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Substrate Selection and Nutrient Supply for Greenhouse Strawberry Yield Optimization

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Abstract This study focuses on the combined effects of substrate selection and nutrient supply in greenhouse strawberry production, and provides a systematic analysis. It mainly discusses how different substrate types and nutrient management strategies influence plant growth, yield formation, and fruit quality. An ideal substrate should maintain a balance in physical structure, chemical buffering capacity, and biological activity, so as to ensure root aeration, water supply, and stable nutrient release. Coconut coir, peat, and their mixed substrates with perlite, vermiculite, and vermicompost show clear advantages in improving the rhizosphere environment, enhancing nutrient use efficiency, and optimizing fruit quality. Integrated water and fertilizer management based on dynamic regulation at different growth stages is a key measure to achieve high yield and good quality. By reasonably adjusting the proportions of elements such as N, K, and Ca, yield can be increased significantly, and the sugar-acid ratio and vitamin content can be improved. Sensor-based precise water and fertilizer management, together with recycling systems, can greatly improve water and nutrient use efficiency while reducing environmental pressure, without reducing yield. Substrate and nutrient supply should be optimized together, and combined with regional resource conditions and sustainability requirements, to build an efficient, stable, and environmentally friendly greenhouse strawberry production system.

Keywords Greenhouse strawberry; Soilless cultivation; Substrate optimization; Nutrient management; Water-fertilizer integration

1 Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is one of the most economically valuable soft fruits in modern horticulture, combining high economic returns with excellent nutritional and sensory quality. Strawberries are rich in vitamin C, polyphenols, and antioxidant compounds, making them an important part of a healthy diet and increasingly promoted as a functional food. Over the past two decades, global strawberry cultivation area and production have increased rapidly, and in many countries it has become one of the most profitable horticultural industries (Rahim Doust et al., 2023). Protected cultivation systems, including greenhouses, high tunnels, and other controlled environments, have played a key role in this expansion. These systems provide frost protection, extend the harvest period, stabilize yields, and improve control over major diseases and abiotic stresses, thus supporting industry growth (Samtani et al., 2019). Within these systems, the development of advanced cultivation techniques—especially soilless culture—has turned strawberry into a representative crop for intensive and urban horticulture, enabling high-density planting, off-season production, and more efficient use of resources (Nichols, 2021; Kouloumprouka Zacharaki et al., 2024).

Consumers now expect strawberries to be available year-round, with not only good appearance—uniform size, consistent color, and attractive shape—but also high sensory quality such as sweetness, aroma, and firmness, along with strong nutritional and functional value (Hernández-Martínez et al., 2023; Cardarelli et al., 2024). This shift in market demand has pushed breeding and production systems to focus more on varieties and cultivation practices that combine high yield with high internal quality. Key targets include improving soluble solids, organic acids, polyphenol content, and antioxidant capacity (Sturzeanu et al., 2025). By optimizing fertilization and water management, it is possible to enhance soluble solids, organic acid levels, color, and bioactive compounds while maintaining yield (Raffaelli et al., 2025).

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 nutrient solution composition and reduces nutrient leaching (Tang et al., 2024). However, strong microbial immobilization or adsorption may temporarily reduce the availability of N, P, and S. In peat-sawdust substrates, it has been observed that initial fertilization is needed to alleviate nutrient immobilization (Depardieu et al., 2016).

2.3 Biological properties

From a biological perspective, the substrate is not only a habitat for microbial communities but also an important factor in regulating nutrient cycling, promoting plant growth, and suppressing diseases. Substrates amended with organic materials (such as livestock manure, vermicompost, mushroom residues, or organic fertilizers) usually contain higher populations of bacteria and fungi, are enriched with phosphate-solubilizing and nitrogen-fixing bacteria (e.g., Azotobacter), and show higher enzyme activities related to carbon and nitrogen cycling (Hindersah et al., 2023).

Amendments such as vermicompost and livestock manure can improve substrate fertility, increase microbial abundance and enzyme activity, and reduce the accumulation of phenolic acids. As a result, they significantly promote plant height, leaf area, root length, and fruit yield and quality, especially in continuous cropping systems (Bai et al., 2025). Sheep manure organic fertilizer can significantly improve soil pH, nutrient availability, and the activity of enzymes such as sucrase, protease, and urease, while also increasing bacterial and fungal diversity, thereby promoting strawberry growth and nutrient supply (Zha et al., 2024).

