Plant Gene and Trait 2026, Vol.17, No.5, 317-331
http://genbreedpublisher.com/index.php/pgt

Feature Review Open Access

Evaluation of Growth Performance and Yield of Strawberry Cultivars under Different Cultivation Systems

Haiya Xu
Sanmen County Kedi Family Farm, Sanmen, 317108, Zhejiang, China
Corresponding email: 657552075@qq.com

Plant Gene and Trait, 2026, Vol.17, No.5 doi: 10.5376/pgt.2026.17.0023
Received: 13 Aug., 2026
Accepted: 15 Sep., 2026
Published: 23 Sep., 2026

Copyright © 2026 Xu, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preferred citation for this article:
Xu H.Y., 2026, Evaluation of growth performance and yield of strawberry cultivars under different cultivation systems, Plant Gene and Trait, 17(5): 317-331 (doi: 10.5376/pgt.2026.17.0023)

Abstract This review examines the environmental characteristics of different cultivation systems and their effects on the growth performance and yield of strawberry cultivars. The differences in plant morphology, root development, physiological responses, and yield components under open-field, protected, soilless, and vertical cultivation systems were analyzed. The reviewed evidence indicates that the effects of cultivation systems on strawberry production performance were highly cultivar-dependent, and suitable cultivation systems should be selected based on cultivar characteristics, environmental conditions, and production objectives. Single-index evaluation methods can rapidly reflect the performance of specific indicators, but they are insufficient for comprehensively evaluating overall production potential. Multi-index comprehensive evaluation and digital technologies provide more scientific approaches for cultivar selection and optimization of cultivation systems. Current strawberry production still faces challenges, including unclear matching mechanisms between cultivars and cultivation systems, incomplete comprehensive evaluation frameworks, and limited applications of intelligent technologies. Future research should focus on the interaction mechanisms among "cultivar–cultivation system–environment" and integrate sensors, artificial intelligence, and precision agriculture technologies to achieve intelligent regulation of strawberry production processes, improve yield stability, fruit quality, and resource-use efficiency, and promote the strawberry industry toward more efficient, precise, and sustainable development.

Keywords Strawberry; Cultivation system; Cultivar adaptability; Yield; Comprehensive evaluation

1 Introduction

Strawberry production has become an increasingly important horticultural sector because the crop holds a strong position in global fruit markets, is highly profitable in many countries, and has expanded markedly over recent decades (Sahoo et al., 2024). At the same time, conventional soil-based production faces persistent constraints, including high water demand, soil-borne diseases, environmental and phytosanitary problems, shrinking water availability in major production regions, and rising production costs under increasingly unstable climates (Ariza et al., 2021; Doust et al., 2023; Fayaz et al., 2025). These pressures have accelerated the diversification of cultivation systems from open-field raised beds toward protected cropping, high tunnels, greenhouse substrate culture, hydroponics, vertical production, and other controlled-environment approaches designed to improve environmental control, extend production periods, reduce disease pressure, and increase resource-use efficiency (Rathod et al., 2021). In this transition, soilless systems have become especially prominent because they can improve root-zone management, enable elevated table-top production, reduce pesticide and fungicide dependence, and adapt strawberry cultivation to unfavorable or contaminated soils and space-limited production environments (Cecatto et al., 2013; Kang et al., 2020).

Current cultivation systems for strawberry can be grouped broadly into soil culture, solid-substrate soilless culture, and water-based hydroponics, with additional variation in structure and environment such as horizontal versus vertical layouts, greenhouse versus open-field soilless systems, and substrate- versus water-culture hydroponics (Rathod et al., 2021). Evidence shows that these systems do not affect performance uniformly. In several comparisons, soilless or hydroponic systems increased vegetative growth, nutrient uptake, photosynthetic capacity, fruit yield, and fruit quality relative to conventional soil culture, and in some settings hydroponics produced substantially higher yields and lower unmarketable fruit ratios (Kang et al., 2020; Rana et al., 2023). Yet the

response is system-specific rather than universally linear. Substrate hydroponics outperformed water-culture systems for yield and resource-use efficiency in greenhouse production, triple-layer vertical glasshouse production exceeded horizontal production for several growth and fruit-quality traits (Madhavi et al., 2023), and greenhouse soilless culture favored vegetative growth and yield whereas open-field soilless culture favored flavor, antioxidant traits, and shelf life (Doust et al., 2023). Other studies report that soil or open-field conditions can still outperform protected or vertical systems for particular yield performance, as seen where soil culture gave higher yield but substrate improved quality, terrestrial cultivation exceeded vertical pipes for fruit yield, and open field with 'Sweet Sensation' produced the greatest yield in one regional trial (Cecatto et al., 2013; Mustafa and Rahman, 2021; Pandey et al., 2024).

The variable performance of cultivation systems is closely tied to genotype, because strawberry cultivars differ in vegetative vigor, fruit size, marketable yield, quality attributes, water use, and their capacity to respond to specific production environments (Doust et al., 2023). Cultivar-dependent responses have been documented across open-field, high tunnel, soil, substrate, and hydroponic conditions. In Virginia, most cultivars had similar total yield in high tunnels, but 'Chandler', 'Rocco', and 'Sweet Ann' were highest yielding in the open field, while cultivars also differed in fruit weight, firmness, soluble solids, and titratable acidity (Liu et al., 2024). In greenhouse comparisons of soil and substrate culture, 'Camarosa', 'Florida Festival', and 'Portola' excelled in soil, whereas cultivar differences were less pronounced in substrate culture (Cecatto et al., 2013). Under contrasting water supplies, cultivars differed substantially in yield efficiency, water consumption, and tolerance to deficit irrigation, indicating that genotype selection is central to resource-efficient production (Ariza et al., 2021). Additional interaction studies show that cultivar×system combinations can determine the best outcome: hydroponics increased growth over traditional culture, but 'Sweet Charlie' and 'Camarosa' differed in vegetative and yield responses (Fayaz et al., 2025); among three cultivars under open field, shade net, and polyhouse conditions, open field with 'Sweet Sensation' produced the strongest growth and yield (Pandey et al., 2024); and in vertical versus terrestrial culture, 'Sweet Charlie' showed superior fruit weight and greenhouse yield among the tested cultivars (Mustafa and Rahman, 2021). Even where plant type did not change yield in soilless 'Albion', agroclimatic conditions still influenced plant behavior, reinforcing that genotype evaluation must be interpreted within a specific production context (Palombini et al., 2023).

This study investigates the effects of different cultivation systems on the growth performance and yield of strawberry cultivars, and analyzes the interactions between cultivar selection and production environments as well as their impacts on production efficiency and marketable output. Although numerous studies have demonstrated that cultivation systems can influence strawberry yield, fruit quality, and resource-use efficiency, systematic comparisons among different cultivation systems remain limited. For example, the advantages and differences between substrate-based hydroponic systems and nutrient solution-based hydroponic systems require further clarification, and the adaptability of different cultivars under diverse environmental conditions needs broader validation. In addition, successful soilless strawberry production depends not only on the selection of cultivation systems but also on the optimization of technical factors, including substrate type, nutrient solution formulation, pH regulation, irrigation strategies, and fertigation management. By systematically evaluating the growth characteristics, yield performance, and adaptability of strawberry cultivars under different cultivation systems, this study provides a theoretical basis for selecting cultivar–cultivation system combinations with high yield stability, superior fruit quality, improved water and energy-use efficiency, and strong production adaptability, thereby promoting the strawberry industry toward more efficient, precise, and sustainable development.

