and reused (Lieten, 2013).

A frontier direction is the integration of sensor networks, modeling, and artificial intelligence. The SmartBerry project is a typical example: by building a greenhouse image dataset covering seven growth stages of strawberry and training deep learning models, the EfficientNetB7 model achieved an accuracy of 0.837 in growth stage recognition. This provides a foundation for stage-specific nutrient management based on automated phenotyping (Darlan et al., 2025). If such AI-based growth stage recognition is integrated with fertigation systems and substrate sensors, it could enable closed-loop control systems, allowing dynamic adjustment of nitrogen, potassium, calcium, and irrigation levels according to crop growth stage, substrate type, and environmental conditions.

Future research should focus on improving system stability under commercial production conditions, compatibility with existing greenhouse control systems, and transparency of decision-making rules, in order to enhance grower acceptance.

8.3 Development of environmentally friendly substrates

The development and promotion of bio-based and recyclable environmentally friendly substrates is one of the key directions for future research, aiming to reduce dependence on peat and rockwool in strawberry production. With proper fertigation management, materials such as wood fiber, green waste compost, bark, vermicompost, spent mushroom substrate, carbonized rice husk, and phytoremediated marine sediments can partially or completely replace peat or coir while maintaining high yields (Martínez-Nicolás et al., 2020).

Wood fiber-based substrates, when mixed with compost or peat, can achieve yields comparable to coir. However, high proportions of wood fiber may require additional nitrogen supplementation to avoid nitrogen immobilization (Aurdal et al., 2022). Substrates composed of wood fiber mixed with biochar, green compost, bark, or mineral residues can also achieve marketable yields comparable to coir and peat over two production cycles, although they may affect fruit size and tissue phosphorus and calcium content. This indicates that nutrient management must be optimized according to substrate type (Tumbure et al., 2025).

Substrates derived from organic waste have clear advantages in circular use. Compost-amended substrates not only improve physical structure but also supply abundant nitrogen, phosphorus, and potassium, reducing mineral fertilizer use by 10%-50% and lowering nutrient losses in drainage and spent substrates. Vermicompost produced from cattle manure or sludge can significantly enhance substrate fertility, microbial activity, and enzyme activity, alleviate continuous cropping problems, and increase yield and fruit quality by 18%-20%, while also improving sugar, vitamin C, and amino acid contents (Yeganeh et al., 2024).

Spent mushroom substrate can replace 15%~25% of peat and increase yield and biomass with little impact on photosynthesis, thus enabling resource recycling of waste (Prasad et al., 2021). End-use assessments show that