An ideal substrate should also have some disease-suppressive ability. This mainly comes from good aeration and drainage conditions (which are unfavorable for many root pathogens) and microbial communities that can compete with or antagonize pathogens. Compared with greenhouse soil, artificial substrates can change the composition and functional pathways of rhizosphere bacterial communities in strawberry, showing enrichment in plant growth-related metabolic pathways (such as flavonoid biosynthesis) and changes in antimicrobial compound synthesis pathways (Zhang et al., 2023).

Substrates with good physical and chemical conditions (such as coir-perlite-vermicompost mixtures, peat combined with rice husk or perlite, and optimized vermicompost-coir/biochar formulations) can promote dense root branching and high survival rates. This increases the surface area for beneficial microbial colonization, further improving nutrient uptake efficiency, yield, and system stability (Yafuso and Boldt, 2024; Selivanova et al., 2025).

3 Common Substrate Types and Their Performance

3.1 Organic substrates

Among organic substrates, coir, peat, compost, and vermicompost-based media are the most widely used. Pure coir or coir-based mixtures have high water-holding capacity, good aeration, and low bulk density, which support strong vegetative growth and canopy development. In both open-field and greenhouse trials, 100% coir or peat-perlite mixtures produced yields comparable to soil cultivation, while also forming larger canopies and higher biomass (Wang et al., 2016).

Peat remains an important reference substrate due to its favorable structural properties and high cation exchange capacity (CEC). Commercial peat-based mixtures (such as peat combined with coir, perlite, vermiculite, or zeolite) often support strong root growth and high long-term productivity in both pot and hydroponic systems (Lee et al., 2023) (Figure 1). Compost- and vermicompost-based substrates can increase organic matter content, improve nutrient supply, and stimulate microbial activity. In particular, mixtures of vermicompost-coir and vermicompost-biochar at about a 0.5:0.1 ratio significantly improved water retention, nitrogen use efficiency, enzyme activity, nutrient uptake, as well as fruit yield and quality (Tang et al., 2024).

However, organic substrates may also have some drawbacks, such as compaction, high electrical conductivity (EC), and nutrient immobilization. For example, peat mixed with sawdust or bark often requires additional fertilization at the early stage to overcome the immobilization of nitrogen, phosphorus, and sulfur. Pure coir may also become compacted under certain conditions, and compared with treatments containing mineral amendments, it may result in fewer fruits (García-López and Cruz-Ortega, 2023).