2 Main Cultivation Systems of Strawberry and Their Environmental Characteristics

2.1 Traditional open-field cultivation system

Traditional open-field cultivation remains the baseline system for strawberry production and is still widely used globally, although its relative importance has declined as protected and soilless systems have expanded (Kouloumprouka Zacharaki et al., 2024). Its main environmental characteristic is direct exposure to ambient weather, which makes crop performance strongly dependent on local climate, seasonal temperature patterns, rainfall, and frost risk (Anderson et al., 2019). Open-field systems therefore show greater year-to-year yield

variability than protected systems, even though they often require less infrastructure and can have lower environmental burdens per unit product than many protected configurations (Boakye-Yiadom et al., 2025). Agronomically, open-field strawberry production also faces persistent constraints from pests, weeds, and soil-borne pathogens, and these problems are among the main reasons growers shift toward alternative systems (Wortman et al., 2016; Rathod et al., 2021).

Despite these constraints, open-field conditions can support strong vegetative growth and high yields in some cultivar–environment combinations. In Southeast Virginia, several cultivars produced their greatest total yields in the open field, with 'Chandler', 'Rocco', and 'Sweet Ann' reaching about 780~870 g per plant (Liu et al., 2024). In Maharashtra, open-field conditions with 'Sweet Sensation' gave the highest plant growth, earliest flowering, and the highest yield per plant and per hectare among the tested growing conditions (Pandey et al., 2024). However, these favorable outcomes are site-specific rather than universal, because open-field production in the U.S. Midwest is limited by pests and a short growing season, and broader European analyses show that open systems tend to be more climatically vulnerable even when they are environmentally less intensive (Wortman et al., 2016; Boakye-Yiadom et al., 2025).

2.2 Protected cultivation system

Protected cultivation includes plastic tunnels, high tunnels, low tunnels, and greenhouses designed to buffer strawberries against cold, frost, rain, hail, and some disease pressures while extending the harvest season (Anderson et al., 2019; Doust et al., 2023; Menzel, 2025). Compared with open-field systems, these environments generally provide greater control over temperature, moisture, and precipitation exposure, which often increases yield and reduces direct weather damage (Boakye-Yiadom et al., 2025). A global review of 133 experiments found that tunnel-grown strawberries had higher marketable yield and total yield than open-field crops, with tunnel-to-open ratios of 1.34 for marketable yield and 1.30 for total yield, while fruit weight was similar between systems. High tunnels also extend the production window; in Virginia, harvest in high tunnels began in January, whereas open-field harvest began in April (Liu et al., 2024).

The benefits of protection are not uniform, because protected systems can also create new microclimatic and management problems. Lower yields under tunnels have been linked to low light, high temperatures under plastic, and greater powdery mildew incidence, making ventilation and cover management important under warming conditions (Menzel, 2025). In cultivar trials, high tunnels reduced fruit losses and promoted rapid vegetative growth in 'Monterey', but did not increase yield in 'Albion' and were associated with more powdery mildew and calcium deficiency. Greenhouse soilless systems similarly increased vegetative growth, photosynthesis, and yield relative to open-field soilless culture, but open-field fruit had better firmness, flavor index, antioxidant status, and shelf life, showing that protected environments often favor productivity more than final fruit quality (Doust et al., 2023).

2.3 Substrate-based and soilless cultivation systems

Substrate-based and soilless systems have expanded rapidly because they reduce dependence on field soil and allow closer control of the root zone, fertigation, aeration, and water supply (Doust et al., 2023). These systems are especially relevant where soils are contaminated, poorly drained, pathogen-infested, or otherwise unsuitable for strawberry production (Wortman et al., 2016). The main forms are solid-substrate culture and water-based hydroponics, with coir, peat, and rockwool among the common media for substrate systems (Rathod et al., 2021; Kouloumprouka Zacharaki et al., 2024). Their environmental characteristics include reduced weed pressure, lower soil-borne disease risk, improved water-use efficiency, and compatibility with elevated table-top production, although they require greater technical management and initial investment than conventional soil culture (Kang et al., 2020).

Performance comparisons generally favor soilless culture over soil culture for growth and marketable production, though responses depend on system design. In cv. 'Festival', both solid substrate and hydroponic systems improved vegetative growth, fruit yield, and fruit nutritional traits relative to soil, with the strongest effects in the solid substrate treatment. In another study, hydroponic cultivation produced higher total yield, higher fruit quality,

and a lower unmarketable fruit ratio than soil cultivation (Kang et al., 2020). Recent greenhouse comparisons among hydroponic systems found that substrate culture outperformed water-culture systems for per-plant yield, water and energy use efficiency, and marketable yield, although scalability and greenhouse pollination constraints still need further study. Successful hydroponic production also depends on technical optimization, including nutrient formulation, irrigation strategy, and pH buffering (Sahoo et al., 2024; Yafuso and Boldt, 2024).

2.4 Vertical cultivation and other novel cultivation systems

Vertical cultivation and related novel systems aim to increase production per unit ground area by stacking plants or using alternative growing devices in protected or urban environments (Figure 1) (Kouloumprouka Zacharaki et al., 2024). Their defining environmental characteristic is efficient space use, which makes them attractive for high-value protected structures and urban agriculture, where year-round production and local supply are important goals. Vertical systems are commonly integrated with hydroponics or substrate culture in high tunnels and greenhouses because these combinations reduce soil-related problems while improving access for harvesting and crop management (Kang et al., 2020). However, these systems also introduce new management complexities, including microclimatic gradients within stacked layers, cultivar choice, pollination, and nutrient dynamics across tower levels (Wortman et al., 2016).

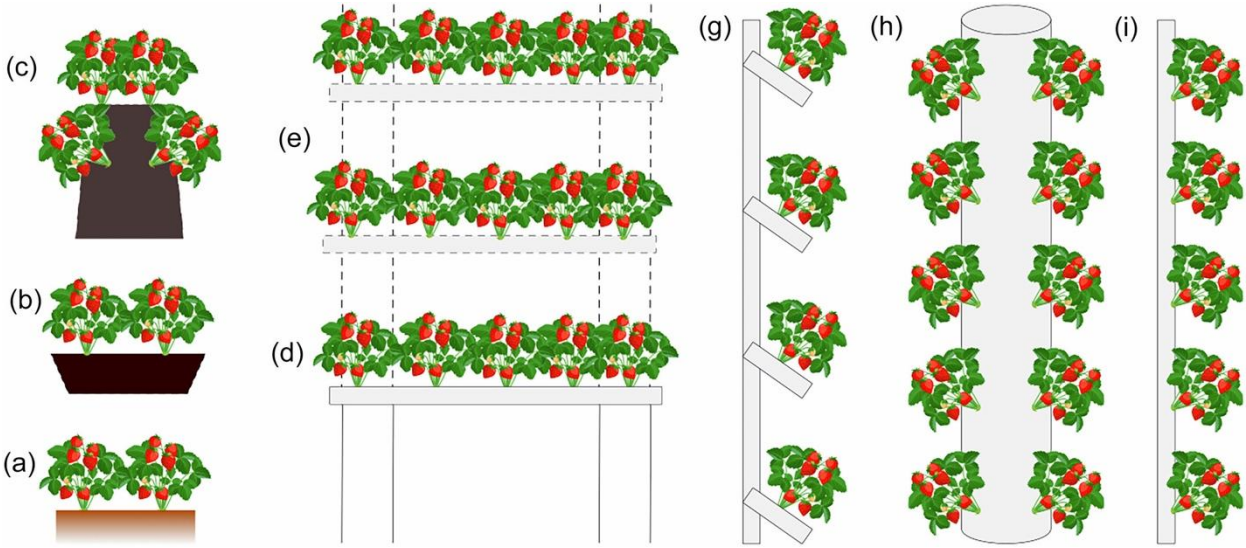


Figure 1 Illustration of the equipment layouts used in strawberry cultivation in urban farms (Adopted from Kouloumprouka Zacharaki et al., 2024)

