



**REVIEW**

# Growth Characteristics and Sustainable Cultivation Management Techniques of Small Berries: A Review with a Focus on Strawberry under Protected Agriculture

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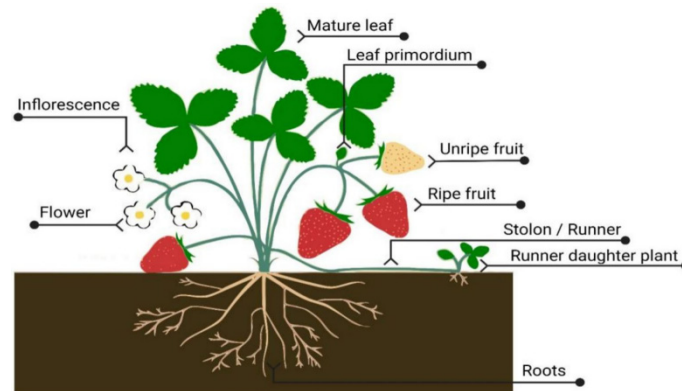
**ABSTRACT:** Small berries, represented by strawberries, blueberries, raspberries, and aronia berries, are increasingly valued worldwide for their rich nutritional content and economic potential. This review systematically outlines the growth characteristics of these berries, with a focused analysis on strawberries-including their ecological adaptations and responses to soil, water, temperature, light, and nutrition. It further elaborates on the integrated technical system for protected strawberry cultivation, covering cultivar selection, seedling propagation, transplanting, water and nutrient management, environmental control, flower and fruit regulation, green pest control, and post-harvest handling. The paper also discusses innovative models for industry development, such as leisure agriculture integration and smart farming. The findings emphasize that precision management based on growth traits, supported by technological innovation and sustainable practices, is essential for enhancing yield, quality, and industry sustainability in protected small berry production.

**KEYWORDS:** Strawberry; protected cultivation; cultivation management; growth characteristics; sustainable production

## 1 Introduction

Small berries, a general term for fruits characterized by their small size and fleshy, juicy pulp-including strawberries, blueberries, raspberries, and aronia berries-are rapidly emerging worldwide as a highly dynamic emerging industry within modern agriculture, owing to their unique nutritional value and significant economic benefits [1,2]. These fruits are generally rich in anthocyanins, vitamin C, polyphenolic compounds, flavonoids, and various essential trace elements, and are regarded by modern nutrition science as “functional foods” or “superfruits”. For instance, strawberries (Fig. 1) contain 11.7 times more vitamin C than an equivalent weight of apples and five times more than bilberries, contributing to enhanced immunity, promotion of collagen synthesis, and improved gut health [3]. Blueberries are abundant in components such as pterostilbene and anthocyanins, which demonstrate notable effects in antioxidation, cardiovascular protection, and cognitive improvement [4,5]. Aronia berries, with their exceptionally high proanthocyanidin content, represent a natural reservoir of antioxidants and show great potential in anti-inflammatory responses and regulating blood lipids and glucose levels [6]. These prominent health

benefits align precisely with the growing consumer demand for healthy diets and high-quality lifestyles, leading to continuously increasing market acceptance and premium pricing capabilities.



**Figure 1:** An overview of the architecture of a strawberry plant.

From an economic perspective, the small berry industry has become a significant driver of rural revitalization and increased farmer income. Crops such as strawberries and blueberries are characterized by relatively short growth cycles, high output value per unit area, and suitability for agritourism and pick-your-own operations. For example, protected cultivation of strawberries can achieve an extended harvesting window of over six months (e.g., from December to June of the following year), yielding substantially higher economic returns compared to traditional field crops. Furthermore, the small berry industry features a long and value-added supply chain [7–9]. Beyond fresh consumption, the fruits are widely processed into products such as wines, jams, juices, lyophilized products, functional food additives, and cosmetic ingredients, significantly enhancing overall industrial value [10,11]. The sector's vigorous development not only generates direct planting revenue but also stimulates synergistic growth in related industries including seedling propagation, agricultural input supply, cold-chain logistics, food processing, and leisure tourism. This creates a notable industrial cluster effect, holding profound practical significance for optimizing agricultural structure and promoting rural value chain integration.

Protected agriculture, which utilizes artificial structures such as greenhouses and tunnels coupled with environmental control technologies to create optimal microclimates for crop growth, has become a pivotal approach to overcoming natural environmental constraints and achieving enhanced quality, efficiency, and sustainable development in the small berry industry [12,13]. Its significant role is primarily manifested in the following aspects. First, protected cultivation enables the off-season and year-round production of small berries. By regulating environmental factors like light, temperature, water, and air, protected agriculture can effectively mitigate natural disasters encountered in open-field cultivation—such as frost damage, heat stress, drought, and flooding [14]. This allows berries like strawberries to reach the market during the winter and spring off-seasons, meeting the continuous market demand for fresh berries and significantly increasing cultivation profitability. Second, the controlled environment facilitates precise and sustainable cultivation management. Within enclosed or semi-enclosed structures, integrated water and fertilizer delivery through drip irrigation or micro-sprinkler systems enables precise supply, substantially improving resource-use efficiency while minimizing waste and non-point source pollution [15]. Concurrently, physical measures—including insect-proof nets, sticky traps, supplemental lighting, and automated ventilation—combined with biological control methods (e.g., releasing natural predators or applying biopesticides) can drastically reduce dependence on chemical pesticides. This effectively ensures

fruit quality, safety, and sustainable production standards, aligning with the requirements of modern sustainable agriculture [16]. Third, protected agriculture serves as an ideal platform for integrating smart farming technologies. Modern information technologies—such as IoT sensors, automated environmental control systems, UAV-based field monitoring, and data management platforms—allow for real-time tracking and intelligent regulation of in-house temperature, humidity, light intensity, soil moisture, and crop growth status [17].

China is a major producer and consumer of small berries, with strawberries holding a particularly prominent position in its agricultural industry. After years of development, five major advantageous production regions have emerged in China: the Northeast, the Huang-Huai-Hai area, the Middle and Lower Reaches of the Yangtze River, the Southwest, and South China. These widely distributed cultivation zones accommodate diverse climatic conditions. Statistics indicate that by 2025, the cultivation area for strawberries had reached 147,500 hectares, with a total output nearing 4 million metric tons, ranking first in the world for both area and yield. The proportion of protected strawberry cultivation has increased annually, with solar greenhouse strawberry production in northern China becoming a highlight of winter agriculture [18,19]. As an emerging berry crop with rapid development, blueberries have seen continuous expansion of their cultivation areas since their introduction in the 1980s. Major production regions now include the Changbai Mountains and Greater and Lesser Khingan Mountains, the Jiaodong Peninsula, the Yunnan-Guizhou Plateau, the Middle and Lower Reaches of the Yangtze River, and South China. By the end of 2024, the national cultivation area for blueberries had reached approximately 66,400 hectares, with a total output of 347,200 metric tons, generating significant economic benefits. The raspberry industry is primarily concentrated in Northeast, Northwest, and North China, as well as the Middle and Lower Reaches of the Yellow River, with a cultivation area exceeding 12,000 hectares [20,21]. Aronia berry, a distinctive functional fruit, has achieved scale cultivation in Northeast China, Inner Mongolia, Shandong, Xinjiang, and other regions, with a total area of about 5500 hectares and an annual output of approximately 6000 metric tons. It is currently in a phase of rapid industrial growth, as shown in Table 1. Overall, China's small berry industry exhibits a pattern characterized by “strawberry dominance with concurrent development of multiple berry types”. The cultivation area and yield are steadily increasing, with regional specialization and large-scale production becoming increasingly distinct, laying a solid foundation for market supply and industrial advancement.

**Table 1:** Key health-related compounds in representative small berries.

Berry	Notable Phytochemicals
Strawberry	Very high vitamin C ( $\approx 11.7\times$ apple), anthocyanins, polyphenols
Blueberry	
Aronia	Rich in anthocyanins and pterostilbene
Raspberry	Exceptionally high proanthocyanidins and anthocyanins
	High in ellagitannins, anthocyanins, and ellagic acid; rich in vitamin C and dietary fiber

Despite the rapid expansion and economic significance of protected small berry cultivation, a critical gap persists in the literature: the absence of a systematic and integrated framework that explicitly links the specific growth characteristics of these crops—particularly strawberry—to a holistic, full-chain management system optimized for controlled environments. Existing studies often address individual components such as pest control, fertilization, or environmental regulation in isolation, without comprehensively integrating these practices with the plant's underlying physiological requirements, such as its shallow root system, precise water and temperature needs, and distinct phenological stages. Furthermore, the potential to synergize these biological fundamentals with emerging technologies (e.g., IoT-based environmental control,

soilless culture) and innovative industrial models (e.g., agritourism, smart farming) remains underexplored in a consolidated manner. To fill this gap, this study systematically synthesizes the growth characteristics of major small berry crops, with particular emphasis on strawberries, and provides a comprehensive evaluation of cultivation strategies and management practices under protected conditions. By integrating knowledge on plant ecological adaptability, physiological requirements, and production technologies, it aims to establish a theoretical and technical foundation to support scientific, standardized, and efficient development of the protected small berry industry. Representative species, including strawberry, blueberry, raspberry, and aronia, are comparatively analyzed to elucidate their growth behaviors and environmental adaptations, while strawberries are further examined in detail with respect to their responses to soil properties, water availability, temperature, light, and nutrient regimes. Building on these biological insights, a systematic management framework covering the entire cultivation chain is developed, encompassing cultivar selection, propagation, transplanting, water and fertilizer regulation, environmental control, reproductive management, integrated pest and disease control, and harvesting. In addition, emerging production models that combine protected horticulture with leisure and smart agriculture are discussed to highlight pathways for industrial upgrading. Current constraints and developmental bottlenecks are critically evaluated, and future trends together with practical recommendations are proposed to promote sustainable and high-quality growth of the industry.

## 2 Overview of Growth Characteristics of Small Berries

As shown in Fig. 2, small berries encompass a diverse range of species, each with unique attributes, yet they share common features such as compact fruit size, high nutrient density, and considerable economic value. A thorough understanding of the distinct growth characteristics and ecological adaptations of different small berries is a prerequisite for scientific cultivation aimed at achieving high quality and yield. This chapter outlines the basic botanical features and core environmental requirements of four representative small berries: strawberry, blueberry, raspberry, and aronia berry.



**Figure 2:** Representative small berries: (a) strawberries, (b) blueberries, (c) raspberries, (d) aronia berries.

## 2.1 Strawberry (*Fragaria* × *ananassa*)

The strawberry is a perennial herbaceous plant belonging to the family Rosaceae and genus *Fragaria* (Fig. 2a). As the primary species of modern cultivated strawberry, it is grown extensively worldwide. Understanding its biological foundations and environmental needs forms the starting point for precise cultivation management [22].

### 2.1.1 Botanical Characteristics and Ecological Habits

The strawberry plant is low-growing, typically reaching a height of 10–40 cm. Its leaves are trifoliate with short-petioled leaflets that are mostly obovate or rhombic in shape and dark green in color. The flowers are hermaphroditic, white, with nearly round or obovate-elliptical petals. The fruit is an aggregate accessory fruit, formed from the enlarged receptacle, with numerous achenes on its surface; the true seeds are contained within these achenes. The plant has a short, compressed stem and a fibrous, shallow root system concentrated primarily within the top 15–20 cm of soil. New roots are white, aging to brown. A notable ecological characteristic of the strawberry is its vegetative reproduction via stolons (runners), which serves as the primary method for propagating new plants but also requires management within the field [23,24].