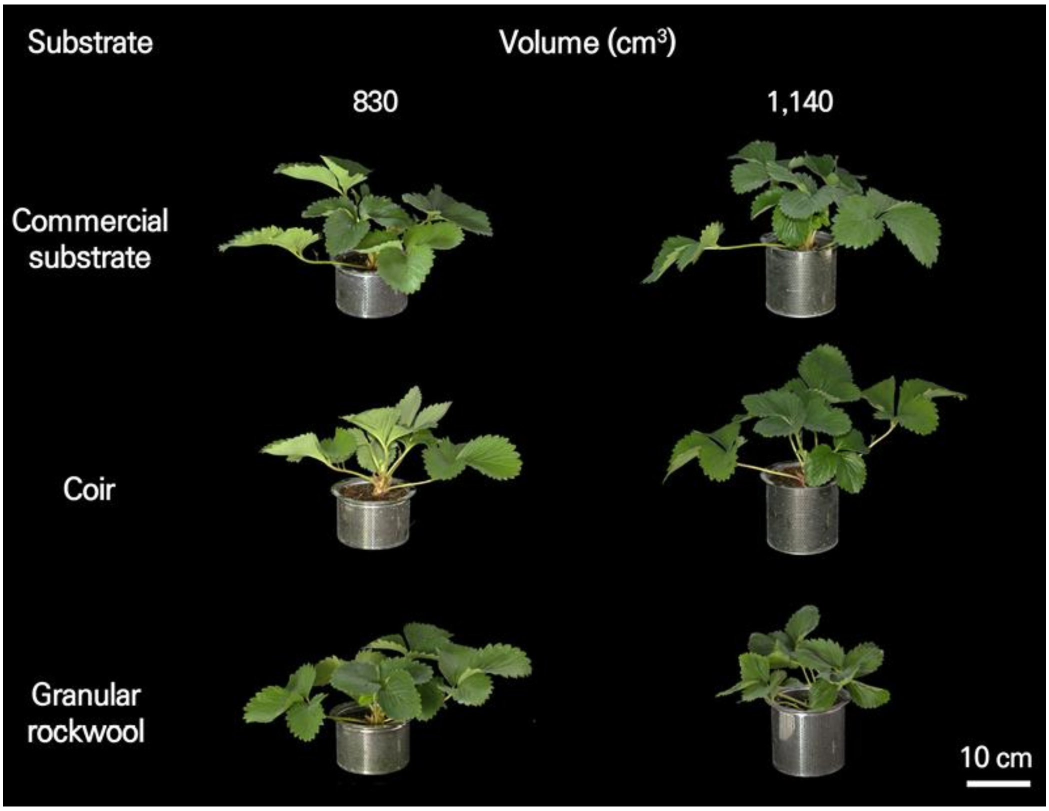

Figure 1 Plants grown with two different pot volumes (830 and 1 140 cm^3) with three different substrate types (commercial substrate, coir, and granular rockwool) treatment 63 days after transplant (Adopted from Lee et al., 2023)

3.2 Inorganic substrates

Common inorganic substrates include perlite, vermiculite, and rockwool, as well as other mineral materials such as tuff and volcanic rock. Perlite is highly porous and has very low bulk density, which helps improve drainage and aeration. When mixed with peat, vermicompost, or plant compost (e.g., perlite:peat = 1:1, perlite:vermicompost = 3:2, perlite:compost = 4:1), it can significantly enhance vegetative growth, leaf area, nutrient accumulation, yield, and fruit quality compared to substrates with poor aeration (El-Sayed et al., 2016).

Vermiculite has higher water-holding capacity and CEC than perlite. Coir-vermiculite and coir-vermiculite-perlite mixtures, compared with sand culture, can increase petiole length, canopy size, root biomass, and total soluble solids (TSS), indicating that vermiculite improves water and nutrient retention without seriously reducing aeration when used in proper proportions.

Rockwool is a uniform and inert substrate with excellent control over root-zone moisture. In greenhouse soilless systems, rockwool can promote earlier transition to reproductive growth in strawberry and produce more fruits and higher total yield than coir. In contrast, coir is more favorable for vegetative growth, and there is little difference between the two in terms of sugar content and fruit firmness. Granular rockwool has very high water retention, and improper irrigation management may lead to water stress and restricted root growth.

Volcanic rock (tezontle), used alone or mixed with coir at a 1:1 ratio, produced more fruits per plant as well as larger berries and higher individual fruit weight than soil cultivation. This suggests that properly graded mineral substrates, when combined with precise water and nutrient management, can match or even exceed organic substrates in yield performance (Lekavičienė et al., 2025).

3.3 Mixed substrate systems

Mixed substrates combine organic components that supply water, nutrients, and biological activity with inorganic components that provide structural stability and improved aeration, creating a synergistic effect. Coir-perlite (4:1) and peat-perlite (4:1) mixtures performed better than pure tuff or tuff-organic mixtures in terms of photosynthesis, 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 $kg \cdot hm^{-2}$, 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 firmness, shelf life, and resistance to physiological and abiotic stresses. Most Ca in plants accumulates in vegetative organs, and insufficient Ca supply is common in commercial production systems, often associated with reduced fruit formation and quality decline.

Magnesium is an important component of chlorophyll and also acts as an activator for many enzymes. It is distributed between leaves and fruits, and its uptake is positively correlated with plant height and the number of fruits per plant (Quddus et al., 2025).

Elements such as Fe, Zn, Mn, Cu, and B are essential for photosynthesis, respiration, enzyme activation, and hormone balance. Application of Fe, Zn, and Ca through foliar spray or substrate can improve vegetative growth, flowering, yield, and fruit quality (such as vitamin C content and firmness) (Marchenko et al., 2024; Singh et al., 2024).