Image caption: Soil cultivation is the simpler method of growing strawberries, with minimum requirements of equipment, fertigation and knowledge of plant physiology (a); Pots and planters are often used on the ground or hanging, filled with soil, compost or substrate (b); Stackable planters or short towels with openings at the vertical side as well as the top of the towel, filled with soil, compost or substrate (c); The commercially used tabletop systems (d), vertically stacked horizontal systems (e) or vertically stacked horizontal systems in inclination (g) with substrate in grow bags or pots, and drip irrigation with nutrient solution, nutrient film technique (NFT) or aeroponics; Towers where plants are grown at the sides of the cylindrical tower through opening (h) and vertical walls or lines such as ZipGrow where plants are grown towards one direction (i), fertigation provided by mist or drippers (Adopted from Kouloumprouka Zacharaki et al., 2024)

Therefore, the performance of vertical cultivation depends not only on structural design but also on environmental regulation and cultivar adaptability. Current research findings on vertical cultivation remain inconsistent. In a glasshouse experiment, a three-layer vertical structure outperformed horizontal cultivation systems in terms of chlorophyll content, fruit number, fruit weight, and total soluble solids content (Madhavi et al., 2023). However, another comparative study of different cultivation devices found that horizontal soilless cultivation achieved the highest total yield, while the vertical system increased fruit diameter and fruit weight but still produced lower overall yields than the best-performing horizontal treatment (Sheel et al., 2019). Furthermore, studies on vertical hydroponic high-tunnel systems have shown that cultivar and substrate type significantly influence yield performance, with considerable variations observed among different years and locations. In some Midwestern

production systems, mixtures of perlite with coir or vermiculite resulted in the highest yields (Wortman et al., 2016). Overall, vertical and other novel cultivation systems expand the production options for strawberry cultivation; however, their performance is highly dependent on facility design, regional environmental conditions, and cultivar-cultivation system interactions, rather than being determined solely by the cultivation structure itself.

3 Evaluation of Growth Performance of Strawberry Cultivars under Different Cultivation Systems

3.1 Evaluation of vegetative growth characteristics

Vegetative growth is one of the most widely used indicators for evaluating strawberry adaptation because plant height, leaf number, leaf area, crown formation, canopy spread, and total biomass strongly condition later flowering and yield potential (Ahn et al., 2021; Ullah et al., 2024). Evidence across cultivation systems shows substantial cultivar variation in these traits. Under open field, 'Sweet Sensation' produced the greatest plant height, canopy spread, and leaf area in Maharashtra, while under both open and 50% shade-net conditions 'Winter Dawn' showed the highest plant height, leaf number, leaf area, crown number, and fruit production, indicating that vigor rankings can shift with region and environment (Pandey et al., 2024; Gogoi et al., 2025). Under low polytunnels, genotype effects remained pronounced, with 'Sweet Sensation' showing the greatest plant height and spread, whereas 'Shimla Delicious' had the largest leaf area (Bhardwaj et al., 2025).

Protected and controlled systems often magnify differences in canopy architecture and biomass accumulation. In greenhouse gutter culture, 'San Andreas' produced 30% larger leaves and nearly three-fold greater fresh and dry biomass than 'Ostara' (Lema-Rumińska et al., 2021). In a plant factory with artificial lighting, 'Koiminori' achieved 2.0-fold greater total dry weight and a much larger leaf area than 'Tochiotome', and its taller canopy likely improved light interception near the lamp source (Takahashi et al., 2024). Soilless systems also tend to enhance vegetative growth relative to soil culture: in cv. 'Festival', both hydroponic and solid-substrate systems increased root and shoot fresh and dry weights, root size, leaf number, and total leaf area, with the strongest effect in the solid-substrate treatment. Even within one greenhouse season, cultivar-specific growth trajectories differ: 'Seolhyang' and 'Keumsil' showed stronger vegetative growth than 'Jukhyang' and 'Maehyang', while increasing leaf number was positively associated with total fresh weight (Ahn et al., 2021).

3.2 Evaluation of root growth and rhizosphere adaptation

Root growth and rhizosphere adaptation are central to cultivar evaluation because strawberry has a shallow root system and is highly sensitive to soil-borne diseases, water supply, salinity, and oxygen conditions in the root zone. Soilless cultivation is therefore valued not only for avoiding infected or unfavorable soils, but also for enabling tighter control of the active root environment (Rathod et al., 2021; Doust et al., 2023). Comparative studies support this advantage. In 'Festival', soilless systems significantly increased root fresh and dry mass and root size over traditional soil culture, and anatomical responses suggested improved uptake and transport capacity through thicker xylem, phloem, and mesophyll tissues. These results indicate that rhizosphere adaptation should be assessed not only by visible rooting traits but also by internal transport traits linked to nutrient acquisition and shoot support.

System design also changes root architecture. In protected soilless cultivation of 'Sweet Charlie', vertical 90 mm PVC systems produced the maximum root surface area, root-shoot ratio, secondary root number, root density, and root length density, whereas soil cultivation produced thicker primary and secondary roots. This suggests that substrate configuration can favor either extensive fine-root exploration or thicker roots, with different implications for nutrient and water capture. At the same time, not all water-culture systems provide an equally suitable rhizosphere. In hydroponic comparisons, substrate systems outperformed water-culture systems overall for yield and resource efficiency, implying that the root-zone stability of substrate may better support sustained cultivar performance. Evidence from NFT reviews identifies a specific limitation: progressive root mat development can reduce oxygenation, impair root membrane integrity, alter exudation, and increase susceptibility to *Pythium* root rot, while strawberry lacks the aerenchyma-based tolerance seen in some other crops (Scott and Villouta, 2026).

3.3 Evaluation of photosynthetic characteristics and physiological responses

Photosynthetic and physiological traits provide a mechanistic basis for explaining why cultivars differ across cultivation systems. In greenhouse gutter culture, 'San Andreas' had 20% more chlorophyll a, 30% more chlorophyll b, about 14% higher intercellular CO_2 concentration, and an almost two-fold higher photosynthetic rate than 'Ostara', alongside much higher biomass and fruit production (Lema-Rumińska et al., 2021). In plant-factory production, 'Koiminori' had a 2.2-fold higher single-plant photosynthetic rate and a 1.4-fold higher single-leaf photosynthetic rate than 'Tochiotome', mainly because greater plant height and larger leaf area improved light capture rather than because of intrinsic differences in biochemical photosynthetic capacity (Takahashi et al., 2024). These results show that physiological evaluation should integrate both gas-exchange capacity and canopy structure.

Environmental control modifies these responses substantially. In soilless strawberries, greenhouse conditions promoted stronger vegetative growth, photosynthesis, and yield than open-field conditions, whereas open-field conditions enhanced antioxidant activity and quality-related biochemical traits (Doust et al., 2023). Relative humidity is also important in protected cultivation: under more than 60% RH, both 'Arihyang' and 'Keumsil' showed higher root activity, greater photosynthetic efficiency, and higher electron transport-related parameters than under less than 40% RH (Choi and Jeong, 2020). Under drought stress, physiological tolerance becomes a key evaluation criterion. Water deficit reduced chlorophyll, gas exchange, relative water content, and growth, while increasing proline and oxidative stress markers. Cultivars differed in these responses: 'Camarosa' maintained higher relative water content and stronger antioxidant and soluble carbohydrate responses than 'Gaviota', while 'California' showed the highest flower and fruit numbers under drought in another study (Zahedi et al., 2023).

3.4 Comprehensive evaluation of cultivar adaptability

Comprehensive evaluation of cultivar adaptability requires combining vegetative, root, physiological, and yield performance rather than relying on a single indicator. Broad screening confirms that cultivars differ significantly for most growth-related attributes, and weighted ranking methods can separate vigorous, medium, and weak growth types; in one 31-cultivar evaluation, 'Kabarla', 'Alba', 'Amiga', 'Asia', 'Favette', 'Fortuna', 'Fronteras', 'Hood', 'Jive', 'Roxana', 'Sabrina', and 'Splendor' were classified as vigorous, whereas 'Albion', 'Merced', and 'Tillamook' were weak (Ullah et al., 2024). Seasonal greenhouse studies likewise show that high vegetative vigor does not automatically predict highest yield: 'Seolhyang' and 'Keumsil' had stronger vegetative growth, but 'Arihyang' produced the greatest total yield and fruit weight per fruit (Ahn et al., 2021). In high tunnels and open fields, principal component analysis further suggested that moderate plant size may favor a greater proportion of large, marketable berries (Liu et al., 2024).