### 2.1.2 Requirements for Soil, Water, Temperature, and Light

**Soil:** Strawberries prefer loose, well-aerated soil rich in organic matter with good water retention and fertility. The optimal soil pH range is 5.5–6.5. Heavy, compacted, saline, alkaline, or poorly drained soils severely inhibit root development, leading to poor plant growth and increased susceptibility to root diseases. Consequently, raised beds or ridges are commonly used in production to improve the rhizosphere environment [25]. **Water:** Due to their shallow root system and significant transpirational water loss, strawberries require consistent moisture but are intolerant of waterlogging. Water needs vary distinctly across growth stages: they are high during seedling establishment and runner production; soil moisture should be maintained at around 70% of field capacity during flowering; the fruit enlargement stage is a critical period requiring the highest water input, with moisture at approximately 80% of field capacity; during flower bud differentiation and berry ripening, water should be moderately restricted (around 60% field capacity) to promote quality development. Balanced irrigation is crucial, as drought stresses growth while waterlogging causes root rot and fruit decay [26]. **Temperature:** Strawberries thrive in cool to warm climates, exhibiting moderate cold tolerance but poor heat tolerance. Root activity begins above 2°C, with new root growth occurring above 10°C; the optimal root growth temperature is 15–24°C. The optimum temperature for aerial growth is 20–25°C. The flowering and fruiting stages are temperature-sensitive: optimal daytime temperatures are 22–25°C during flowering (8–10°C at night) and 20–22°C during fruit enlargement (6–8°C at night). Growth is inhibited above 30°C, with heat damage likely above 35°C. Frost damage to flowers and young fruit can occur below –1°C [27]. **Light:** Strawberries are light-preferring but tolerate partial shade. Ample light promotes robust plant growth, flower bud initiation, fruit coloration, and sugar accumulation. Generally, they require 12–15 h of light per day. Insufficient light leads to elongated, weak plants with slender petioles, poor fruit color, and reduced sugar content [28–30]. However, intense direct sunlight combined with high summer temperatures can scorch leaves and fruit, necessitating the use of shade nets in protected cultivation during hot periods. Supplemental lighting is often employed in greenhouses during winter or early spring when natural light is inadequate.

## 2.2 Blueberry (*Vaccinium spp.*)

Blueberries (Fig. 2b) are perennial shrubs or small bush fruits within the heath family (Ericaceae) and genus *Vaccinium*, renowned as the “king of berries”. Their cultivation success is closely tied to specific physiological requirements [31,32].

### 2.2.1 Ecological Distribution and Cultivation Zoning

Blueberries are naturally distributed primarily across the Northern Hemisphere. Since their introduction to China in the 1980s, several major production regions have been established based on climatic conditions: (1) The Northeast region (Changbai Mountains, Greater and Lesser Khingan Mountains), focusing on cold-hardy lowbush and half-highbush types; (2) The Jiaodong Peninsula region, suitable for northern highbush blueberries; (3) The Middle and Lower Reaches of the Yangtze River region, developing southern highbush and rabbiteye blueberries; (4) The Yunnan–Guizhou Plateau region, an emerging base for premium southern highbush blueberries due to its cool summers; (5) The South China region, mainly cultivating rabbiteye blueberries. By the end of 2024, the national cultivation area had reached approximately 66,400 hectares with a total output of 347,200 metric tons, demonstrating a clear regionalized industry structure [20,21,33].

### 2.2.2 Analysis of Growth Environment Adaptability

**Soil:** Blueberries are representative acid-loving plants with a strict requirement for low soil pH, optimal between 4.0 and 5.5, which is the primary limiting factor for successful cultivation. They require loose, fertile soil with high organic matter content (preferably >5%) and excellent drainage and aeration. In soils with excessively high pH, blueberries suffer from impaired uptake of elements like iron and magnesium, leading to chlorosis and severely stunted growth. Therefore, soil amendment (e.g., applying sulfur to lower pH, incorporating abundant organic matter) is a critical step in establishing a blueberry orchard [34]. **Climate:** Blueberries prefer cool conditions and grow well in regions with an average annual temperature of 15–25°C. Most cultivars require a certain amount of winter chilling (accumulated hours below 7.2°C) to break dormancy and flower normally. They are also sensitive to severe cold, requiring soil banking or protective measures for overwintering in some regions [35]. Blueberries have a relatively consistent water demand, preferring moist but not waterlogged conditions, particularly during fruit development when irrigation is essential.

## 2.3 Raspberry (*Rubus idaeus L.*)

The raspberry (Fig. 2c) is a perennial deciduous shrub within the rose family (Rosaceae) and genus *Rubus*, prized for its translucent, aromatic fruit and its combined ecological and economic value [36].

### 2.3.1 Cold and Poor Soil Tolerance, and Ecological Restoration Function

Raspberries exhibit remarkable adaptability and vigor. They possess a well-developed root system and outstanding cold hardiness, with many cultivars tolerating temperatures below –25°C, enabling successful overwintering in high-latitude regions like Northeast and Northwest China [37]. Simultaneously, raspberries are not demanding regarding soil fertility and can grow in relatively poor, mountainous, or hilly soils, demonstrating considerable tolerance to low fertility. Consequently, they are often used in soil and water conservation and ecological restoration projects, playing a positive role in revegetating wastelands and improving ecological environments, making them an excellent eco-economic species [38].

### 2.3.2 Cultivation Patterns and Site Requirements

Raspberry cultivation in China has developed a regionalized layout, such as red raspberry zones in the Northeast and Northwest, and red/black raspberry zones in North China, with a total area exceeding 12,000 hectares. Planting is conducted mainly in spring (April-May) or autumn (late September). Cultivation patterns vary based on a cultivar's suckering ability: for highly suckering types, the "hedgerow" or "hill" system is used with row spacing of 2.0–3.5 m and plant spacing of 0.40–0.75 m; for weakly suckering types, the "stool" system is employed, planting 3–4 plants per hole with row spacing of 1.5–2.0 m, resulting in a density of approximately 500–600 plants per mu ( $\approx 7500$ – $9000$  plants per hectare). Raspberries are sun-loving and should be planted in fully exposed sites. While tolerant of poor soils, they yield best in terms of both quantity and quality in deep, fertile, well-drained, slightly acidic to neutral soils (pH 5.5–7.0). Soil banking for winter protection is necessary in colder regions [39].

## 2.4 Aronia Berry (*Aronia melanocarpa*)

The aronia berry, also known as black chokeberry, is a deciduous shrub in the rose family (Rosaceae) and genus *Aronia*, native to North America (Fig. 2d). It integrates edible, medicinal, ornamental, and ecological value, representing a highly promising functional berry [40].

### 2.4.1 Ecological Value and Multifunctional Uses

*Aronia* plants are vigorous with deep root systems and strong adaptability, offering excellent benefits for soil/water conservation and landscape greening. Their greatest value lies in the exceptional health-promoting properties of their fruit. *Aronia* berries are exceptionally rich in polyphenols, particularly proanthocyanidins and anthocyanins, ranking among the highest levels found in known edible fruits, making them a potent natural antioxidant. Research indicates that aronia extracts possess significant bioactive properties, including antioxidant, anti-inflammatory, lipid-regulating, antihypertensive, and glucose metabolism-improving effects, earning it the reputation as a "natural medicine chest". Beyond fresh consumption, the fruits are widely processed into juice, wine, jam, pigments, nutraceuticals, and cosmetic ingredients, indicating substantial potential for value-chain extension [41,42].

### 2.4.2 Soil and Climate Adaptability

*Aronia* exhibits broad environmental adaptability. It tolerates a wide soil pH range, growing well in acidic to slightly alkaline soils with a pH of 5.0–8.0. It prefers deep (>40 cm), fertile, well-drained soil but can also grow normally on slopes of less than 30 degrees in mountainous or hilly areas [43]. Climatically, aronia is extremely cold-hardy, tolerating temperatures as low as  $-40^{\circ}\text{C}$ , allowing it to overwinter safely in most northern regions of China; it is also relatively drought-tolerant. Initial planting density varies based on site conditions [44]. For instance, on flat, fertile loam, a spacing of  $2.5\text{ m} \times 1.8\text{ m}$  is common ( $\approx 2220$  plants per hectare), while a higher density of  $2.0\text{ m} \times 1.5\text{ m}$  ( $\approx 3330$  plants per hectare) might be used on poorer sloped land. This flexible adaptability gives it broad potential for expansion across vast regions of Northeast, Northwest, and North China.

A summary of the ecological adaptations of these four representative small berries is provided in Table 2, highlighting their distinct soil pH preferences and climatic tolerances.

**Table 2:** Ecological adaptations of representative small berry species.

Berry	Optimal Soil pH	Cold Tolerance	Key Adaptation
Strawberry	5.5–6.5	Down to $-1^{\circ}\text{C}$ (flowers)	Shallow fibrous roots (15–20 cm)
Blueberry	4.0–5.5	Requires winter chill ( $\approx 0-7^{\circ}\text{C}$ dormancy)	Acidophilic with high organic-matter soil
Raspberry	5.5–7.0	Tolerates $\leq -25^{\circ}\text{C}$	Very cold-hardy; tolerant of poor soils
Aronia	5.0–8.0	Tolerates $\leq -40^{\circ}\text{C}$	Very cold-hardy and drought-tolerant

### 3 In-Depth Analysis of Strawberry Growth Characteristics

The achievement of high quality and yield in strawberry production is fundamentally based on a precise understanding and meticulous regulation of its growth characteristics. Compared to other small berries, strawberries have a shorter growth cycle, faster organ turnover, and their economic yield-the fruit-develops directly from the reproductive receptacle [45]. Consequently, they exhibit extremely sensitive and rapid responses to environmental factors and nutritional conditions. A thorough analysis of their core requirements and response mechanisms regarding soil, water, temperature, light, and nutrition forms the theoretical cornerstone for achieving scientific and precise management in protected strawberry cultivation (Fig. 3 shows strawberries grown using protective cultivation methods.).



**Figure 3:** Strawberries grown under protected cultivation. Strawberries have shallow roots ( $\approx 15-20$  cm) and specific environmental needs.

### 3.1 Soil Environmental Adaptability

#### 3.1.1 Suitable Soil Types and pH Range

Soil serves as the medium for root growth and function; its physical, chemical, and biological properties directly determine plant establishment and growth potential. The strawberry's fibrous root system is concentrated mainly within the top 15–20 cm of soil, characterized by high oxygen demand and shallow distribution. This trait dictates an exceptionally high requirement for soil permeability [46]. The ideal soil for strawberry cultivation is a loose, fertile sandy loam or loam with good aggregate structure, abundant organic matter content (recommended >1.5%), strong water and nutrient retention capacity, and good drainage. Heavy clay soils are prone to compaction, resulting in poor aeration that impedes root respiration and penetration, increasing susceptibility to diseases like root rot. Excessively sandy soils, conversely, have weak water and nutrient-holding capacity, leading to leaching and potential plant decline. Soil acidity or alkalinity (pH) is a key chemical parameter affecting nutrient availability and root health in strawberries [47]. Research and practice consistently indicate that strawberries thrive best in slightly acidic to neutral soils, with an optimal pH range of 5.5–6.5. Within this range, the availability of nitrogen, phosphorus, potassium, and various micronutrients is maximized, facilitating optimal root uptake. When soil pH falls below 5.5 (too acidic), the solubility of ions like aluminum and manganese increases, potentially causing root toxicity, while calcium and magnesium become prone to leaching. When pH exceeds 7.0 (alkaline), micronutrients such as iron, manganese, zinc, and boron become immobilized, drastically reducing their availability. This leads to nutrient deficiency chlorosis in plants, and roots become stubby, curved, with significantly reduced lateral root development, severely impairing absorption capacity. Therefore, monitoring and adjusting soil pH before orchard establishment and during cultivation is crucial [48–50]. The ideal soil conditions for strawberry cultivation are summarized in Table 3, emphasizing the importance of texture, pH, drainage, and root zone characteristics.