Long-term investigations of leaf nutrient status in commercial plantations show that although N, P, K, and Mg are usually sufficient, deficiencies of Ca, S, Zn, and Cu occur in more than half of the samples, which may limit yield and fruit quality under both open-field and protected conditions (Osvalde et al., 2023). Typical deficiency symptoms include chlorosis and poor growth caused by Fe and Mg deficiency, weak pedicels and soft fruits caused by Ca deficiency, and reduced fruit set, smaller fruit size, or lower sugar content due to insufficient Zn, B, and other micronutrients, ultimately reducing marketable yield and economic returns (Sangeeta et al., 2019; Sayğı, 2022).

4.3 Nutrient uptake dynamics

Under greenhouse soilless cultivation, nutrient uptake is influenced not only by root physiological characteristics but also by the interaction between substrate and nutrient solution. The uptake of most macronutrients is lowest in the early stage after autumn planting and reaches a peak from flowering to fruit maturity. Among these, K shows the highest uptake rate, followed by N, Ca, Mg, and P. Roots and crowns store nitrogen during autumn and winter, and about 40% of the stored nitrogen is remobilized for new growth during flowering.

Analysis of leaves, crowns, roots, and fruits indicates that during fruit maturation, N, P, and K are mainly transported to fruits, while Ca is largely retained in leaves and roots, and Mg is distributed between vegetative organs and fruits. This suggests that continuous nutrient supply is required during the reproductive growth stage (Ikegaya et al., 2020).

In hydroponic and low-substrate-volume systems, root uptake patterns are strongly affected by the composition of the nutrient solution (such as N/K and K/Ca ratios), electrical conductivity (EC), pH, and cultivar-specific uptake characteristics. Adjusting these ratios at different growth stages can improve photosynthetic efficiency, promote earlier fruit ripening, increase yield by about 20%~26%, and improve the sugar-acid ratio and vitamin C content, while maintaining stable substrate pH (Shirko et al., 2018).

Substrate properties further affect nutrient availability. pH determines the solubility of micronutrients and the risk of deficiency or toxicity, while EC, cation exchange capacity (CEC), and organic matter content regulate the fixation and release of N, P, S, K, and Mg. Organic amendments (such as vermicompost and mushroom waste) can increase total and available N, P, and K in soil, enhance microbial and enzyme activity, and alleviate continuous cropping obstacles, thereby promoting nutrient uptake and improving yield and fruit quality (Allayorov et al., 2023). In contrast, peat-based substrates with low fertility may lead to deficiencies of N, P, and K if fertilization is not properly managed, further indicating that substrate selection and nutrient solution design must be optimized together to meet nutrient uptake dynamics at different growth stages.

5 Nutrient Supply Strategies in Soilless Cultivation

5.1 Fertigation management

The composition and concentration of nutrient solutions must be adjusted according to crop growth stage and cultivar. In practice, the ratios of N:K and K:Ca are usually modified during the vegetative stage, flowering stage, and fruit expansion stage. This helps improve photosynthetic efficiency, promote rapid fruit ripening, enhance sugar-acid balance and vitamin C content, and at the same time reduce overall fertilizer input (Nakro et al., 2023). However, excessively high nutrient concentrations or long-term use of a “single formula” often lead to nutrient imbalance and salt accumulation. Moderately reducing concentration (e.g., to 65% of the standard level) may maintain yield in short-cycle production, but in long-cycle cultivation from autumn to spring, it may reduce yield.

Irrigation scheduling has a strong influence on nutrient supply and leaching losses. Timer-based fertigation or high leaching fractions (20%~40% of applied water) are common, but they often result in over-irrigation (Savvas et al., 2024). Sensor-based strategies, such as using substrate volumetric water content (VWC) or combined VWC-EC thresholds, allow fertigation only when needed. This approach can reduce water use by 26%~38% and nutrient solution consumption by up to 38%, while increasing marketable yield and improving water and nutrient use efficiency by 46%~74%, clearly outperforming timer-based control (Hutchinson et al., 2025a).