Adaptability must therefore be defined as cultivar×system fit. Under open-field and shade-net conditions, 'Winter Dawn' remained consistently strong across vegetative and reproductive traits (Gogoi et al., 2025). Under open field in Maharashtra, 'Sweet Sensation' combined vigorous growth with the highest yield (Pandey et al., 2024). In soilless summer–autumn protected culture, 'Murano' showed better adaptation than 'Vivara' through higher total yield, even though fruit quality remained modest for both cultivars (Capocasa et al., 2021). Under contrasting farming regimes in Punjab, conventional farming favored vegetative growth, whereas natural farming favored yield formation; 'Capri' excelled in plant height, spread, fruit number, and yield, while 'Camarosa' showed stronger leaf development, chlorophyll index, berry weight, and yield efficiency (Chauhan et al., 2024). Overall, evaluation of growth performance under different cultivation systems should treat cultivar adaptability as a multidimensional trait shaped by environment, root-zone conditions, and management intensity rather than as a fixed genetic ranking.

4 Yield Formation and Evaluation of Strawberry under Different Cultivation Systems

4.1 Analysis of yield components

Yield formation in strawberry is primarily determined by fruit number per plant, mean fruit weight, and the fraction of fruit that meets market standards, rather than by total biomass alone (Cecatto et al., 2013; Cardarelli et

al., 2024). Studies comparing systems therefore evaluate not only total yield, but also commercial yield, discarded fruit, and causes of unmarketability such as small, malformed, rotten, or diseased fruit (Kang et al., 2020; Altieri et al., 2025). Fruit weight and total yield are partly independent traits because the genetic correlation between them can be close to zero, so cultivars with larger berries do not necessarily produce the highest total yield (Chiomento et al., 2023; Chacón et al., 2025).

Cultivation system shifts these components in different ways. A global review found that tunnels increased marketable yield by about 34% and total yield by about 30% relative to open field, while fruit weight changed little (Menzel, 2025). In soilless and hydroponic systems, yield often rises through both heavier fruit and a higher proportion of marketable fruit; hydroponics lowered the unmarketable fruit ratio relative to soil, while soilless systems increased yield per plant and fruit dry matter over soil controls (Kang et al., 2020). System design also changes which component dominates: in one alternative-device study, the horizontal system produced the most fruits and the highest total yield, whereas the vertical system produced heavier and wider fruits (Sheel et al., 2019). Likewise, triple-layer vertical glasshouse culture increased fruit number, fruit weight, and soluble solids relative to horizontal greenhouse culture (Madhavi et al., 2023).

4.2 Relationship between fruit quality and yield performance

Higher yield does not consistently translate into better fruit quality. In soilless strawberries, greenhouse conditions increased growth and yield, but open-field conditions improved firmness, dry matter, taste index, antioxidant capacity, vitamin C, and shelf life (Doust et al., 2023). In greenhouse comparisons of soil versus substrate culture, soil produced higher yield, whereas substrate improved fruit quality traits overall (Cecatto et al., 2013). These results indicate that yield evaluation based only on kilograms per plant misses important commercial and nutritional dimensions (Boakye-Yiadom et al., 2025).

Quality itself is multidimensional, and the most relevant indicators for strawberry are soluble solids, titratable acidity, the TSS/TA ratio, firmness, color, anthocyanins, and dry matter (Patel et al., 2023). Some systems improve both yield and parts of quality at the same time: low tunnels increased marketable yield over open field without changing total soluble solids, and hydroponic cultivation improved fruit quality relative to soil while also increasing yield (Anderson et al., 2019; Kang et al., 2020). However, trade-offs remain common among cultivars. In soilless greenhouse culture, ‘Fronteras’ and ‘Monterey’ were most productive, ‘Albion’ and ‘Fronteras’ had the largest fruits, ‘Albion’ had the sweetest flavor balance, and ‘Camino Real’ had the highest phytochemical content (Chiomento et al., 2023). Early-yield-promoting treatments can also differ from quality-promoting ones: synthetic auxin and bacterial filtrate increased early yield through flowering and fruit set, whereas protein hydrolysate improved firmness and soluble solids while sustaining longer fruit set (Cardarelli et al., 2024).

4.3 Differential responses of strawberry cultivars to cultivation systems

Cultivar responses to cultivation systems are clearly differential rather than uniform. In open-field and high-tunnel annual hill production, most cultivars had similar total yield in tunnels, but ‘Chandler’, ‘Rocco’, and ‘Sweet Ann’ had the greatest total yields in the open field (Liu et al., 2024). The same trial showed cultivar separation for market traits: ‘Albion’, ‘Merced’, ‘Ruby June’, ‘San Andreas’, and ‘Sweet Ann’ had the largest fruit, while ‘Camino Real’ and ‘Ruby June’ had the firmest fruit (Liu et al., 2024). In a related fruit-quality study, genetics significantly affected anthocyanins, TSS, TA, and acidity, whereas environment did not significantly change TSS but did alter anthocyanin content and acidity traits (Figure 2) (Patel et al., 2023).

Differential response is also evident in protected and soilless systems. In Mediterranean organic greenhouse production, ‘Elide’ had the highest total yield, ‘Arwen’ combined good production with the lowest discarded fruit percentage, and the advanced selection AN16,53,54 combined precocity with yield comparable to commercial cultivars and good nutraceutical quality (Altieri et al., 2025). In eastern North Carolina tabletop greenhouse production, ‘Brilliance’ and ‘Florida Sensation’ produced more consistent winter yields than ‘Albion’ and ‘Monterey’, while ‘Brilliance’ also showed high firmness and, in one year, high sweetness (Johnson and Hoffmann, 2024). In hydroponic system comparisons, substrate culture outperformed water-culture systems overall for yield and resource-use efficiency, but vertical towers still showed promising performance. Across sites

and years, breeding evidence further shows that fruit weight is more genetically stable than total or marketable yield, reinforcing that cultivar rankings for productivity are strongly modified by environment and system choice (Chacón et al., 2025).



Figure 2 Top row, ‘Camino Real’ plants during the harvest season in high-tunnel (A) and open-field environments (B); Bottom row, ‘Ruby June’ plants during the harvest season in high-tunnel (C) and open-field environments (D) (Adopted from Patel et al., 2023)

5 Comprehensive Evaluation Methods for Strawberry Cultivars and Cultivation Systems

5.1 Single-index evaluation methods

Single-index evaluation methods assess cultivars or cultivation systems using one trait at a time, such as total yield, commercial yield, number of fruits, mean fruit weight, firmness, soluble solids, acidity, or sugar-acid ratio. This approach remains common because these indicators are easy to measure, directly interpretable, and closely linked to grower or market goals (Cecatto et al., 2013; Lapshin et al., 2019; Barth et al., 2022). In cultivar trials, single traits often identify different “best” materials depending on the target attribute: ‘Strawberry Festival’ and FRF 102.21 ranked highest for production in semi-hydroponics, ‘Jonica’ and FRF 85.4 for marketable fruit percentage, and ‘Pircinque’ for sugar content (Dos Santos et al., 2021). A similar pattern appears in greenhouse soilless culture, where ‘Fronteras’ and ‘Monterey’ were most productive, ‘Albion’ and ‘Fronteras’ had the largest fruits, and ‘Albion’ had the sweetest flavor balance (Chiomento et al., 2023).