**Table 3:** Optimal soil conditions for protected strawberry cultivation.

Condition	Requirement/Effect on Strawberries
Soil texture	Loose sandy loam or loam with good structure; high organic matter (>1.5%)
Soil pH	Slightly acidic to neutral ( $\approx$ 5.5–6.5); outside this range causes nutrient stress
Drainage	Excellent drainage required; heavy clay $\rightarrow$ poor aeration/rot; very sandy $\rightarrow$ leaching
Root zone	Shallow, high oxygen demand; roots concentrated in top 15–20 cm

#### 3.1.2 Relationship Between Soil Fertility and Root Development

Soil fertility, particularly its organic matter content and nutrient balance, is intrinsically linked to the development and vitality of strawberry roots. Abundant organic matter not only provides comprehensive, slow-release nutrition but, more importantly, improves soil physical structure, enhances buffering capacity, and increases water and nutrient retention. This creates an optimal micro-environment with a harmonious balance of water, nutrients, air, and temperature for the root zone. Strawberry roots exhibit a characteristic of being “nutrient-loving but salt-sensitive”. On one hand, sufficient base fertilizer (primarily well-decomposed organic matter) promotes extensive and deep root growth, forming a large and active absorption network. On the other hand, strawberry roots are sensitive to salt concentration. Excessive single applications of chemical fertilizer or the use of undecomposed organic manure can elevate soil solution concentration (EC value), causing “fertilizer burn”. Symptoms include yellowing and withering of root tips, and even complete necrosis of roots [47,51]. Therefore, strawberry fertilization should follow the principle of “frequent but light applications”, emphasizing the combination of organic and inorganic fertilizers. Employing fertigation

technology-dissolving fertilizer and applying it in small, frequent doses via a drip irrigation system-can meet continuous nutrient demands while avoiding salt accumulation and maintaining root vitality.

### 3.2 Water Requirement

Patterns Water constitutes the primary component and metabolic medium of the strawberry plant. Its shallow root system and abundant foliage determine a high sensitivity and dependence on water supply.

#### 3.2.1 Key Points for Water Management at Different Growth Stages

Strawberry water requirements exhibit distinct stage-specific characteristics, necessitating “on-demand” supply management. **Transplanting and Establishment Phase:** Immediately after transplanting, a thorough “settling-in water” is required, followed by maintaining consistent soil moisture for about a week, which is critical for survival [52].

**Vegetative Growth Stage:** This includes the runner production stage and early flower bud differentiation. Soil moisture should be kept adequate maintaining field capacity at around 70% to promote leaf growth and normal flower bud initiation.

**Flowering Stage:** This period is sensitive to water. Both excess and deficit moisture are detrimental to pollination and fertilization. Generally, maintaining field capacity at approximately 70% is suitable. Excessive humidity (greenhouse air humidity >80%) also increases the risk of gray mold (*Botrytis cinerea*).

**Fruit Enlargement Stage:** This is the period of highest water demand in the strawberry’s life cycle. Adequate water is directly related to fruit cell expansion and final yield. Field capacity should be increased to about 80%.

**Fruit Coloring and Ripening Stage:** Moderate water restriction is needed, reducing field capacity to around 60%. This favors sugar accumulation, aroma compound development, increased fruit firmness, and reduces fruit rot, thereby enhancing quality.

It is important to note that strawberries are “moisture-loving but waterlogging-intolerant”. Soil waterlogging exceeding 24 h causes root suffocation due to oxygen deprivation, impairing function, accelerating decay of old roots, and preventing new root formation. Above-ground symptoms include sudden wilting of leaves, growth cessation, and eventual plant death. Therefore, raised-bed cultivation and a thorough drainage system are prerequisites for effective strawberry water management. The target soil moisture levels for strawberries at key growth stages are outlined in Table 4, providing a practical reference for irrigation scheduling.

**Table 4:** Water requirement for strawberries at different growth stages.

Growth Stage	Target Soil Moisture ( $\approx$ % of Field Capacity)
Seedling establishment	High ( $\approx$ 70% or more)
Flowering	$\approx$ 70%
Fruit enlargement	$\approx$ 80% (highest water demand)
Bud differentiation/harvest	$\approx$ 60% (water moderately restricted)

#### 3.2.2 Application of Water-Saving Irrigation Techniques

Traditional flood irrigation is unsuitable for modern protected strawberry production due to high water use, soil structure degradation, increased humidity promoting disease [53]. Drip irrigation has become the mainstream water-saving technology. Drip irrigation delivers water and fertilizer directly and uniformly to the strawberry root zone. Water infiltrates slowly, minimizing surface evaporation and deep

percolation, achieving water use efficiency often exceeding 90% [54]. Furthermore, it allows precise control of irrigation volume and soil wetting depth, maintaining a loose, aerated root zone and effectively reducing greenhouse air humidity, creating an environment less favorable for pathogen spread. When integrated with soil moisture sensors or tensiometers, it enables smart, on-demand irrigation. This technology is indispensable for achieving precise water and nutrient management, improving quality and efficiency in protected strawberry cultivation [55].

### **3.3 Response Mechanisms to Temperature and Light**

#### **3.3.1 Impact of Temperature on Growth and Development**

As a “controllable factor” in protected environments, the regulation of temperature and light directly drives strawberry growth processes, determining production timing, yield, and quality. Strawberries are temperature-sensitive plants. They have differing temperature requirements for vegetative and reproductive growth [56].

**Root Growth:** Root activity begins at a soil temperature of 2°C, with new root growth initiating at 10°C. The optimal soil temperature for root growth is 15–20°C. Temperatures too low halt root activity, while temperatures too high (>25°C) accelerate root aging.

**Shoot Growth:** The optimal temperature for leaf photosynthesis is 20–25°C. Within this range, plants grow vigorously with extended leaf functionality. Photosynthesis is inhibited above 30°C, slowing growth; sustained temperatures above 35°C cause heat stress symptoms. Shoot growth essentially ceases below 5°C [57].

**Flower Bud Differentiation, Flowering, and Fruit Set:** Flower bud initiation requires induction by low temperatures and short days, but the quality of differentiation is temperature-dependent. The flowering period has strict temperature requirements: optimal daytime temperatures are 22–25°C, with nighttime temperatures of 8–10°C. Temperatures too low (<5°C) impair pollen viability, while temperatures too high (>28°C) cause pollen abortion, both leading to increased malformed fruit [58,59].

**Fruit Development:** The optimal temperature for fruit enlargement is 20–22°C during the day and 6–8°C at night. A diurnal temperature variation of 8–12°C favors the transport and accumulation of photosynthetic products into the fruit, which is key to enhancing sugar content and flavor [60]. Excessively high temperatures shorten the fruit development period, resulting in small, sour, and pale fruits; excessively low temperatures delay development and increase the likelihood of malformed fruits.

#### **3.3.2 Light Intensity and Photoperiod Regulation**

Light intensity (photosynthetic photon flux density, PPFD) and photoperiod are critical determinants of strawberry growth and productivity. Increasing PPFD generally enhances biomass accumulation, crown diameter, and runner production. For instance, in ‘Albion’ strawberries, increasing light intensity from 250 to 450  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  significantly increased daughter plant number, dry mass, and fresh mass [61,62]. Similarly, elevated light intensity during the nursery stage improved crown diameter, shoot dry weight, and root-to-shoot ratio in ‘Benihoppe’ [63]. Photoperiod also plays a key role: extended photoperiods (e.g., 16 h  $\text{d}^{-1}$ ) promote runner formation in many cultivars, while also accelerating flowering and increasing fruit yield when combined with adequate light intensity [61,64]. However, excessive daily light integral (DLI) may suppress runner elongation and reduce photosynthetic capacity, indicating the need for optimized light regimes.

### 3.3.3 Light Quality (Spectral Composition) and Photomorphogenesis

Beyond light intensity and duration, light quality—the spectral composition of radiation—profoundly influences strawberry physiology, morphology, and secondary metabolism [65,66]. Plants perceive light through specialized photoreceptors: phytochromes (sensing red and far-red light), cryptochromes and phototropins (sensing blue and UV-A light), and UVR8 (sensing UV-B light) [67]. These photoreceptors mediate a wide range of developmental and metabolic responses.

Red light (600–700 nm) is efficiently absorbed by chlorophyll and drives photosynthesis. Studies have shown that red light enhances shoot regeneration, increases photosynthetic pigment concentrations, and promotes biomass accumulation in strawberry plantlets during tissue culture [68,69]. In ‘Elsanta’ and ‘Akihime’ strawberries, red light treatment increased leaf carotenoid content and enhanced plant resistance to *Botrytis cinerea* by activating antioxidant defense systems [67,70]. Additionally, red light applied via selective plastic films increased petiole length, leaf area, and individual fruit weight in ‘Akihime’ 6868. At the molecular level, red light influences phytochrome-mediated signaling, regulating the expression of genes involved in chlorophyll biosynthesis and stress responses [67].

Blue light (400–500 nm) is perceived by cryptochromes and phototropins and plays a critical role in stomatal opening, photomorphogenesis, and secondary metabolite accumulation. Blue light has been shown to enhance photosynthetic rates, stomatal conductance, and antioxidant enzyme activities in strawberry leaves [71,72]. In terms of fruit quality, blue light irradiation increases anthocyanin content and antioxidant capacity in postharvest strawberry fruit by upregulating the expression of genes such as FaMYB10 and FaCHS [73–75]. However, the effects of blue light can be cultivar-dependent and bandwidth-specific. For instance, narrow-band blue LED light (436 nm) reduced anthocyanin content in ‘Elsanta’ strawberries compared to fluorescent light, whereas blue plastic films with broader spectra increased anthocyanin accumulation in ‘Yueli’ [76,77]. This suggests that optimal blue light conditions may require spectral fine-tuning to target both phototropin and cryptochrome pathways [66].

Red: blue combinations and broad-spectrum light often yield superior results compared to monochromatic light. A red: blue ratio of 1:1 (RBL) significantly promoted anthocyanin and proanthocyanidin accumulation during fruit development in two strawberry genotypes (‘Toyonaka’ and ‘Tokun’), and induced earlier fruit coloration by upregulating the expression of structural genes (CHS, DFR, ANS, UFGT) and regulatory genes (FaMYB10) [75]. Similarly, a spectrum comprising 20% green, 20% blue, and 60% red light achieved high fruit yield in ‘Albion’, whereas increasing green light beyond 20% reduced productivity, possibly due to changes in crown biomass allocation [78]. Full-spectrum white LEDs, especially those with added blue wavelengths, have been shown to enhance runner formation and vegetative growth in ‘Maehyang’ and ‘Akihime’ strawberries [79,80].

Far-red light (700–800 nm) influences plant morphology and flowering through phytochrome-mediated shade-avoidance responses. Supplementing red: blue background lighting with far-red light increased leaf area and shoot dry mass in ‘Monterey’ and accelerated flowering in long-day cultivars such as ‘Albion’ [81]. End-of-day far-red light treatments have also been used to induce flowering in short-day strawberries under long-day conditions, with effectiveness depending on temperature and plant age [82–84].

Ultraviolet (UV) radiation (UV-A, 315–380 nm; UV-B, 280–315 nm; UV-C, <280 nm) acts as both a stressor and a signaling cue. Moderate doses of UV-B radiation enhance the accumulation of phenolic compounds, including anthocyanins and flavonoids, by activating the UVR8 photoreceptor pathway and upregulating MYB transcription factors [65,85]. Preharvest UV-C treatment has been shown to increase polyphenol content, antioxidant capacity, and disease resistance in strawberry fruits, although excessive doses may reduce volatile compounds and impair flavor [86–88]. UV-A radiation, while less

studied, contributes to leaf expansion and secondary metabolite accumulation, with effects that are often genotype-dependent.

In summary, the regulation of light intensity, photoperiod, and spectral composition—each with distinct effects on morphology, photosynthesis, secondary metabolism, and stress responses—is integral to achieving high yield and quality in protected strawberry cultivation. Advances in LED technology now enable precise tailoring of light environments to specific growth stages and cultivars, offering a powerful tool for sustainable intensification. Future research should focus on optimizing light recipes for different strawberry genotypes and developing dynamic lighting strategies that integrate real-time crop feedback.