Experiments with different irrigation frequencies show that dividing fertigation into multiple daily applications (e.g., four times per day), compared with low-frequency irrigation, significantly promotes vegetative growth, increases early yield, improves fruit quality, and enhances leaf and root biomass (Malekzadeh et al., 2024). In addition, partial deficit irrigation strategies (such as alternating wet and dry conditions in half of the root zone volume) can save up to 50% of water and fertilizer inputs without reducing yield, while improving fruit quality by limiting excessive vegetative growth (Alavi et al., 2025).

5.2 Controlled-release fertilizers

Controlled-release and slow-release fertilizers (CRFs/SRFs) release nutrients gradually, better matching crop demand. Compared with conventional quick-release fertilizers, they can significantly reduce nutrient losses caused by leaching, volatilization, and denitrification (Jariwala et al., 2022; Duan et al., 2023). In greenhouse strawberry production, the use of controlled-release fertilizers can increase plant height, stem diameter, leaf area, photosynthetic rate, chlorophyll content, root activity, and fresh fruit yield by more than 10%, while maintaining high agronomic efficiency of nitrogen, phosphorus, and potassium.

Compared with conventional fertilizers, controlled-release fertilizers are more effective in maintaining fruit quality, such as vitamin C content and flavor. In contrast, traditional fertilizers often have higher initial salt concentrations, which may reduce sensory quality. Long-term soil experiments have shown that the use of controlled-release compound fertilizers in strawberry cultivation increases plant nitrogen and phosphorus content and forms a nutrient release pattern that matches the needs of different growth stages. Soil available nutrients increase first and then decrease, avoiding excessive accumulation.

5.3 Recirculating vs. non-recirculating systems

Nutrient solution management can be divided into open (free drainage) and closed (recirculating) systems. Open systems usually operate with high leaching fractions. They are simple to manage but have low nutrient use efficiency (NUE) and can easily cause nitrate and phosphate pollution.

Closed recirculating systems collect and reuse drainage solution, which can reduce water consumption by about 20%~40% and fertilizer use by 40%~50%, while almost eliminating nutrient discharge (Savvas et al., 2024). In greenhouse strawberry production, a well-managed closed hydroponic system, combined with nutrient correction every 2~4 weeks based on drainage ion analysis, can maintain yields comparable to open systems. At the same time, nutrient use efficiency can increase by 32%~36% compared with uncorrected systems and by up to 94% compared with open systems (Lim et al., 2024).

If the recirculation process is controlled only by drainage EC, salt accumulation and ion imbalance may occur over time, reducing yield and requiring periodic discharge. Therefore, ion monitoring and precise regulation are essential. In addition, when strawberry drainage is reused for other crops (such as maize), improper evaluation of its fertilizer value and application rate may lead to soil salinization, reflecting environmental risks associated with unregulated discharge (Kopeć et al., 2020).

Life cycle assessment studies also show that in hydroponic vegetable systems, closed-loop recirculation can reduce eutrophication impacts by 35%~54%. Although additional infrastructure may slightly increase energy use and carbon emissions, this can be offset by higher yields and long-term system use (Rufí-Salís et al., 2020).

6 Interaction between substrate and nutrient supply

6.1 Effects of substrate on nutrient retention and release

Different organic and inorganic components show clear differences in nutrient adsorption, fixation, and slow release. In soilless strawberry cultivation, low-peat substrates containing wood fiber and compost can retain a relatively large proportion of Ca (76%~88%), Mg (70%~85%), and N (61%~81%) after use, while K is mainly removed through aboveground biomass. This indicates that different elements have specific retention patterns, which should be considered when designing fertigation strategies (Vandecasteele et al., 2023a).

Substrates amended with compost can supply large amounts of P and K, reducing fertigation input by 10%-50% and lowering nutrient losses in drainage. However, during long spring cultivation cycles, when compost mineralization slows down, additional N input is required (Vandecasteele et al., 2018). Similarly, biochar or lignocellulosic materials can act as nutrient adsorbents, recovering nitrate, phosphate, Ca, and sulfate, and stabilizing the chemical properties of nutrient solutions. At the same time, they may increase pH and change K dynamics, thereby affecting nutrient availability (Haraz et al., 2020).