The main limitation of single-index methods is that they can favor genotypes that excel in one trait while performing poorly in others. Direct selection on one characteristic is traditional in strawberry breeding, but it often fails to meet the combined demands of producers and consumers (Barth et al., 2020; Barth et al., 2022; Da Silva et al., 2023). This limitation is especially important when cultivation systems shift trait expression. In greenhouse comparisons, soil culture produced higher yield while substrate culture produced better fruit quality, so a system judged only by yield or only by quality would be ranked differently (Cecatto et al., 2013). Likewise, in non-chemically disinfected systems, both cropping system and cultivar altered yield, plant size, firmness, soluble solids, and acidity, and cultivars that performed best in one system did not necessarily do so in another (Ariza et al., 2025).

5.2 Multi-index comprehensive evaluation methods

Multi-index comprehensive evaluation methods integrate several agronomic, quality, and sometimes biochemical traits into a joint ranking. The most widely used tools are principal component analysis, cluster analysis, selection

indices, path analysis, and normalized or weighted scoring systems (Lapshin et al., 2019; Barth et al., 2020). Their value is that they reduce dimensionality, reveal trait structure, and rank cultivars on an overall performance basis rather than on isolated variables. In 17 short-day cultivars, normalized indices combined with PCA, Ward clustering, and Wilcoxon ranking identified six superior cultivars for the joint set of yield and berry quality. In tropical breeding material, genotype-ideotype indices plus PCA consistently identified four promising genotypes with higher yields and quality than commercial controls, and the repeatability across methods supported selection reliability (Figure 3) (Da Silva et al., 2023).



Figure 3 Strawberry fruit production from the genotype RVCS44CR-130 (Adopted from Da Silva et al., 2023)

These methods are particularly useful because strawberry evaluation usually involves unfavorable trait correlations and strong genotype × environment interaction. Multivariate analysis has been shown to improve early-stage selection by balancing agronomic, biometric, and biochemical traits better than direct selection on one or a few characters. Path analysis also helps identify which traits most strongly drive yield: the number of commercial fruits had a greater direct contribution to commercial fruit mass than mean fruit mass, making it a more informative target when yield is the objective. Different indices can favor different breeding goals. The Smith-Hazel index produced the greatest predicted gains for yield, whereas Mulamba-Mock and genotype-ideotype approaches better captured biochemical improvement (Barth et al., 2022). Weighting also matters: when fresh market and processing traits were assigned different weights, hybrid rankings changed, showing that comprehensive evaluation must match the intended production and marketing use.

5.3 Evaluation methods based on models and digital technologies

Model-based and digital methods extend evaluation from static field measurements to continuous, predictive, and non-destructive assessment. Recent work uses UAVs, RGB and multispectral imaging, computer vision, machine learning, Bayesian inference, and knowledge-guided models to estimate growth, fruit number, maturity, and yield (Oliveira et al., 2023; Yoon et al., 2023; Yang et al., 2024). These tools address a clear bottleneck: manual monitoring is labor-intensive, subjective, and difficult to scale in modern strawberry systems (Chen et al., 2019; Li et al., 2024). UAV-based deep learning has already shown practical value for yield forecasting. Faster R-CNN detected flowers, mature fruits, and immature fruits from aerial orthoimages, with mean average precision of 0.83 at 2 m altitude and flower-counting accuracy of 84.1%, enabling spatial yield maps. Multispectral UAV models were even more accurate for some production traits: linear regression estimated average fruit weight, fruit number, and leaf number with about 99.9%, 99.6%, and 99.9% accuracy, although the model was built in a single experimental area and still needs broader validation.

Digital evaluation is also moving beyond plot-level prediction toward fruit-level growth modeling and automated quality assessment. A receptacle-detection system combined Faster R-CNN with Bayesian modeling and predicted end-of-season yield more effectively than relying on first-month cumulative yield, even though object

detection was imperfect (Yoon et al., 2023). Knowledge-guided computer vision in greenhouse strawberries reduced fruit-diameter RMSE by 74% as image sequences accumulated and improved yield prediction from R^2 0.25 to 0.73, outperforming a process-based model in capturing harvest dynamics (Yang et al., 2024). For growth-stage monitoring, the lightweight SGSNet model achieved 99.50% mAP@0.5 and was designed for dense greenhouse conditions and portable deployment (Li et al., 2024). Digital quality evaluation has advanced in parallel: PCA and analytic hierarchy process applied to 14 fruit indicators produced a comprehensive quality score that correlated strongly with sensory evaluation ($r = 0.9239$), showing that mathematical models can approximate human judgment in strawberry quality assessment.

6 Current Research Challenges and Future Development Directions

6.1 Insufficient understanding of the matching mechanism between cultivars and cultivation systems

A central research challenge is that the matching mechanism between strawberry cultivars and cultivation systems remains only partly understood, even though genotype×environment interaction is consistently important for productivity, quality, and stability (Palmieri et al., 2017). Studies across climatic zones show that growing conditions can modify quantitative traits strongly, and the same cultivar can be governed mainly by genotype in one region but by genotype-environment interaction in another (Lapshin et al., 2019; Zareei et al., 2023). This problem is especially visible where imported cultivars are deployed outside their breeding target environments, because temperate-origin cultivars often underperform in tropical and subtropical systems and fail to express their full genetic potential (Da Silva et al., 2023; Nascimento et al., 2023; Rutz et al., 2023). Climate change further complicates matching, because cultivars once adapted to specific climates now face altered temperature regimes and changing harvest dynamics (Altieri et al., 2025; Pacheco-Ruiz et al., 2026).

Mechanistic understanding is still limited because most studies identify differential responses without fully resolving the environmental drivers and physiological pathways behind them. Relative humidity, temperature, sunshine duration, UV radiation, and harvest timing all affect fruit quality and metabolite accumulation, but these effects are not uniform across cultivars (Palmieri et al., 2017; Cervantes et al., 2020; Leonardou et al., 2021; Altieri et al., 2025). Multi-omics evidence now shows that flavour compounds and related transcriptional patterns are shaped by cultivar-specific G×E interactions, and cooler fruit-development conditions can favor sugars and key aroma compounds (Pacheco-Ruiz et al., 2026). These findings explain why future research needs multi-environment, multi-season, and system-specific trials that track adaptability, temporal stability, and response mechanisms together rather than treating cultivar performance as a fixed attribute (Aminova et al., 2021; Nascimento et al., 2023).

6.2 Need for improvement of comprehensive evaluation systems

A second challenge is that comprehensive evaluation systems for strawberry cultivars and cultivation systems remain incomplete, because single-trait selection is still common even though yield, quality, stability, and adaptability are only weakly aligned. Independent culling of individual traits remains traditional in breeding, but it ignores trait correlations and can miss superior multi-trait combinations (Barth et al., 2020). This matters because fruit weight can be highly heritable and relatively stable across years and locations, whereas total and marketable yield are more environmentally sensitive and genetically independent from fruit weight (Chacón et al., 2025). Quality assessment is also difficult to standardize: organoleptic traits are complex, often assessed subjectively, and formal sensory panels are too costly for early-stage selection (Cockerton et al., 2021).

Current evidence supports a shift toward multi-index evaluation, but existing frameworks still need refinement. Principal component analysis, cluster analysis, Euclidean-distance approaches, genotype-ideotype indices, and mixed linear models have all improved selection of balanced, stable genotypes across environments (Lapshin et al., 2019; Da Silva et al., 2023; Nascimento et al., 2023). These methods have identified promising tropical and regional genotypes, and large diversity panels show very wide variation in ripening time, fruit quality, runnering, and morphology that could be exploited more systematically (Da Silva et al., 2023; Hummer et al., 2023). Even so, weighting schemes change cultivar rankings for fresh market versus processing, identity errors in germplasm remain a real problem, and environment-specific quality stability still differs sharply among varieties (Barth et al.,

2020; Cervantes et al., 2020). Future evaluation systems therefore need standardized phenotyping, verified germplasm identity, and integrated scoring that combines yield structure, postharvest quality, stress resilience, and temporal stability.