### *3.3.4 Light Regulation of Chlorophyll Metabolism and Photosynthetic Efficiency*

Strong light stress can accelerate chlorophyll degradation and induce photoinhibition, particularly during summer nursery periods or in high-altitude production systems. Under high light intensity, strawberry leaves exhibit a significant decrease in total chlorophyll, chlorophyll *a*, and chlorophyll *b* content, with chlorophyll *b* degrading more rapidly than chlorophyll *a*, leading to an increased chlorophyll *a*/*b* ratio. This shift reflects an adaptive response to high-light conditions, as chlorophyll *b* is primarily associated with light-harvesting complexes. Mechanistically, strong light upregulates the expression and activity of key chlorophyll degradation enzymes, including pheophytin pheophorbide hydrolase (PPH) and pheophorbide *a* oxygenase (PAO), as well as the corresponding genes FaPPH and FaPAO. These findings highlight the importance of managing light intensity to prevent excessive chlorophyll degradation and maintain photosynthetic capacity in protected strawberry production [89].

### *3.3.5 Integrated Light Management for Yield and Quality*

The combined effects of light intensity, photoperiod, and spectrum must be considered to optimize strawberry production in controlled environments. For example, supplemental lighting with red and blue LEDs during winter months increases fruit yield, sugar content, and anthocyanin accumulation by enhancing photosynthesis and carbohydrate allocation to fruits [90,91]. However, once natural solar radiation exceeds a critical threshold, the marginal benefit of supplemental lighting diminishes, emphasizing the need for dynamic light management strategies based on real-time environmental monitoring [92]. Moreover, the interaction between light and temperature is critical; high temperatures can inhibit flowering even under optimal photoperiods, and light quality may modulate temperature sensitivity [93,94].

In summary, the regulation of light intensity, photoperiod, and spectral composition—each with distinct effects on morphology, photosynthesis, secondary metabolism, and stress responses—is integral to achieving high yield and quality in protected strawberry cultivation. Advances in LED technology now enable precise tailoring of light environments to specific growth stages and cultivars, offering a powerful tool for sustainable intensification. Future research should focus on optimizing light recipes for different strawberry genotypes and developing dynamic lighting strategies that integrate real-time crop feedback.

## **3.4 Nutritional Demand Characteristics**

Strawberries grow rapidly, yield highly, and under year-round production models, have substantial nutrient consumption, resulting in demands that are both “high in quantity” and “balanced”.

### *3.4.1 Demand Ratios for Major Mineral Elements*

Strawberries have the greatest demand for the three major elements nitrogen (N), phosphorus (P), and potassium (K), with the demand for K often exceeding that for N, closely related to the high potassium

requirement for fruit development. Research indicates that to produce 1000 kg of strawberries, approximately 6–10 kg of N, 2–4 kg of P<sub>2</sub>O<sub>5</sub>, and 9–13 kg of K<sub>2</sub>O are absorbed, with an approximate absorption ratio of N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O = 1:0.4:1.5. Additionally, secondary nutrients like calcium (Ca) and magnesium (Mg), and micronutrients such as boron (B), zinc (Zn), and iron (Fe) are indispensable. Calcium strengthens cell walls, enhancing fruit firmness and storability while reducing physiological disorders (e.g., fruit soft rot). Boron is crucial for pollen germination and pollen tube growth, directly affecting fruit set. Iron and magnesium are core elements for chlorophyll synthesis; their deficiency leads to leaf chlorosis [95,96]. The approximate nutrient uptake by strawberries per 1000 kg of harvested fruit is detailed in Table 5, illustrating the relative demand for N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O.

**Table 5:** Nutrient uptake by strawberries (per 1000 kg of harvested fruit).

Nutrient	Amount Absorbed Per 1000 kg Fruit	Relative Ratio (N:P <sub>2</sub> O <sub>5</sub> :K <sub>2</sub> O)
N	6–10 kg	1:0.4:1.5
P <sub>2</sub> O <sub>5</sub>	2–4 kg	
K <sub>2</sub> O	9–13 kg	

### 3.4.2 Deficiency Symptoms and Correction Measures

**Nitrogen (N) Deficiency:** Uniform chlorosis and yellowing of older leaves; slow, weak plant growth. Correction: Timely top-dressing with N fertilizer or high-N compound fertilizer; foliar spray of 0.3% urea solution.

**Phosphorus (P) Deficiency:** Dark green or purplish-red older leaves; inhibited growth; reduced flowering and fruiting. Correction: Apply P fertilizer as base or top dressing; foliar spray of 0.2%–0.3% potassium dihydrogen phosphate.

**Potassium (K) Deficiency:** Scorching of leaf margins (“burning edges”) on older leaves; poor fruit coloring and low sugar content. Correction: Increase potassium sulfate application; foliar spray of potassium dihydrogen phosphate during fruit enlargement.

**Calcium (Ca) Deficiency:** Crinkling and withering of margins on new leaves (“golden edging”); susceptibility to tip-end soft rot (blossom-end rot) in fruits. Correction: Avoid soil drought or waterlogging; foliar spray of 0.3% calcium nitrate or calcium chloride solution.

**Iron (Fe) Deficiency:** Interveinal chlorosis of new leaves while veins remain green, giving a net-like appearance. Common in alkaline soils. Correction: Adjust soil pH; foliar spray of 0.1%–0.2% ferrous sulfate or chelated iron solution.

**Boron (B) Deficiency:** Inhibited growth points; deformed, crinkled new leaves; small flowers; low fruit set; malformed fruits. Correction: Apply borax as base fertilizer; foliar spray of 0.1%–0.2% borax or boric acid solution before flowering.

In summary, the growth characteristics of strawberry constitute an interconnected and dynamic system. In protected cultivation, it is essential to treat the five factors—soil, water, temperature, light, and nutrition—as an integrated whole. Through real-time monitoring and intelligent regulation, the growth environment can be synergistically optimized to maximally satisfy its physiological demands, ultimately achieving high-quality, efficient, and sustainable production of protected strawberries.

## 4 Technical System for Protected Strawberry Cultivation Management

Protected cultivation creates a controlled environment for strawberry growth, but realizing its potential for high quality, yield, and efficiency necessitates reliance on a complete, meticulous, and synergistic

management system. For instance, hydroponic systems, as shown in Fig. 4, represent an advanced cultivation model that enhances resource use efficiency and spatial productivity. The system depicted is a nutrient film technique (NFT) hydroponic system, in which strawberry plants are grown in individual containers filled with soilless growing media-typically a coconut coir and perlite blend-placed along slightly inclined channels. A thin layer of nutrient solution continuously flows through the channels, providing roots with a balanced supply of water, oxygen, and essential minerals while allowing excess solution to be recirculated. This design enables precise regulation of root zone conditions, minimizes water and fertilizer waste, and effectively eliminates soil-borne diseases that commonly plague conventional strawberry production under continuous cropping regimes.



**Figure 4:** Hydroponic rows of strawberry plants in a greenhouse.

#### ***4.1 Cultivar Selection and Seedling Production***

High-quality cultivars and vigorous seedlings form the essential foundation for successful strawberry cultivation, directly determining the starting point of production.

##### ***4.1.1 Comparison of Major Cultivated Cultivars***

The selection of strawberry cultivars for protected cultivation in China is diverse, with choices made based on regional market demand and climatic conditions. Japanese-bred cultivars and their hybrids are particularly prominent.

‘Benihoppe’ (‘Red Face’): Often marketed as “Chocolate Strawberry”, it is currently one of the most widely planted cultivars in Chinese protected cultivation. The plant exhibits strong growth vigor, an upright habit, and thick, dark green leaves, making it relatively easy to manage. The fruit is conical, with a bright red, glossy color, medium firmness, a balanced sweet-tart flavor, and a rich aroma, making it highly popular with consumers. While high-yielding, it has slightly weaker resistance to powdery mildew and anthracnose, requiring careful management [97].

‘Akihime’ (‘Princess Shou’): Commonly called “Cream Strawberry”. The plant has strong, somewhat open growth and excellent continuous fruiting ability. The fruit is long-conical, uniform and attractive, with a light red color and pale red flesh. It has a soft, tender texture, high sweetness, and a distinctive aroma, representing premium quality. However, its lower fruit firmness makes it less suitable for long-distance transport and storage, favoring pick-your-own farms or local markets [98].

‘Xiangye’ (‘Fragrant Wild’): A high-quality cultivar independently bred in China. It shows vigorous growth and relatively strong disease resistance. The fruit is a standard conical shape with a bright red color, excellent form, high firmness, and good storability and transportability. It offers a sweet, fragrant taste, combining the color of ‘Benihoppe’ with the flavor of ‘Akihime’, resulting in outstanding overall performance. It has become an important supplementary main cultivar [99].

Other Cultivars: Cultivars such as ‘Xue Qin Xiang’ (disease-resistant, high-yielding) and ‘Sweet Charlie’ (early-ripening, high firmness) also have distinct characteristics. Growers should make scientific selections based on target markets (fresh consumption, pick-your-own, long-distance sales), local climate, and facility conditions.

#### 4.1.2 Virus-Free Seedling Production and Standards for Vigorous Seedlings

Strawberries are susceptible to virus infections, leading to cultivar degeneration, weak growth, and reduced yield and quality. Therefore, using virus-free planting material is a fundamental requirement for modern production. Virus-free seedlings are typically obtained through meristem tissue culture combined with virus indexing and are subsequently propagated in strictly isolated, dedicated nurseries. High-quality, vigorous seedlings should meet the following standards:

Complete Plant Structure: Possess 4–6 healthy, fully expanded leaves with dark green color and thick, short petioles. Well-Developed Root System: Have abundant, thick, fibrous roots with a milky-white color; the crown diameter should exceed 1.0 cm. Free of Pests and Diseases: Carry no quarantine pests or diseases, especially soil-borne pathogens like anthracnose and root rot, or pests like aphids and spider mites. Excellent Nutritional Status: Seedling fresh weight over 30 g; plants should be stocky and compact, not elongated. Before transplanting, a root-dip treatment with agents such as *Bacillus subtilis* or metalaxyl + pyrimethanil can be applied to prevent disease and improve survival rates [100,101].

#### 4.1.3 Selection and Management of Soilless Growing Media

In protected strawberry cultivation, particularly under continuous cropping or where soil-borne pathogens such as *Phytophthora cactorum* and *Fusarium oxysporum* are prevalent, the use of soilless growing media offers an effective alternative to soil fumigation and field rotation. Soilless cultivation systems can be broadly categorized into two types: substrate-based systems, which use solid media such as coconut coir, peat, perlite, vermiculite, or their blends; and true hydroponic systems (e.g., deep-flow technique, DFT; nutrient film technique, NFT), where plant roots are directly immersed in or intermittently irrigated with nutrient solution without a solid substrate [102,103]. Common soilless substrates include coconut coir, peat, perlite, vermiculite, and rice hulls, which are often used alone or in formulated blends

to achieve desirable physical and chemical properties for root development and plant productivity. For instance, Wortman et al. reported that strawberry yield in vertical hydroponic systems was greatest when plants were grown in a perlite–coco coir (1:1 by volume) mixture, compared with perlite alone. The inclusion of coco coir or vermiculite improved water retention and root zone aeration, which are critical for the shallow and oxygen-sensitive root system of strawberry [104].

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In China, the adoption of soilless cultivation for protected strawberry production has accelerated in recent years, driven by the need to overcome soil-borne diseases, mitigate continuous cropping obstacles, and improve resource use efficiency. Among the various soilless systems, substrate-based culture using locally available materials remains the most widely practiced, while DFT and NFT hydroponic systems are increasingly employed in high-tech greenhouses and urban agriculture facilities. Commonly used substrates in Chinese hydroponic strawberry production include coconut coir, perlite, vermiculite, peat, and rice hulls, which are often used in various blends to optimize root zone conditions. Coconut coir has emerged as a particularly favored substrate due to its high water-holding capacity (up to  $0.95 \text{ cm}^3 \cdot \text{cm}^{-3}$  at saturation), excellent aeration, biodegradability, and relatively low cost. Perlite and vermiculite are frequently added to coir-based blends to improve drainage and prevent root zone hypoxia—a critical consideration for the shallow, oxygen-sensitive root system of strawberry. Peat is valued for its high cation exchange capacity and organic matter content, but concerns over sustainability have led to increased use of coir as a renewable alternative. Rice hulls, an agricultural byproduct abundant in China, are sometimes incorporated as a lightweight, cost-effective component to enhance porosity [105].