The addition of organic amendments can increase cation exchange capacity (CEC), pH buffering capacity, and the storage of NH_4^+ and K, while reducing P fixation, thus improving fertilizer use efficiency. This effect is especially obvious in sand–coco coir mixed substrates. The buffering effect of different substrates is closely related to pH regulation and ion balance. Substrates rich in coco coir have strong pH buffering capacity and nutrient storage ability, which can promote vigorous plant growth. However, if fertilization does not match crop demand, it may lead to excessive nutrient accumulation (Xu et al., 2021). Compost and spent mushroom substrate often contain high nutrient levels at the early stage, promoting root and shoot growth and increasing marketable yield. However, their mineralization rate changes over time, so nutrient supply should be adjusted in stages to avoid excess in the early stage and deficiency later.

In contrast, substrates with low CEC, such as sand or mixtures with a high proportion of wood fiber, have weaker buffering capacity, and nutrient concentrations in the root zone are more directly affected by fertigation management. Although this allows for rapid adjustment, improper fertilization can more easily lead to osmotic stress or nutrient deficiency.

6.2 Regulation of the rhizosphere environment

Besides chemical properties, substrates also influence nutrient uptake efficiency by regulating the physical environment of the rhizosphere, especially aeration, water distribution, and temperature. Studies in soilless cultivation show that root function depends on sufficient oxygen supply. When aeration is poor or waterlogging occurs in the root zone, nutrient uptake and plant growth are inhibited even if nutrient solution concentration is high (Balliu et al., 2021).

Studies in both hydroponic and soil systems indicate that moderate increases in rhizosphere oxygen can improve root length, root volume, root activity, and P uptake capacity, thereby increasing yield and quality. However, both excessive and insufficient oxygen can inhibit growth (Wang et al., 2022; Nitu et al., 2024). Under waterlogged or low-oxygen conditions, even with adequate nutrient supply, the uptake of K, Mg, and Ca decreases, and shoot growth is also restricted. This shows that good aeration is a prerequisite for efficient fertilizer use.

Substrate structure, such as pore distribution, water-holding capacity, and bulk density, determines the balance between water and oxygen. Mixed substrates of peat, coco coir, and compost or organic composites, combined with inorganic nutrient supply, can improve both aeration and water retention, thus promoting root development and increasing strawberry yield (Prasad et al., 2022). Materials such as wood fiber can increase porosity and moisture, but they immobilize nitrogen during decomposition, so additional N fertilization is needed to maintain nutrient balance.

In addition, substrate pH regulation is critical for nutrient availability. Most macronutrients are most easily absorbed at pH 6~6.5, while higher pH reduces the solubility of micronutrients and disrupts nutrient balance. This has been confirmed in container experiments with peat substrates (Ferrarezi et al., 2022).

6.3 Optimization model of substrate-nutrient combinations

Building an efficient production system requires coordinated design of substrate characteristics and nutrient management strategies, rather than considering them separately. Long-term strawberry experiments show that in substrates with added compost or reduced peat content, fertigation strategies must be recalibrated to account for nutrients supplied and retained by the substrate itself. When compost mineralization is high in autumn, inputs of N, P, and K should be reduced. In extended spring cultivation, when the internal nutrient supply capacity of the substrate declines, inputs should be increased.

Current optimization approaches increasingly rely on quantitative models that link substrate physicochemical properties with plant performance. For example, structural equation modeling has been used to analyze how vermicompost indirectly promotes plant growth, fruit morphology, and yield by altering substrate nutrients, microbial activity, and enzyme activity (Bai et al., 2025).

7 Case Studies and Practical Applications

7.1 Regulation model based on vermicompost

Under continuous greenhouse cultivation, substrate degradation and continuous cropping obstacles are key factors limiting the stability of strawberry yield and quality. Bai et al. (2025) conducted a study under greenhouse conditions in Hebei, China, using a randomized block design with the strawberry cultivar “Xiangye.” They compared the effects of different substrate types and vermicompost application methods on plant growth, yield, and quality. The experiment included two background conditions: new substrate (0 years) and substrate continuously cultivated for 2 years. On this basis, three treatments were set: no vermicompost (CK), cattle manure-derived vermicompost, and sludge-derived vermicompost. The experiment covered a full strawberry growing season. Plant growth parameters (plant height, leaf area, root length), substrate physicochemical properties (nutrient content, microbial quantity, enzyme activity), yield, and fruit quality indicators (soluble sugars, vitamin C, and amino acids) were systematically measured.