6.3 Future trends toward intelligent and precision cultivation

The main development direction is toward intelligent and precision cultivation, where sensors, IoT platforms, machine learning, and computer vision are used to monitor crop status and support real-time management. Strawberry production is well suited to this transition because the crop is sensitive to humidity, temperature, pests, and diseases, and conventional monitoring is labor-intensive and often reactive. Recent systems already integrate environmental sensing, outlier detection, and disease recognition on unified platforms; one edge-computing IoT system detected seven common diseases in real time with 92% accuracy (Cruz et al., 2022). Sensor-driven models can also predict harvest quality before picking, including color and sweetness, with error ranges low enough to support future closed-loop control of soil conditions (Elashmawy and Uysal, 2023).

The future trend is not just digitization, but scalable decision systems that connect sensing, prediction, and automated intervention. Recent reviews show rapid growth in RGB imaging, hyperspectral sensing, robotics, UAVs, and AI applications for yield prediction, quality estimation, harvesting automation, and pest detection, but they also identify persistent gaps in standardized datasets, model validation, generalization, and scalability (Bitakou et al., 2026). Broader precision-agriculture work suggests that flexible IoT platforms, edge computing, 5G or LoRaWAN connectivity, and cloud-based analytics can reduce labor, improve resource efficiency, and support autonomous irrigation and crop monitoring. However, adoption still depends on solving high investment costs, technical training needs, data ownership disputes, cybersecurity risks, and limited multi-climate validation datasets (Elashmawy and Uysal, 2023; Mansoor et al., 2025). In future strawberry systems, the most useful advances will likely be those that link cultivar-specific response models with real-time environmental control, allowing precise matching of genotype, cultivation system, and local microclimate.

7 Conclusions and Perspectives

Different cultivation systems influence strawberry growth, yield formation, and fruit quality by altering the root-zone environment, resource availability, and environmental stress conditions. Controlled-environment and soilless cultivation systems have become important approaches in modern strawberry production due to their advantages in precise water and nutrient management, reduced environmental constraints, and improved production stability. However, the effectiveness of different cultivation systems depends strongly on system design and management practices rather than on cultivation type alone. Therefore, optimizing strawberry production requires comprehensive consideration of environmental regulation, cultivation structure, and production management.

In soilless cultivation systems, yield formation is jointly affected by nutrient management strategies and substrate characteristics. Appropriate nutrient solutions and suitable substrates can significantly improve strawberry growth, photosynthetic performance, and fruit yield, but the effects of different systems are not always consistent. Some hydroponic systems may promote vegetative growth, whereas soil cultivation may still show advantages in certain fruit number and quality traits. Different substrate materials also regulate the balance between vegetative and reproductive growth. Therefore, cultivation system selection should consider cultivar characteristics, production objectives, and resource-use efficiency to achieve coordinated improvement in yield and quality.

Cultivar adaptability is a key factor determining the success of strawberry production. The same cultivar may show different performance rankings under different years, locations, and cultivation systems. Therefore, cultivar evaluation should not rely only on yield, but should integrate yield stability, fruit quality, and environmental adaptability. Previous studies have demonstrated that different cultivars possess distinct advantages in productivity, quality, and stability, indicating that cultivar selection should be targeted toward specific production systems rather than based on general high-yield performance.

Future strawberry production should establish a coordinated optimization system integrating "cultivar–cultivation system–environment" rather than optimizing individual factors separately. Multi-environment studies have shown that temperature, humidity, light conditions, carbon dioxide concentration, and root-zone water and nutrient status interact with cultivar characteristics to determine growth and fruit development. With the development of digital agriculture technologies, intelligent cultivation based on sensors, artificial intelligence, and automated management systems will become an important future direction. Real-time monitoring, predictive modeling, and precise environmental regulation can improve water and nutrient management, optimize resource allocation, and support quality prediction, thereby promoting efficient, high-quality, and sustainable strawberry production.

Acknowledgment

The author acknowledges the researchers whose published work on strawberry cultivation and cultivar evaluation provided the basis for this review.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Ahn M.G., Kim D.S., Ahn S.R., Sim H.S., Kim S.B., and Kim S.K., 2021, Characteristics and trends of strawberry cultivars throughout the cultivation season in a greenhouse, Horticulturae, 7(2): 30.
https://doi.org/10.3390/horticulturae7020030

Altieri G., Curcio D., Lepore A., Grobler E., Maffia A., Gargano N., Tedesco A., Graziano M.L., Mazzei P., Capocasa F., Mezzetti B., and Celano G., 2025, Yield and quality of new strawberry advanced breeding selections and commercial cultivars, grown under warm-temperate climatic conditions, Agriculture, 15(13): 1406.
https://doi.org/10.3390/agriculture15131406

Aminova E.V., Salimova R.R., and Merezhko O.E., 2021, Variability assessment of productivity traits and quality of berries in the genetic collection of garden strawberry (*Fragaria ananassa* Duch.) in the Orenburg region, IOP Conference Series: Earth and Environmental Science, 845(1): 012015.
https://doi.org/10.1088/1755-1315/845/1/012015

Anderson H.C., Rogers M.A., and Hoover E.E., 2019, Low tunnel covering and microclimate, fruit yield, and quality in an organic strawberry production system, HortTechnology, 29(5): 590-598.
https://doi.org/10.21273/HORTTECH04319-19

Ariza M.T., Miranda L., Gómez-Mora J.A., Medina J.J., Lozano D., Gavilán P., Soria C., and Martínez-Ferri E., 2021, Yield and fruit quality of strawberry cultivars under different irrigation regimes, Agronomy, 11(2): 261.
https://doi.org/10.3390/agronomy11020261

Ariza M.T., Soria C., Miranda L., Gómez-Mora J.A., Medina J.J., de los Santos B., and Martínez-Ferri E., 2025, The effect of non-chemically disinfected cropping systems on the yield and quality of six strawberry cultivars compared to conventional system, Journal of Berry Research, 15(3): 187-198.
https://doi.org/10.1177/18785093251345449

Barth E., de Resende J.T.V., Mariguele K.H., de Resende M.D.V., da Silva A.L.B.R., and Ru S., 2022, Multivariate analysis methods improve the selection of strawberry genotypes with low cold requirement, Scientific Reports, 12(1): 11458.
https://doi.org/10.1038/s41598-022-15688-4

Barth E., de Resende J.T.V., Moreira A.F.P., Mariguele K.H., Zeist A.R., Silva M.B., Stulzer G.C.G., Mafra J.G.M., Gonçalves L.S.A., Roberto S.R., and Youssef K., 2020, Selection of experimental hybrids of strawberry using multivariate analysis, Agronomy, 10(4): 598.
https://doi.org/10.3390/agronomy10040598

Bhardwaj T., Rana V.S., and Chanderkant, 2025, Vegetative and floral characteristics of different strawberry cultivars growing in low polytunnels under Shivalik foothills, Journal of Agriculture and Ecology Research International, 26(4): 86-94.
https://doi.org/10.9734/jaeri/2025/v26i4685

Bitakou E., Kotzabasaki M., Psiroukis V., Nychas K., Demestichas K., Bartzanas T., Magazin N., and Vujić S., 2026, AI-driven approaches in precision agriculture for strawberry production: a systematic literature review, Smart Agricultural Technology, 14: 101944.
https://doi.org/10.1016/j.atech.2026.101944

Boakye-Yiadom K.A., Olivi L., Ilari A., Costantini E., Mazzoni L., Capocasa F., Wagner H., Waurich V., Olbricht K., Zucchi P., Osti L., Karhu S., Rantanen M., Haikonen T., Sargent D.J., Yadav C.B., Sönmez D.A., Kafkas E., Kafkas S., Mattioli M., Zaccarini M., Mezzetti B., and Duca D., 2025, Breeding for sustainable strawberries: Evaluating the environmental impact of different cultivation systems across Europe, Food and Energy Security, 14(6): e70152.
https://doi.org/10.1002/fes3.70152