A systematic comparison between hydroponic (soilless) systems and conventional soil cultivation reveals distinct advantages in terms of yield, fruit quality, disease control, and resource efficiency. Ref. [106] conducted a comprehensive evaluation of strawberry hydroponics using the ‘Akihime’ cultivar and reported that an optimized hydroponic system employing a modified Yamazaki strawberry formula with a coconut coir–perlite substrate blend achieved an average fruit weight of 16.72 g per fruit and a total yield exceeding 200 g per plant. In contrast, soil-grown control plants under the same protected conditions produced only 5.04 g per fruit and 64.93 g per plant, representing a yield increase of more than 200% in the hydroponic system. Similarly, Ref. [107] demonstrated that the improved Yamazaki strawberry formula in soilless culture resulted in superior vegetative growth, with plant height reaching 7.6 cm, leaf area  $6.1 \text{ cm}^2$ , and root length 15.7 cm—significantly exceeding those of soil-grown plants. Notably, the hydroponic system also exhibited a marked reduction in root diseases, with 100% survival rates across most treatment combinations compared to 71–90% in soil cultivation.

From a nutritional management perspective, the pH and electrical conductivity (EC) of the nutrient solution are critical parameters in hydroponic systems. Guan et al. identified pH 5.6 as optimal for strawberry hydroponics, yielding maximum plant height, leaf area, root length, and biomass accumulation. pH values below 5.4 or above 6.0 resulted in significantly reduced growth due to impaired nutrient uptake. Regarding nutrient formulation, the modified Yamazaki strawberry formula (containing  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  590.5  $\text{mg} \cdot \text{L}^{-1}$ ,  $\text{KNO}_3$  345  $\text{mg} \cdot \text{L}^{-1}$ ,  $\text{NH}_4\text{H}_2\text{PO}_4$  86  $\text{mg} \cdot \text{L}^{-1}$ ,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  308  $\text{mg} \cdot \text{L}^{-1}$ , with appropriate micronutrients) was found to be the most suitable for strawberry hydroponics in China, outperforming both the standard Yamazaki formula and the Hoagland–Arnon formula in terms of growth, yield, and fruit quality. Furthermore, Zhang et al. conducted an orthogonal optimization experiment and identified an optimal nutrient formulation comprising  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  472  $\text{mg} \cdot \text{L}^{-1}$ ,  $\text{KNO}_3$  303  $\text{mg} \cdot \text{L}^{-1}$ ,  $\text{KH}_2\text{PO}_4$  100  $\text{mg} \cdot \text{L}^{-1}$ , and  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  246.5  $\text{mg} \cdot \text{L}^{-1}$ , with corresponding micronutrients, which achieved the highest yield (200.96 g per plant), greatest fruit weight (16.72 g), and earliest flowering among all tested formulations.

Hydroponic systems also offer substantial advantages in terms of production flexibility and spatial efficiency. Vertical hydroponic towers, multi-layer DFT systems, and A-frame structures have been successfully implemented in Chinese urban agriculture and high-tech greenhouses, allowing for planting densities 2–3 times higher than conventional soil-based systems while improving light interception and labor efficiency. These systems eliminate the need for weeding, reduce labor inputs for soil management, and enable precise fertigation scheduling based on real-time monitoring of EC and pH using Internet of Things (IoT) technologies.

Despite these clear advantages, several challenges must be addressed for widespread adoption of hydroponic strawberry production in China. The initial capital investment for hydroponic infrastructure—including troughs, pumps, sensors, and climate control equipment—is substantially higher than for soil cultivation. The technical complexity requires skilled management and continuous monitoring to prevent nutrient imbalances, salt accumulation, and pathogen outbreaks in recirculating systems. Additionally, the disposal of spent nutrient solutions and growing media poses environmental concerns that require sustainable management strategies. However, with the rapid advancement of IoT-based environmental monitoring, automated fertigation systems, and the development of low-cost substrate alternatives, these challenges are increasingly being addressed, making hydroponic strawberry production a viable and sustainable alternative to traditional soil cultivation in protected agriculture.

In practice, the management of soilless media also requires attention to salt accumulation and vertical gradients within production systems. Wortman et al. observed that electrical conductivity of effluent from the bottom of vertical towers increased over time, indicating salt buildup that could be temporarily alleviated by leaching with water alone. Moreover, leaf greenness—a proxy for chlorophyll content—varied significantly across tower levels, suggesting differential nutrient availability and light interception within the canopy. These findings underscore the importance of regular monitoring of substrate EC, pH, and moisture status, particularly in vertical or containerized systems where root volume is restricted and fertigation frequency is high [108].

In summary, the adoption of soilless growing media in protected strawberry cultivation enables precise control over root-zone conditions, mitigates soil-borne disease risks, and enhances resource use efficiency. In China, hydroponic systems using optimized substrate blends (e.g., coconut coir–perlite mixtures) and tailored nutrient formulations (e.g., modified Yamazaki strawberry formula) have demonstrated clear advantages over conventional soil cultivation in terms of yield (200% or higher increase), fruit quality, and production stability. Successful implementation requires careful selection of substrate components, integration with appropriate fertigation regimes, and ongoing monitoring to maintain optimal physical

and chemical conditions throughout the production cycle. Future research should focus on developing low-cost, locally available substrate alternatives, optimizing nutrient solution formulations for different strawberry cultivars and growth stages, and integrating smart sensing technologies to further improve the sustainability and profitability of hydroponic strawberry production in protected agriculture.

#### 4.2 Transplanting Techniques and Density Regulation

Transplanting is the critical step moving strawberries from the nursery to the production field, determining initial plant arrangement and subsequent canopy structure [109].

##### 4.2.1 Transplanting Timing, Method, and Depth Control

In protected cultivation in northern China, transplanting typically occurs from late August to mid-September. Temperatures begin to decline during this period, facilitating seedling establishment and root growth, and ensuring flower bud differentiation is completed before the onset of winter cold, laying the foundation for early spring harvests. Transplanting should be done on cloudy days or in the late afternoon on sunny days to avoid seedling desiccation and wilting from high temperature and exposure. The principle of “deep enough to avoid exposed roots, shallow enough to avoid buried crowns” must be strictly followed. Planting too deep, with soil covering the growing point (crown), can lead to crown rot and plant death. Planting too shallow, with roots exposed, leads to desiccation. The correct depth positions the base of the crown (the “arch” or bend) level with the bed surface, allowing roots to spread fully within the soil. During planting, the concave side of the crown (“arch”) should face the outer side of the raised bed. This orientation encourages fruit clusters to hang over the sides of the bed, facilitating management, harvest, and improving ventilation and light penetration [110].

##### 4.2.2 Rational Planting Density and Raised Bed Configuration

The standard practice within protected structures is double-row planting on raised beds. Beds are typically 50–60 cm wide and 30–35 cm high, with 20–30 cm spacing (furrow width) between beds. Two rows are planted per bed, with 25–30 cm between rows and 15–20 cm between plants within a row. This configuration results in a planting density of approximately 9000 to 11,000 plants per mu ( $\approx 667 \text{ m}^2$ ) [109]. Rational density ensures sufficient productive plants per unit area while maintaining good inter-plant airflow and light exposure, reducing pest and disease incidence. This is key to balancing population and individual plant development for achieving high yield and quality. After transplanting, thorough “settling-in” irrigation is immediately required, with consistent soil moisture maintained for about a week to promote establishment. A typical configuration for double-row raised beds in protected strawberry cultivation is presented in Table 6, which serves as a guideline for optimizing planting layout and density.

**Table 6:** Configuration for double-row raised beds in protected strawberry cultivation.

Parameter	Recommendation
Bed width	50–60 cm
Bed height	30–35 cm
Distance between beds	20–30 cm
Rows per bed	2 rows
Row spacing (within bed)	25–30 cm
Plant spacing (within row)	15–20 cm
Planting density	$\approx 9000$ – $11,000$ plants/mu

### **4.3 Integrated Water and Nutrient Management**

Strawberries have a long growth cycle, high nutrient demands, and distinct water requirement patterns. Fertigation technology is the core means to achieve precise supply, improving both quality and efficiency. International research has demonstrated significant advancements in water and nutrient management for protected strawberry production. In the United States, studies in California have shown that optimized drip fertigation systems can achieve water use efficiencies of 85–90%, with nitrogen use efficiency improved by 30–40% compared to conventional furrow irrigation, while maintaining fruit yields of 35–45 t·ha<sup>-1</sup> [111]. In Europe, particularly in the Netherlands and Belgium, closed-loop soilless systems have been developed to recirculate nutrient solutions, reducing water consumption by up to 50% and fertilizer inputs by 30–40% compared to open systems, with minimal environmental impact [Van Os et al., 2019; Voogt et al., 2020]. In Japan, precision fertigation strategies incorporating real-time soil moisture sensors and crop growth models have been implemented in high-end greenhouse strawberry production, achieving fruit sugar content (Brix) of 10–12% while reducing nitrogen application by 25–30% compared to conventional practices [15,111]. These international case studies collectively indicate that water and fertilizer efficiency can be substantially improved through technology adoption without compromising yield or fruit quality.

#### **4.3.1 Base Fertilizer and Top-Dressing Ratio Techniques**

Fertilization should follow the principle of “emphasis on base fertilizer, frequent top-dressing”. Base fertilizer primarily consists of high-quality, fully decomposed organic matter, such as farmyard manure or commercial organic fertilizer, with a recommended application rate of 3–5 t per mu. This is combined with 50–75 kg of NPK compound fertilizer (e.g., 15-15-15), incorporated into the soil through deep plowing to provide a long-lasting, comprehensive nutrient foundation for the entire growth cycle [112]. Top-dressing is applied according to the demands of different growth stages. From post-establishment until pre-flowering, the focus is on promoting root and vegetative growth, applying balanced water-soluble fertilizer 1–2 times. After flowering and fruit set, during peak nutrient demand, emphasis shifts to high-potassium water-soluble fertilizers to promote fruit enlargement and sugar accumulation, applied via drip irrigation every 10–15 days. Concurrently, foliar sprays of secondary and micronutrients like 0.2%–0.3% potassium dihydrogen phosphate, calcium, and boron fertilizers can supplement root uptake, improving fruit set and quality [113,114].

#### **4.3.2 Drip Irrigation and Synergistic Water-Nutrient Regulation**

The drip irrigation system is the vehicle for fertigation. Soluble fertilizers are dissolved in an injection tank and mixed with irrigation water at a set ratio. This nutrient solution is then delivered directly and uniformly to the root zone of each strawberry plant via drip lines running along the beds. This method achieves “nutrient regulation via water, growth promotion via fertilizer”, synchronizing water and nutrient application and significantly improving use efficiency (saving 30%–50% water and 20%–30% fertilizer) [115]. It also maintains soil porosity, reduces greenhouse air humidity, and minimizes disease incidence at its source. Managers need only adjust irrigation frequency, duration, fertilizer formula, and concentration based on weather, soil moisture status, and plant growth to achieve precise control.

### **4.4 Intelligent Environmental Control**

The essence of protected cultivation lies in controlling environmental factors, with modern information technology enabling this control to become intelligent and precise [116].

#### *4.4.1 Precise Temperature and Humidity Management*

Strawberries have precise temperature and humidity requirements across different growth stages:

Bud Emergence: Day 25–28°C, Night 10–12°C. Flowering: Day 22–25°C, Night 8–10°C, Humidity 40%–60%. Fruit Enlargement: Day 20–22°C, Night 6–8°C. Fruit Harvest: Day 18–20°C, Night 5–8°C. Sensors placed throughout the greenhouse transmit real-time data to a control system. When temperatures fall below the set minimum, heating equipment (e.g., air heaters) activates automatically; when they exceed the maximum, vents or fan-and-pad cooling systems activate. Humidity is primarily controlled via ventilation, with automatic window opening to expel excess moisture. This dynamic, precise management creates an optimal microclimate for strawberry growth [117,118].