The addition of vermicompost significantly improved the substrate environment. Compared with the control, nutrient content in the substrate increased by about 12.04%~42.54%. At the same time, microbial populations and related enzyme activities were clearly enhanced, while the content of phenolic autotoxins decreased significantly. This effect was more obvious in continuously cropped substrates, indicating that vermicompost plays an important role in alleviating continuous cropping obstacles. The improved substrate environment further promoted plant growth. In the treatment groups, plant height, leaf area, and root length increased by about 15.01%~32.77% and 23.75%~32.78%, showing that root vitality and nutrient uptake capacity were enhanced.

Under new substrate conditions, yield increased by about 18.29%, while in continuously cropped substrate the increase reached 19.64%. Fruit quality was also improved. During the peak fruiting stage, soluble sugar content increased by about 9.62%~42.62%, and both vitamin C and free amino acid contents increased significantly, indicating improvements in both flavor and nutritional value (Figure 2).

7.2 Substrate cultivation combined with integrated water-fertilizer management

In greenhouse soilless cultivation systems, the traditional practice of using a fixed nutrient solution throughout the whole growth period often cannot meet the different nutrient requirements of strawberries at different growth stages. Yu et al. (2023) conducted a greenhouse experiment in the Xiaotangshan Modern Agricultural Demonstration Park in Beijing, China, based on dynamic adjustment of nutrient solution according to growth stages. The study used an elevated substrate cultivation system with strawberry ‘Ssanta’ as the test material. Under volcanic rock substrate, horticultural substrate, and commercial substrate conditions, they compared the traditional Yamazaki standard nutrient solution (control) with an optimized nutrient solution adjusted according to growth stages. The treatment increased nitrogen supply during the vegetative stage, gradually increased potassium supply and adjusted the K/Ca ratio during flowering and fruit expansion stages, and optimized the ratio of NO_3^--N to NH_4^+-N.