Capocasa F., Balducci F., Mazzoni L., Marcellini M., Pergolotti V., and Mezzetti B., 2021, Preliminary results of different strawberry cultivars in multi-cropping soilless cultivation, Acta Horticulturae, 1309: 579-584.
https://doi.org/10.17660/ActaHortic.2021.1309.83

Cardarelli M., El Chami A., Rouphael Y., Ciriello M., Bonini P., Erice G., Cirino V., Basile B., Corrado G., Choi S., Kim H.J., and Colla G., 2024, Plant biostimulants as natural alternatives to synthetic auxins in strawberry production: physiological and metabolic insights, Frontiers in Plant Science, 14: 1337926.
https://doi.org/10.3389/fpls.2023.1337926

Cecatto A.P., Calvete E.O., Nienow A.A., Costa R.C., Mendonça H.F.C., and Pazzinato A.C., 2013, Culture systems in the production and quality of strawberry cultivars, Acta Scientiarum. Agronomy, 35(4): 471-478.
https://doi.org/10.4025/actasciagron.v35i4.16552

Cervantes L., Ariza M.T., Miranda L., Lozano D., Medina J.J., Soria C., and Martínez-Ferri E., 2020, Stability of fruit quality traits of different strawberry varieties under variable environmental conditions, Agronomy, 10(9): 1242.
https://doi.org/10.3390/agronomy10091242

Chacón J.G., Fernandez G.E., and Işık F., 2025, Genetic variation in yield and fruit weight among strawberry (*Fragaria×ananassa*) cultivars and the interaction with year and location effect, Plant Breeding, 144(2): 263-272.
https://doi.org/10.1111/pbr.13246

Chauhan N., Bakshi M., Singh S.K., and Sharma J.B., 2024, Comparative evaluation of strawberry cultivars under Subhash Palekar natural farming and conventional farming regimes in Doaba region of Punjab conditions, Journal of Applied and Natural Science, 16(1): 282-288.
https://doi.org/10.31018/jans.v16i1.5309

Chen Y., Lee W.S., Gan H., Peres N.A., Fraisse C.W., Zhang Y., and He Y., 2019, Strawberry yield prediction based on a deep neural network using high-resolution aerial orthoimages, Remote Sensing, 11(13): 1584.
https://doi.org/10.3390/rs11131584

Chiomento J.L.T., De Nardi F.S., Kujawa S.C., Deggerone Y.S., Fante R., Kaspary I.J., Dornelles A.G., Huzar-Novakowiski J., and Trentin T.S., 2023, Multivariate contrasts of seven strawberry cultivars in soilless cultivation and greenhouse in Southern Brazil, Advanced Chemicobiology Research, 2(1): 62-76.
https://doi.org/10.37256/acbr.2120232332

Choi H.G., and Jeong H.J., 2020, Comparison of chlorophyll fluorescence and photosynthesis of two strawberry cultivars in response to relative humidity, Horticultural Science and Technology, 38(1): 66-77.
https://doi.org/10.7235/hort.20200007

Cockerton H.M., Karlström A., Johnson A.W., Li B., Stavridou E., Hopson K.J., Whitehouse A.B., and Harrison R.J., 2021, Genomic informed breeding strategies for strawberry yield and fruit quality traits, Frontiers in Plant Science, 12: 724847.
https://doi.org/10.3389/fpls.2021.724847

Cruz M., Mafra S., Teixeira E., and Figueiredo F., 2022, Smart strawberry farming using edge computing and IoT, Sensors, 22(15): 5866.
https://doi.org/10.3390/s22155866

Da Silva I.F.L., Shimizu G.D., dos Santos E.L., Erpen-Dalla Corte L., Zeist A.R., Roberto S.R., and de Resende J.T.V., 2023, Breeding short-day strawberry genotypes for cultivation in tropical and subtropical regions, Horticulturae, 9(6): 614.
https://doi.org/10.3390/horticulturae9060614

Dos Santos M.F.S., Fagherazzi A.F., de Lima J.M., Costa B.M., Nerbass F.R., Kretzschmar A.A., and Rufato L., 2021, Agronomic performance of new strawberry cultivars in Southern Brazil, Revista de Ciências Agroveterinárias, 20(2): 149-158.
https://doi.org/10.5965/223811712022021149

Doust J., Nazarideljou M.J., Arshad M., and Ferrante A., 2023, Comparison of the growth, physio-biochemical characteristics, and quality indices in soilless-grown strawberries under greenhouse and open-field conditions, Horticulturae, 9(7): 774.
https://doi.org/10.3390/horticulturae9070774

Elashmawy R., and Uysal I., 2023, Precision agriculture using soil sensor driven machine learning for smart strawberry production, Sensors, 23(4): 2247.
https://doi.org/10.3390/s23042247

Fayaz S., Khan F.A., Chand G., Bhat S.A., Narayan S., Mir S.A., Kumar A., Gul S., Khan F., and Amir M., 2025, Hydroponic system of cultivation and runner removal enhanced plant growth and yield of strawberry cultivars, Plant Science Today, 12(1): 1-10.
https://doi.org/10.14719/pst.3271

Gogoi B., Dutta S., Basumatary P., and Barthakur S., 2025, Study on morpho-physico traits of strawberry (*Fragaria ananasa* Duch.) cultivars under open and protected condition, International Journal of Agriculture Extension and Social Development, 8(4): 157-163.
https://doi.org/10.33545/26180723.2025.v8.i4c.1756

Hummer K.E., Bassil N.V., Zurn J.D., and Amyotte B., 2023, Phenotypic characterization of a strawberry (*Fragaria×ananassa* Duchesne ex Rosier) diversity collection, Plants, People, Planet, 5(2): 209-224.
https://doi.org/10.1002/ppp3.10316

Johnson J., and Hoffmann M., 2024, Evaluation of yield, fruit chemistry, and firmness of seven strawberry (*Fragaria×ananassa*) cultivars in an Eastern North Carolina greenhouse, HortScience, 59(11): 1634-1643.
https://doi.org/10.21273/HORTSCI18084-24

Kang D.I., Hu J., Li Y., and Jeong B.R., 2020, Growth, productivity, and quality of strawberry as affected by propagation method and cultivation system, Protected Horticulture and Plant Factory, 29(4): 326-336.
https://doi.org/10.12791/ksbec.2020.29.4.326

Kouloumprouka Zacharaki A., Monaghan J.M., Bromley J.R., and Vickers L.H., 2024, Opportunities and challenges for strawberry cultivation in urban food production systems, Plants, People, Planet, 6(3): 611-621.
https://doi.org/10.1002/ppp3.10475

Lapshin V.I., Yakovenko V.V., Shcheglov S.N., and Podorojny V.N., 2019, A methodical approach for evaluating the variability of productivity and fruit quality in the genetic collections of strawberry (*Fragaria×ananassa* Duch.), Vavilov Journal of Genetics and Breeding, 23(6): 675-682.
https://doi.org/10.18699/VJ19.540

Lema-Rumińska J., Kulus D., Tymoszuk A., Miler N., Woźny A., and Wenda-Piesik A., 2021, Physiological, biochemical, and biometrical response of cultivated strawberry and wild strawberry in greenhouse gutter cultivation in the autumn-winter season in Poland—Preliminary study, Agronomy, 11(8): 1633.
https://doi.org/10.3390/agronomy11081633

Leonardou V.K., Doudoumis E., Tsormpatsidis E., Vysini E., Papanikolopoulos T., Papasotiropoulos V., and Lamari F.N., 2021, Quality traits, volatile organic compounds, and expression of key flavor genes in strawberry genotypes over harvest period, International Journal of Molecular Sciences, 22(24): 13499.
https://doi.org/10.3390/ijms222413499

Li Z., Wang J., Gao G., Lei Y., Zhao C., Wang Y., Bai H., Liu Y., Guo X., and Li Q., 2024, SGSNet: a lightweight deep learning model for strawberry growth stage detection, Frontiers in Plant Science, 15: 1491706.
https://doi.org/10.3389/fpls.2024.1491706