#### *4.4.2 Supplemental Lighting and CO<sub>2</sub> Fertilization Technology*

During winter and early spring when natural light is insufficient, artificial supplemental lighting is crucial. Using LED plant growth lights to extend the photoperiod in the morning and evening, achieving a total daily light duration of 12–15 h, can significantly enhance photosynthesis, prevent plant elongation, promote earlier flowering, and increase yield and quality. In well-sealed modern greenhouses, CO<sub>2</sub> concentration during peak daytime photosynthesis often falls below atmospheric levels, becoming a limiting factor. Applying food-grade CO<sub>2</sub> to increase the concentration inside the greenhouse to 800–1000 ppm can substantially boost photosynthetic efficiency, promoting plant growth and fruit development. This is a key technical measure for achieving super-high yields [119,120].

### **4.5 Flower and Fruit Management Techniques**

Flower and fruit management directly impacts final fruit marketability and represents the final step in elaborate production to enhance profitability.

#### *4.5.1 Flower/Fruit Thinning and Assisted Pollination*

Excessive numbers of flowers and fruits on a strawberry inflorescence lead to nutrient dilution, resulting in small, poor-quality fruit. Weak and malformed flower buds from higher-order positions (e.g., the 4th and 5th) should be promptly thinned, retaining 3–5 strong buds per inflorescence. After fruit set, diseased, malformed, and undersized fruits are removed, retaining 5–8 well-developed fruits per plant. The lack of natural pollinators within protected structures necessitates assisted pollination. The most cost-effective method is introducing bees (e.g., Italian honeybees or bumblebees). Hives are typically introduced when approximately 15% of flowers are open, at a density of one hive per mu, placed centrally with the hive entrance facing south. Bee pollination significantly improves fruit set and reduces malformed fruit. During prolonged periods of cold, cloudy weather when bee activity is low, manual pollination using a soft brush can supplement [121,122].

#### *4.5.2 Fruit Development Regulation and Harvest Standards*

Maintaining suitable diurnal temperature variation (8–12°C) and sufficient light during fruit development favors the accumulation of sugars and flavor compounds. The harvest period is critical for final quality; appropriate water restriction can enhance fruit firmness and sugar content. Strawberries should be harvested when 80%–90% of the fruit surface has developed its characteristic color. Harvesting is best done in the morning (8–10 AM) or late afternoon (4–6 PM) when fruit temperature is lower, aiding preservation. Fruit should be picked by pinching the stem with thumb and forefinger, breaking or cutting it

0.5–1 cm from the fruit base, retaining the complete calyx. Gentle handling is essential to avoid mechanical damage and maximize shelf life.

#### **4.6 Green Pest and Disease Control**

Adhering to the principle of “prevention first, integrated control”, a green pest management system should be established, based on cultural, physical, and biological methods, with chemical control as a supplementary measure [123,124].

##### *4.6.1 Control of Major Diseases*

Gray Mold (*Botrytis cinerea*): A disease favored by cool, humid conditions. Control focuses on reducing greenhouse humidity (<80%) and promptly removing infected fruit and senescent leaves. At disease onset, spray with fungicides such as 50% fludioxonil or 50% boscalid. Powdery Mildew: Favored by moderate temperature and humidity. Improve ventilation and maintain proper planting density. Alternate sprays of fungicides like 42.8% fluopyram + trifloxystrobin or 10% difenoconazole. Anthracnose (*Colletotrichum* spp.): Favored by high temperature and humidity, primarily harming plants during the seedling and early establishment stages. Use disease-free planting material and apply fungicide root-dips before transplanting. Post-infection, apply fungicides like 25% pyraclostrobin or 25% prochloraz via drench or spray.

##### *4.6.2 Integrated Pest Management Strategies*

Aphids & Whiteflies: Install 60-mesh insect-proof nets on ventilation openings as a barrier; hang yellow sticky traps inside the greenhouse (approx. 45 per mu) for mass trapping; apply low-toxicity insecticides like 10% imidacloprid if necessary. Spider Mites (*Tetranychidae*): Maintain relatively high humidity (>60% inhibits reproduction); release predatory mites (e.g., *Neoseiulus cucumeris*) for biological control; if infestation is severe, apply specific miticides like 3.2% abamectin. Chemical control should be a last resort, strictly observing pre-harvest intervals and rotating chemical groups to delay resistance development.

#### **4.7 Harvest and Post-Harvest Handling**

Post-harvest handling is the final step in preserving strawberry market value and achieving premium pricing.

##### *4.7.1 Harvest Timing and Technical Details*

As mentioned, harvesting should avoid the midday heat. Harvesters should wear gloves and use dedicated picking containers lined with soft padding, adhering to “gentle picking, gentle handling, gentle placement”. Perform preliminary grading in the field to remove diseased, damaged, and inferior fruit.

##### *4.7.2 Preservation and Storage/Transport Technology*

As highly perishable berries, strawberries must be pre-cooled immediately after harvest to rapidly reduce their core temperature to 0–2°C. This is followed by grading and packing. Packaging in vented plastic clamshells protects the fruit while allowing gas exchange. Storage and transport require an unbroken low-temperature (0–2°C) cold chain throughout. Utilizing cold-chain logistics combined with technologies like modified atmosphere packaging (MAP) can extend the shelf life of high-quality strawberries to 7–10 days or more, effectively expanding their market radius.

## 5 Development Models and Innovation Pathways for the Protected Small Berry Industry

Driven by consumption upgrading and technological advancement, the protected small berry industry has evolved beyond traditional single-output production models toward higher-level forms characterized by diversified integration, technology-driven operations, and brand leadership. Exploring its innovative pathways and development models is crucial for enhancing the industry's comprehensive benefits and competitiveness [125].

### 5.1 Case Studies of Industrial Integration

Industrial integration serves as an effective means to extend the industry chain and enhance value. The protected small berry industry, with its appealing orchard aesthetics, palatable fruit, and controllable environment, possesses unique advantages for integrated development. As illustrated in Fig. 5, the integration of IoT sensors, intelligent robots, and automated control systems exemplifies the practical application of smart farming technologies in protected berry production, facilitating real-time monitoring and precision management of crop growth environments.

#### 5.1.1 Integration of Strawberry Picking and Leisure Agriculture

Protected small berry orchards, with strawberries as the prime example, have become highlights of urban leisure agriculture. This model directly combines agricultural production with tourism experience, creating a synergistic “1 + 1 > 2” value effect. For instance, County have developed protected strawberry cultivation, attracting numerous urban visitors for sightseeing and fruit picking. This transformation shifts “farmland into parks, labor into experiences, and products into commodities”. The advantages of this model are threefold: First, it multiplies economic returns, as strawberries sold directly through pick-your-own activities typically command prices higher than wholesale market rates while saving on harvesting and marketing costs. Second, it exhibits a strong ripple effect, effectively stimulating the development of surrounding service industries such as catering, accommodation, and transportation. Third, it provides excellent promotional effects, as firsthand visitor experience serves as the most potent brand communication, helping to establish a loyal customer base and positive market reputation. Success hinges on the orchard's landscape design, the provision of supporting facilities like parking lots, restrooms, and resting areas, and a focus on service quality and safety. The goal is to create a comprehensive leisure destination integrating picking, education, recreation, and gastronomy.

#### 5.1.2 Construction of Smart Agriculture Parks Integrating Industry, Academia, Research, and Extension

The establishment of smart agriculture parks, led by enterprises in collaboration with research institutes, represents a high-end model for driving technological upgrading and commercialization of research outcomes. Some company not only constructed high-standard agricultural tunnels and smart greenhouses but, more importantly, signed technical service agreements with research institutions like the Agricultural Information Institute of the Chinese Academy of Agricultural Sciences. This fosters deep “Industry-Academia-Research-Extension” collaboration and joint development of digital agriculture projects. The park integrates and applies advanced equipment such as IoT sensors, fertigation systems, intelligent cultivation management systems, and plant protection drones, achieving real-time monitoring and intelligent control of the crop growth environment. The core value of this model lies in: (1) Technology Integration and Demonstration, creating a visible, learnable, and replicable model of modern agriculture; (2) Accelerated R&D-Application Feedback Loop, where practical enterprise needs directly inform research, and new findings are rapidly validated and applied on-site; (3) Professional Talent

Cultivation, supplying the industry with technical experts proficient in both theory and practice. This “technology-led, enterprise-operated, multi-party collaborative” park model represents a future direction for protected agriculture.



(a)



(b)



(c)

**Figure 5:** Application of smart farming technologies in protected small berry cultivation: (a) intelligent spraying robot, (b) temperature-humidity sensor module, and (c) IoT-integrated greenhouse for strawberry production.

## 5.2 Technological Innovation Trends

Technological innovation is the core driving force of industrial development. Currently, the protected small berry industry is undergoing a technological revolution characterized by digitalization, automation, and ecological sustainability. Key smart farming technologies applicable to protected berry production, including IoT environmental sensing and UAV-based operations, are summarized in Table 7, highlighting their functions and benefits.

**Table 7:** Smart farming technologies for protected berry production.

Technology	Function	Benefits
IoT environmental sensing	Real-time greenhouse monitoring (temp, humidity, light, CO <sub>2</sub> , etc.)	Enables automated control (vents, fans, lights, irrigation) for stable growth; reduces labor.
UAV/drones	Aerial crop surveillance and targeted spraying of biopesticides/fertilizers	Early pest/disease detection; precise, uniform application; increased efficiency and worker safety.

### 5.2.1 IoT and Intelligent Environmental Monitoring

The Internet of Things (IoT) enables comprehensive, uninterrupted sensing of the greenhouse environment through the deployment of various sensors (for temperature, humidity, light, soil moisture, CO<sub>2</sub> concentration, etc.) and network devices. Data is collected and transmitted in real-time to a cloud platform. Based on algorithmic analysis, the system can automatically or semi-automatically control actuators such as roof vents, fans, cooling pads, supplemental lights, and drip irrigation valves, precisely regulating environmental parameters within optimal ranges for crop growth. For example, the system can automatically execute ventilation, heating, or cooling operations according to preset temperature and humidity values for the flowering or fruit-enlargement stages [126,127]. This not only significantly reduces labor intensity but, more importantly, represents a qualitative leap in environmental control from “experience-based judgment” to “data-driven decision-making”, making production management more scientific, stable, and efficient.

### 5.2.2 Fertigation and UAV-Based Plant Protection

Fertigation technology has evolved from simple “fertilizer with water” delivery to precision variable-rate application based on crop nutrient demand patterns and soil conditions. Integrated with EC/pH monitoring and crop growth models, the system can dynamically adjust the ratio and concentration of various nutrients in the irrigation solution, achieving genuine “on-demand supply”. This optimizes fruit quality while conserving water and fertilizer. The application of Unmanned Aerial Vehicles (UAVs/drones) in plant protection for protected berries is also becoming increasingly widespread. Drones equipped with multispectral cameras can conduct aerial surveys to detect pest and disease hotspots or areas of abnormal plant growth at an early stage. For pesticide application, drones enable ultra-low volume spraying with excellent atomization and penetration, allowing for precise, targeted chemical delivery. This is particularly effective in large greenhouses or contiguous orchard areas, offering high operational efficiency while reducing operators’ direct exposure to chemicals, thereby enhancing safety. The integration of these two technologies represents the direction of resource-efficient utilization and modernized plant protection [128,129].

## 6 Conclusion

### 6.1 Summary of Main Findings

This paper provides a systematic review of the growth characteristics of small berries, with a focus on strawberry, and the associated technical system for protected cultivation management. The study elucidates that strawberries and other small berries possess distinct physiological and ecological traits—such as a preference for cool temperatures, a shallow root system, and balanced requirements for water and nutrients—which form the fundamental basis for formulating all cultivation practices. Centered on these characteristics, modern protected strawberry cultivation has developed a comprehensive, full-chain technical system. This system encompasses high-quality seedling propagation, precision transplanting, intelligent water and nutrient management, environmental control, meticulous flower and fruit management, green pest control, and efficient post-harvest handling. The core principles of this system are precision and sustainability.