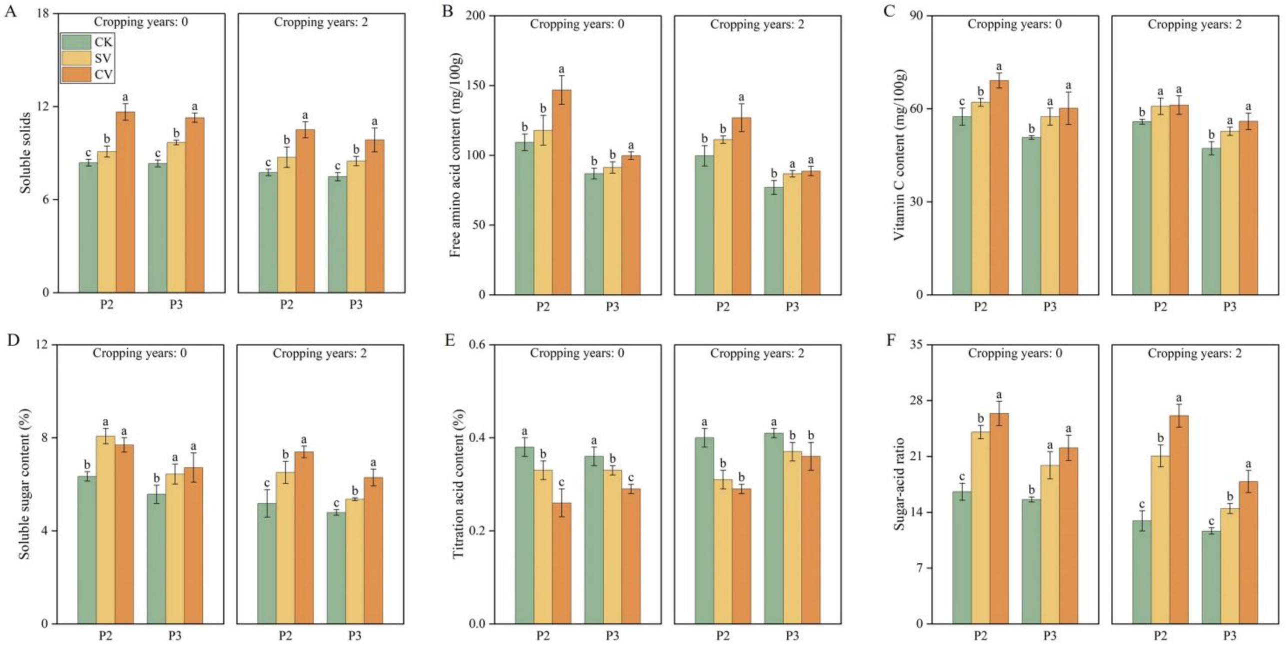

Figure 2 Effects of vermicompost on soluble solids (A), free amino acid content (B), vitamin c content (C), soluble sugar content (D), titration acid content (E) and sugar-acid ratio (F) in different periods. Letters indicate significant differences in the effects of different vermicompost treatments on this indicator at different time periods, with a significance level of $p < 0.05$. P2 and P3 represent peak fruiting period and the senescence phase respectively. Abbreviations for treatment: Control (CK), sludge vermicompost (SV) and cattle manure vermicompost (CV) (Adopted from Bai et al., 2025)

Compared with the traditional fixed formula, the nutrient management model based on growth stage regulation significantly improved strawberry production performance. In terms of yield, total yield per plant increased by about 20%, with the highest increase reaching 26% under horticultural substrate conditions. The peak fruiting stage was advanced by about one week. In terms of physiological performance, the optimized treatment significantly improved photosynthetic capacity during both vegetative growth and flowering stages. Regarding fruit quality, the sugar-acid ratio increased by about 41%, and vitamin C content increased by about 34%, reaching up to 74.1 mg/100 g.

8 Challenges and Future Prospects

8.1 Limitations of current substrate technologies

Although substrate cultivation technology has become relatively mature, its long-term sustainability and system resilience are still constrained by multiple factors. Peat remains the dominant material in commercial strawberry substrates, but peatlands are non-renewable on a practical timescale, and their extraction leads to serious problems such as increased carbon emissions and habitat destruction. Even in regions where peat resources are relatively abundant, it is widely recognized that peat cannot be rapidly regenerated. Therefore, efforts are being made to reduce its carbon footprint through practices such as artificial cultivation of sphagnum moss and partial substitution with local materials like sawdust, bark, and compost.

The reuse of peat, coir, and wood fiber has, to some extent, reduced pressure on resource extraction and waste disposal. Under properly adjusted fertigation management, these substrates can be reused for up to three cycles without significant reductions in yield or physical properties (Vandecasteele et al., 2024; Woznicki et al., 2024). However, reuse also introduces new issues, including nutrient accumulation (especially increases in nitrogen and calcium and depletion of potassium), changes in cellulose content, and the buildup of pathogenic fungi. Therefore, disinfection (such as steam treatment) and nutrient rebalancing are necessary to maintain system stability (Hu et al., 2025).

The disposal and end-use of spent substrates remain major challenges. Rockwool, widely used in greenhouse horticulture, has low organic carbon content and limited value as a soil amendment. It also tends to accumulate 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 organic substrates with reduced peat and added biochar have high carbon sequestration potential and can be reused as soil amendments. Biochar increases carbon content and cation exchange capacity, enabling a cascade use model—first as a cultivation substrate, then as a soil amendment (Vandecasteele et al., 2023b).

Looking ahead, the development of environmentally friendly substrates should be based on local resources (such as wood, crop residues, livestock manure, and sediments), combined with pretreatment and precise nutrient management. Attention should also be given to microbial community changes and pathogen risks during reuse. Achieving coordinated optimization in terms of physical structure, nutrient buffering capacity, and compatibility with precision fertigation systems will be essential for building efficient and low-environmental-impact greenhouse strawberry production systems.

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