Liu D., Samtani J.B., Taghavi T., and Amyotte B., 2024, Agronomic and post-harvest performance of strawberry cultivars in high tunnel and open-field environment in Southeast Virginia, International Journal of Fruit Science, 24(1): 242-255.
https://doi.org/10.1080/15538362.2024.2384395

Madhavi B.G.K., Kim N.E., Basak J.K., Choi G.M., and Kim H.T., 2023, Comparative study of strawberry growth and fruit quality parameters in horizontal and vertical production systems, Horticulture, Environment, and Biotechnology, 64(3): 409-419.
https://doi.org/10.1007/s13580-022-00494-8

Mansoor S., Iqbal S., Popescu S.M., Kim S.L., Chung Y.S., and Baek J.H., 2025, Integration of smart sensors and IoT in precision agriculture: trends, challenges and future prospectives, Frontiers in Plant Science, 16: 1587869.
https://doi.org/10.3389/fpls.2025.1587869

Menzel C.M., 2025, A review of strawberry under protected cultivation: yields are higher under tunnels than in the open field, Journal of Horticultural Science and Biotechnology, 100(3): 286-313.
https://doi.org/10.1080/14620316.2024.2449026

Mustafa M.A., and Abdul Rahman H.B., 2021, A comparison of vertical and conventional cultivation, planting distances and growing medium in the growth and yield of three varieties of strawberry, IOP Conference Series: Earth and Environmental Science, 904(1): 012060.
https://doi.org/10.1088/1755-1315/904/1/012060

Nascimento D.A., Gomes G., de Oliveira L.V.B., de Paula Gomes G.F., Ivamoto-Suzuki S.T., Zeist A.R., Mariguele K.H., Roberto S.R., and de Resende J.T.V., 2023, Adaptability and stability analyses of improved strawberry genotypes for tropical climate, Horticulturae, 9(6): 643.
https://doi.org/10.3390/horticulturae9060643

Oliveira L.S.D., Castoldi R., Martins G.D., and Medeiros M.H., 2023, Estimation of strawberry crop productivity by machine learning algorithms using data from multispectral images, Agronomy, 13(5): 1229.
https://doi.org/10.3390/agronomy13051229

Pacheco-Ruiz P., Senger E., Pott D., Ziegler F.M.R., Jiménez L., Sønsteby A., Krüger E., Chartier P., Masny A., Mott D., Petit A., Savini G., Usadel B., Osorio S., and Vallarino J.G., 2026, Cultivar-by-environment interactions shape strawberry fruit quality: a multi-omics approach across European climates, Food Chemistry, 507: 148161.
https://doi.org/10.1016/j.foodchem.2026.148161

Palmieri L., Masuero D., Martinatti P., Baratto G., Martens S., and Vrhovšek U., 2017, Genotype-by-environment effect on bioactive compounds in strawberry (*Fragaria×ananassa* Duch.), Journal of the Science of Food and Agriculture, 97(12): 4180-4189.
https://doi.org/10.1002/jsfa.8290

Palombini M.C., Palencia P., Pavão J.M.S.J., and Chiomento J.L.T., 2023, Efficiency of strawberry cultivation under the effect of different types of plants in a soilless system in the high-altitude regions of Southern Brazil, Agronomy, 13(8): 2179.
https://doi.org/10.3390/agronomy13082179

Pandey P., Nandre D.R., Patil S., Patil R., and Shirsath R., 2024, Growth and yield performance of strawberry cultivars under different growing conditions in Maharashtra, India, Journal of Advances in Biology & Biotechnology, 27(12): 1-7.
https://doi.org/10.9734/jabb/2024/v27i121748

Patel H., Taghavi T., and Samtani J., 2023, Fruit quality of several strawberry cultivars during the harvest season under high tunnel and open field environments, Horticulturae, 9(10): 1084.
https://doi.org/10.3390/horticulturae9101084

Rana S., Prasad V.M., Kerketta A., and Kushwaha A., 2023, Growth and quality analysis of strawberry (*Fragaria ananassa*) cv. Chandler in two production system, Ecology, Environment and Conservation, 29(Suppl. 2): 283-290.
https://doi.org/10.53550/eec.2023.v29i02s.046

Rathod K.D., Patel A.I., and Chakraborty B., 2021, Strawberry cultivation practices in soilless growing substrates: A review article, International Journal of Chemical Studies, 9(1): 1253-1256.
https://doi.org/10.22271/chemi.2021.v9.i1r.11394

Rutz T., de Resende J.T.V., Mariguele K.H., Zeist A.R., and da Silva A.L.B.R., 2023, Selection of short-day strawberry genotypes through multivariate analysis, Plants, 12(14): 2650.
https://doi.org/10.3390/plants12142650

Sahoo S., Sahoo D., and Sahoo K.K., 2024, Optimization of an efficient hydroponic cultivation method for high yield of strawberry plant, South African Journal of Botany, 167: 429-440.
https://doi.org/10.1016/j.sajb.2024.02.033

Scott S., and Villouta C., 2026, Dissolved oxygen limitation and *Pythium* root rot in strawberry NFT systems: mechanisms, research gaps, and prospects for substrate-free production, Frontiers in Plant Science, 17: 1829367.
https://doi.org/10.3389/fpls.2026.1829367

Sheel M., Al Mamun S.M.A., and Islam M.M., 2019, Evaluation of soilless strawberry (*Fragaria ananassa* Duch.) cultivation using alternative growing devices, Khulna University Studies, 16(1&2): 33-40.
https://doi.org/10.53808/KUS.2019.16.1and2.1907-L

Takahashi A., Yasutake D., Hidaka K., Ono S., Kitano M., Hirota T., Yokoyama G., Nakamura T., and Toro M., 2024, Yield and photosynthesis related to growth forms of two strawberry cultivars in a plant factory with artificial lighting, HortScience, 59(3): 394-399.
https://doi.org/10.21273/HORTSCI17587-23

Ullah I., Demirsoy H., Soysal D., Lizalo A., Doğan D.E., and Demirsoy L., 2024, Evaluation of strawberry cultivars based on growth-related attributes, Applied Fruit Science, 66(3): 431-439.
https://doi.org/10.1007/s10341-023-01025-0

Wortman S.E., Douglass M.S., and Kindhart J.D., 2016, Cultivar, growing media, and nutrient source influence strawberry yield in a vertical, hydroponic, high tunnel system, HortTechnology, 26(4): 466-473.
https://doi.org/10.21273/HORTTECH.26.4.466

Yafuso E.J., and Boldt J.K., 2024, Development of a hydroponic growing protocol for vegetative strawberry production, HortScience, 59(3): 384-393.
https://doi.org/10.21273/HORTSCI17523-23

Yang Q., Liu L., Zhou J., Rogers M., and Jin Z., 2024, Predicting the growth trajectory and yield of greenhouse strawberries based on knowledge-guided computer vision, Computers and Electronics in Agriculture, 220: 108911.
https://doi.org/10.1016/j.compag.2024.108911

Yoon S., Jo J., Kim S.B., Sim H., Kim S.K., and Kim D.S., 2023, Prediction of strawberry yield based on receptacle detection and Bayesian inference, Heliyon, 9(3): e14546.
https://doi.org/10.1016/j.heliyon.2023.e14546

Zahedi S.M., Hosseini M.S., Hoveizeh N.F., Kadkhodaei S., and Vaculík M., 2023, Physiological and biochemical responses of commercial strawberry cultivars under optimal and drought stress conditions, Plants, 12(3): 496.
https://doi.org/10.3390/plants12030496

Zareei E., Karami F., Aryal R., and Saed-Moucheshi A., 2023, Genotypic by phenotypic interaction affects the heritability and relationship among quantity and quality traits of strawberry (*Fragaria×ananassa*), New Zealand Journal of Crop and Horticultural Science, 51(4): 594-613.
https://doi.org/10.1080/01140671.2022.2039725

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.