Concurrently, the industry's development demonstrates clear trends toward integration (combining agriculture with tourism and linking industry, academia, and research) and intelligence (utilizing IoT, drones, etc.). However, challenges such as over-reliance on specific cultivars, a fragmented supply chain, and underdeveloped processing sectors remain bottlenecks constraining the industry's advancement to a higher level of sophistication.

### 6.2 Implications for the Sustainable Development of the Protected Small Berry Industry

The sustainable development of the protected small berry industry must follow a pathway characterized by “technology-driven advancement, quality-oriented leadership, integrated value creation, and ecological friendliness”. Future industry competition will shift from a singular pursuit of yield to a comprehensive contest centered on cultivar, quality, and brand. Achieving this transition requires the adoption of quantifiable sustainability metrics. International studies indicate that advanced drip fertigation can improve water use efficiency from 15–25 kg fruit·m<sup>-3</sup> in conventional systems to 35–50 kg fruit·m<sup>-3</sup>, while closed-loop soilless systems achieve 60–80 kg fruit·m<sup>-3</sup>. Fertilizer use efficiency similarly increases from 30–50% nitrogen use efficiency in conventional practices to 60–75% with precision fertigation, and exceeds 85% in recirculating systems. Energy consumption in protected cultivation ranges from 50–100 kWh·m<sup>-2</sup>·yr<sup>-1</sup> for high tunnels to 200–500 kWh·m<sup>-2</sup>·yr<sup>-1</sup> for high-tech greenhouses, with LED lighting and improved insulation reducing intensity by 20–40%. Greenhouse gas emissions vary from 1.5 to 4.5 kg CO<sub>2</sub>-eq per kg fruit, with renewable energy adoption and improved nutrient management reducing emissions by 50–70% and 20–30%, respectively. These quantitative benchmarks underscore the potential for substantial efficiency gains through technological innovation. This implies the following imperatives: (1) Technology as the Fundamental Driver: Continuous investment in research and development to overcome core breeding challenges and the widespread adoption of smart agriculture technologies are the cornerstones for the industry's long-term resilience. (2) Sustainability as the Essential Foundation: Implementing green production practices throughout the entire process is a prerequisite for ensuring product safety, ecological sustainability, gaining consumer trust, and meeting high-end market demands. (3) Integration as the Value Engine: Promoting deep industrial integration and expanding the ecological, recreational, and cultural functions of agriculture are key to enhancing the industry's added value and overall resilience. (4) Collaboration as the Systemic Guarantee: Fostering a tightly coupled innovation ecosystem that integrates industry, academia, research, extension, and end-users, alongside efficient coordination across the entire industry chain, is essential for transitioning from a “production-oriented sector” to a

“modern industrial system”. Only by persistently innovating, prioritizing quality, deepening integration, and strengthening collaboration can the protected small berry industry fully realize its significant economic and social potential within China’s rural revitalization and agricultural modernization efforts.

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## References

1. Lavefve L, Howard LR, Carbonero F. Berry polyphenols metabolism and impact on human gut microbiota and health. *Food Funct.* 2020;11(1):45–65. [[CrossRef](#)].
2. Wallace TC, Bailey RL, Blumberg JB, Burton-Freeman B, Chen CO, Crowe-White KM, et al. Fruits, vegetables, and health: A comprehensive narrative, umbrella review of the science and recommendations for enhanced public policy to improve intake. *Crit Rev Food Sci Nutr.* 2020;60(13):2174–211. [[CrossRef](#)].
3. Tulipani S, Alvarez-Suarez JM, Busco F, Bompadre S, Quiles JL, Mezzetti B, et al. Strawberry consumption improves plasma antioxidant status and erythrocyte resistance to oxidative haemolysis in humans. *Food Chem.* 2011;128(1):180–6. [[CrossRef](#)].
4. Weaver CM, Ferruzzi MG, Maiz M, Cladis DP, Nakatsu CH, McCabe GP, et al. Crop, host, and gut microbiome variation influence precision nutrition: An example of blueberries. *Antioxidants.* 2023;12(5):1136. [[CrossRef](#)].
5. An H, Zhang J, Zhang L, Li S, Zhou B, Zhang X. Effects of nutrition and light quality on the growth of southern highbush blueberry (*Vaccinium corymbosum* L.) in an advanced plant factory with artificial lighting (PFAL). *Horticulturae.* 2023;9(2):287. [[CrossRef](#)].
6. Staszowska-Karkut M, Materska M. Phenolic composition, mineral content, and beneficial bioactivities of leaf extracts from black currant (*Ribes nigrum* L.), raspberry (*Rubus idaeus*), and Aronia (*Aronia melanocarpa*). *Nutrients.* 2020;12(2):463. [[CrossRef](#)].
7. Lei JJ, Jiang S, Ma RY, Xue L, Zhao J, Dai HP. Current status of strawberry industry in China. In: Proceedings of the 9th International Strawberry Symposium; 2021 May 1–5; Rimini, Italy.
8. Pramanick KK, Kishore DK, Sharma SK, Das BK, Murthy BNS. Strawberry cultivation under diverse agro-climatic conditions of India. *Int J Fruit Sci.* 2013;13(1–2):36–51. [[CrossRef](#)].
9. Xu S, Shi D, Chen H, Ma F, Tao G, Wu W, et al. Substrate cultivation system improved the quality of ‘Hongyan’ strawberry fruits compared with the soil cultivation system. *Food Chem.* 2025;485:144430. [[CrossRef](#)].
10. Lan W, Cheng W, Shen N, Ma R, Pan T, Li N, et al. Advance in brewing process, flavour detection technologies and functional components of fruit wine: A review. *Int J Food Eng.* 2025;21(7):463–74. [[CrossRef](#)].
11. Lu L, Mi J, Chen X, Luo Q, Li X, He J, et al. Analysis on volatile components of co-fermented fruit wines by *Lycium ruthenicum* murray and wine grapes. *Food Sci Technol.* 2022;42:e12321. [[CrossRef](#)].

12. Liu M, Qi D, Zhong T. Agricultural development policy diffusion associated with leading cadre's experience and expansion of protected agriculture in China. *Front Environ Sci.* 2023;11:1078565. [[CrossRef](#)].
13. Shi X, An X, Zhao Q, Liu H, Xia L, Sun X, et al. State-of-the-art Internet of Things in protected agriculture. *Sensors.* 2019;19(8):1833. [[CrossRef](#)].
14. Sabir A, Sabir F, Kara Z, Gayretli Y, Mohammed OJM, Jawshle AIM, et al. Berry set and quality response of soilless grown 'prima' grapes to foliar and inflorescence pulverization of various substances under glasshouse condition. *Erwerbs Obstbau.* 2019;61(1):47–51. [[CrossRef](#)].
15. Samtani JB, Rom CR, Friedrich H, Fennimore SA, Finn CE, Petran A, et al. The status and future of the strawberry industry in the United States. *HortTechnology.* 2019;29(1):11–24. [[CrossRef](#)].
16. Chopra M, Choudhary M, Singh M, Jat HS, Tureevna ZL, Sadykova N, et al. Biocontrol strategies in agricultural green development and soil health management to achieve sustainable growth in agriculture. *Discov Appl Sci.* 2025;7(10):1182. [[CrossRef](#)].
17. Furuya N. Strategic biological control of difficult-to-control plant diseases and pests for sustainable agriculture. *J Gen Plant Pathol.* 2024;90(6):356–60. [[CrossRef](#)].
18. Tong C, Chen X, Yu Z, Deng R, Zhang J. Biodiversity in volatile profiles and nutritional quality among coloured strawberries from China. *J Food Meas Charact.* 2025;19(11):8743–58. [[CrossRef](#)].
19. Durmuş A, Ayyıldız B, Erdal G. Revealed comparative advantage of strawberry production in international trade. *Appl Fruit Sci.* 2025;67(6):448. [[CrossRef](#)].
20. Xie X, Tian J, Wang Y, Shu C, Gui H, Cheng Z, et al. Comparison of the content of taste and nutrition-related non-volatile compounds in cultivated and wild blueberry varieties in Northeast China. *Food Chem X.* 2025;25:102235. [[CrossRef](#)].
21. Wei J, Jiang J, Tian L, Jiang Y, Ge C, Yu H, et al. Effect of rain-shelter cultivation on yield and fruit quality of container-grown rabbiteye blueberry in central-eastern China. *Plants.* 2025;14(8):1167. [[CrossRef](#)].
22. Wang M, Wu Y, Yang H, Zhang C, Wu W, Lyu L, et al. Formation and regulatory network of fruit aroma components of Rosaceae plants. *Food Biosci.* 2025;69:106400. [[CrossRef](#)].
23. Gomez-Salgado S, Flores-Naveda A, Ruelas-Chacon X, Preciado-Rangel P, Muñoz-Urbina A, Rueda-Puente EO. Productive behavior of strawberry (*Fragaria* × *ananassa* D.) with chemical and organic nutrition. *Ecosistemas Recur Agropecu.* 2025;12(3):e4292. [[CrossRef](#)].
24. Sayıncı B, Öztürk Erdem S, Özdemir MH, Karakoyun Mutluay M, Gedik C, Çomaklı M. Strawberry (*Fragaria* × *ananassa* Duch.) fruit shape differences and size characteristics using elliptical Fourier descriptors. *Horticulturae.* 2025;11(11):1281. [[CrossRef](#)].
25. Balcı G, Saltalı K, Türkay FŞH, Kara Z, Yakupoğlu T. Manure application to a strawberry garden: Changes in some soil and plant properties under semi-arid climate conditions. *Appl Fruit Sci.* 2025;67(4):260. [[CrossRef](#)].
26. Hutchinson GK, Nguyen LX, Ames ZR, Nemali K, Ferrarezi RS. Substrate system outperforms water-culture systems for hydroponic strawberry production. *Front Plant Sci.* 2025;16:1469430. [[CrossRef](#)].
27. Wang X, Huang Q, Wu D, Xie J, Cao M, Liu J. Predicting minimum temperatures of plastic greenhouse during strawberry growing in Changfeng, China: A comparison of machine learning algorithms and multiple linear regression. *Agronomy.* 2025;15(3):709. [[CrossRef](#)].
28. Pérez-Romero LF, Hancock RD. Polyphenols content of strawberry fruit grown under Light-Emitting Diodes (LED). *Sci Hort.* 2025;354:114298. [[CrossRef](#)].
29. Hwang HS, Koo JK, Park EW, Yun JH, Hwang SY, Choi HE, et al. Blue LED supplemental lighting enhances flowering and fruit yield of 'kuemsil' strawberries. *HortTechnology.* 2025;35(4):554–63. [[CrossRef](#)].
30. Hwang HS, Hwang JH, Koo JK, Park EW, Yun JH, Hwang SY, et al. LEDs supplemental light treatment promotes flowering and increases yield of 'Kuemsil' strawberries. *Hortic Environ Biotechnol.* 2025;66(1):87–97. [[CrossRef](#)].
31. Becker AL, Crowl AA, Chanderbali AS, Soltis PS, Cellinese N, Fritsch PW. The spatiotemporal origin of Polynesian blueberries (*Vaccinium*). *Am J Bot.* 2025;112(11):e70113. [[CrossRef](#)].
32. Recalde JM, Garavello MF, Alayón Luaces P, González AM. Anther ontogeny and pollen development in southern highbush blueberry (*Vaccinium corymbosum* L.). *Horticulturae.* 2025;11(11):1278. [[CrossRef](#)].
33. Yang HY, Wu YQ, Zhang CH, Wu WL, Lyu LF, Li WL. Comprehensive adaptability evaluation of ten blueberry cultivars under substrate cultivation conditions. *Russ J Plant Physiol.* 2025;72(4):108. [[CrossRef](#)].

34. Ding G, Weng W, Feng X, Gao Y, Zhang Y. Rhizosphere microbiota adaptation under blueberry cultivation: Modified paddy soil versus acidic red soil. *Antonie Van Leeuwenhoek*. 2025;118(9):119. [[CrossRef](#)].
35. Morales L, Rivadeneira MF, Gollán A, Bello F, Tripodi K. Metabolic profiling and fruit quality assessment of fourteen blueberry cultivars (*Vaccinium* sp) well adapted to a subtropical climate. *J Berry Res*. 2026;16(1):28–42. [[CrossRef](#)].
36. Ispiryan A, Kraujutiene I, Viskelis J. Quality characteristics of raspberry by-products for sustainable production. *Foods*. 2024;13(10):1436. [[CrossRef](#)].
37. Shi F, Qin Y, Qiu S, Luo Y. Nutrients, phytochemicals, and antioxidant capacity of red raspberry nectar fermented with *Lactobacillus paracasei*. *Foods*. 2024;13(22):3666. [[CrossRef](#)].
38. Pylak M, Oszust K, Panek J, Siegieda D, Cybulska J, Zdunek A, et al. Impact of microbial-based biopreparations on soil quality, plant health, and fruit chemistry in raspberry cultivation. *Food Chem*. 2025;462:140943. [[CrossRef](#)].
39. Yu Y, Yang G, Sun L, Song X, Bao Y, Luo T, et al. Comprehensive evaluation of 24 red raspberry varieties in Northeast China based on nutrition and taste. *Foods*. 2022;11(20):3232. [[CrossRef](#)].
40. Bushmeleva K, Vyshtakalyuk A, Terenzhev D, Nikitin E. Antioxidant and membranotropic properties of extracts from *Aronia melanocarpa* (Rosaceae) berries. *Eur J Clin Investig*. 2019;49:119.
41. Ghendov-Mosanu A, Ungureanu-Iuga M, Mironeasa S, Sturza R. Aronia extracts in the production of confectionery masses. *Appl Sci*. 2022;12(15):7664. [[CrossRef](#)].
42. Lee JH, Choi IS. Physicochemical characteristics and consumer acceptance of puddings fortified with *Cudrania tricuspidata* and *Aronia melanocarpa* extracts. *Food Sci Nutr*. 2020;8(9):4936–43. [[CrossRef](#)].
43. Paunović SM, Mašković P, Milinković M. Optimization of primary metabolites and antimicrobial activity in Aronia Berries as affected by soil cultivation systems. *Erwerbs Obstbau*. 2022;64(4):581–9. [[CrossRef](#)].
44. Skrede G, Martinsen BK, Wold AB, Birkeland SE, Aaby K. Variation in quality parameters between and within 14 Nordic tree fruit and berry species. *Acta Agric Scand Sect B*. 2012;62(3):193–208. [[CrossRef](#)].
45. Fan L, Zhang C, Li J, Liu Y. The use of Arbuscular mycorrhizal fungi to alleviate the growth and photosynthetic characteristics of strawberry under salt stress. *Acta Physiol Plant*. 2024;46(12):118. [[CrossRef](#)].
46. Zhang M, Kong Z, Fu H, Shu X, Xue Q, Lai H, et al. Rhizosphere microbial ecological characteristics of strawberry root rot. *Front Microbiol*. 2023;14:1286740. [[CrossRef](#)].
47. Cao H, Han Y, Peng J, Peng X. Improving soil moisture content to increase strawberry growth indicators using the hydroponic method. *Water Supply*. 2023;23(7):2927–39. [[CrossRef](#)].
48. Samoraj M, Tuhy Ł, Chojnacka K. Valorization of biomass into micronutrient fertilizers. *Waste Biomass Valorization*. 2019;10(4):925–31. [[CrossRef](#)].
49. Singh P, Singh NP, Khokhar Y, Sharda R, Sharma P. Optimizing Fe, Zn and Mn dosages for potential fruit yield and quality of strawberry under north-western Indo-Gangetic Plains. *J Soil Sci Plant Nutr*. 2025;25(4):9614–31. [[CrossRef](#)].
50. Jia Z, Zhang J, Jiang W, Wei M, Zhao L, Li G. Different nitrogen concentrations affect strawberry seedlings nitrogen form preferences through nitrogen assimilation and metabolic pathways. *Sci Hortic*. 2024;332:113236. [[CrossRef](#)].
51. de Azevedo Kuhn TM, Loeck AE, Zawadneak MAC, Garcia MS, Botton M. Parâmetros biológicos e tabela de vida de fertilidade de *Neopamera bilobata* (Hemiptera: Rhyparochromidae) em morangueiro. *Pesq Agropec Bras*. 2014;49(6):422–7. [[CrossRef](#)].
52. Ariza MT, Miranda L, Gómez-Mora JA, Medina JJ, Lozano D, Gavilán P, et al. Yield and fruit quality of strawberry cultivars under different irrigation regimes. *Agronomy*. 2021;11(2):261. [[CrossRef](#)].
53. Morillo JG, Martín M, Camacho E, Díaz JAR, Montesinos P. Toward precision irrigation for intensive strawberry cultivation. *Agric Water Manag*. 2015;151:43–51. [[CrossRef](#)].
54. Perea RG, García IF, Arroyo MM, Rodríguez Díaz JA, Poyato EC, Montesinos P. Multiplatform application for precision irrigation scheduling in strawberries. *Agric Water Manag*. 2017;183:194–201. [[CrossRef](#)].
55. Gendron L, Létourneau G, Cormier J, Depardieu C, Boily C, Levallois R, et al. Using pulsed water applications and automation technology to improve irrigation practices in strawberry production. *HortTechnology*. 2018;28(5):642–50. [[CrossRef](#)].
56. Tang Y, Ma X, Li M, Wang Y. The effect of temperature and light on strawberry production in a solar greenhouse. *Sol Energy*. 2020;195:318–28. [[CrossRef](#)].

57. Diengngan S, Murthy BNS, Rymbai H. *In vitro* culture genotypic efficacy of different strawberry cultivars as affected by growth promoting substances. *Ind Jour Hort.* 2016;73(4):482. [[CrossRef](#)].
58. English-Loeb G, Pritts M, Kovach J, Rieckenberg R, Kelly MJ. Compensatory ability of strawberries to bud and flower removal: Implications for managing the strawberry bud weevil (Coleoptera: Curculionidae). *J Econ Entomol.* 1999;92(4):915–21. [[CrossRef](#)].
59. Wan C, Mi L, Chen B, Li J, Huo H, Xu J, et al. Effects of nitrogen during nursery stage on flower bud differentiation and early harvest after transplanting in strawberry. *Braz J Bot.* 2018;41(1):1–10. [[CrossRef](#)].
60. Mertoglu K, Ali Sarıdaş M, Ağçam E. Boron-mediated regulation of productivity, pomology and nutritional composition across sequential harvests in high-tunnel-cultivated ‘Rubygem’ strawberries. *J Sci Food Agric.* 2026;106(3):1890–903. [[CrossRef](#)].
61. Park Y, Sethi R, Temnyk S. Growth, flowering, and fruit production of strawberry ‘Albion’ in response to photoperiod and photosynthetic photon flux density of sole-source lighting. *Plants.* 2023;12(4):731. [[CrossRef](#)].
62. Xu X, Hernández R. The effect of light intensity on vegetative propagation efficacy, growth, and morphology of “Albion” strawberry plants in a precision indoor propagation system. *Appl Sci.* 2020;10(3):1044. [[CrossRef](#)].
63. Zheng J, He D, Ji F. Effects of light intensity and photoperiod on runner plant propagation of hydroponic strawberry transplants under LED lighting. *Int J Agric Biol Eng.* 2019;12(6):26–31. [[CrossRef](#)].
64. Hamano M, Yamazaki H, Morishita M, Imada S. Effect of chilling and day length on runner of everbearing type strawberry. *Acta Hort.* 2009;842(842):671–4. [[CrossRef](#)].
65. Warner R, Wu BS, MacPherson S, Lefsrud M. A review of strawberry photobiology and fruit flavonoids in controlled environments. *Front Plant Sci.* 2021;12:611893. [[CrossRef](#)].
66. Choi HG, Moon BY, Kang NJ. Effects of LED light on the production of strawberry during cultivation in a plastic greenhouse and in a growth chamber. *Sci Hort.* 2015;189:22–31. [[CrossRef](#)].
67. Meng L, Höfte M, Van Labeke MC. Leaf age and light quality influence the basal resistance against *Botrytis cinerea* in strawberry leaves. *Environ Exp Bot.* 2019;157:35–45. [[CrossRef](#)].
68. Qin Y, Zhang S, Asghar S, Zhang L, Qin Q, Chen K, et al. Regeneration mechanism of Toyonoka strawberry under different color plastic films. *Plant Sci.* 2005;168(6):1425–31. [[CrossRef](#)].
69. da Rocha PSG, de Oliveira RP, Scivittaro WB, dos Santos UL. Light-emitting diodes and BAP concentrations in the *in vitro* strawberry multiplication. *Cienc Rural.* 2010;40(9):1922–8. [[CrossRef](#)].
70. Lauria G, Lo Piccolo E, Ceccanti C, Paoli L, Giordani T, Guidi L, et al. Supplemental red light more than other wavebands activates antioxidant defenses in greenhouse-cultivated *Fragaria × ananassa* var. Elsanta plants. *Sci Hort.* 2023;321:112319. [[CrossRef](#)].
71. Wu CC, Yen YH, Chang MY, Fang W. Effects of light quality and CO<sub>2</sub> concentration on diurnal photosynthetic characteristics of strawberry. *Acta Hort.* 2012;956(956):247–53. [[CrossRef](#)].
72. Wei H, Liu C, Hu J, Jeong BR. Quality of supplementary morning lighting (SML) during propagation period affects physiology, stomatal characteristics, and growth of strawberry plants. *Plants.* 2020;9(5):638. [[CrossRef](#)].
73. Xu F, Cao S, Shi L, Chen W, Su X, Yang Z. Blue light irradiation affects anthocyanin content and enzyme activities involved in postharvest strawberry fruit. *J Agric Food Chem.* 2014;62(20):4778–83. [[CrossRef](#)].
74. Zhu X, Trouth F, Yang T. Preharvest UV-B treatment improves strawberry quality and extends shelf life. *Horticulturae.* 2023;9(2):211. [[CrossRef](#)].
75. Zhang Y, Jiang L, Li Y, Chen Q, Ye Y, Zhang Y, et al. Effect of red and blue light on anthocyanin accumulation and differential gene expression in strawberry (*Fragaria × ananassa*). *Molecules.* 2018;23(4):820. [[CrossRef](#)].
76. Miao L, Zhang Y, Yang X, Xiao J, Zhang H, Zhang Z, et al. Colored light-quality selective plastic films affect anthocyanin content, enzyme activities, and the expression of flavonoid genes in strawberry (*Fragaria × ananassa*) fruit. *Food Chem.* 2016;207:93–100. [[CrossRef](#)].
77. Nadalini S, Zucchi P, Andreotti C. Effects of blue and red LED lights on soilless cultivated strawberry growth performances and fruit quality. *Eur J Hort. Sci.* 2017;82(1):12–20. [[CrossRef](#)].
78. Avendaño-Abarca VH, Alvarado-Camarillo D, Valdez-Aguilar LA, Sánchez-Ortiz EA, González-Fuentes JA, Cartmill AD. Response of strawberry to the substitution of blue light by green light in an indoor vertical farming system. *Agronomy.* 2023;13(1):99. [[CrossRef](#)].

79. Lee H, Park SW, Pham MD, Hwang H, Chun C. Effect of the light spectrum of white LEDs on the productivity of strawberry transplants in a plant factory with artificial lighting. *Hortic Environ Biotechnol.* 2020;61(6):971–9. [[CrossRef](#)].
80. Chen J, Ji F, Gao R, He D. Reducing red light proportion in full-spectrum LEDs enhances runner plant propagation by promoting the growth and development of mother plants in strawberry. *Front Plant Sci.* 2024;15:1465004. [[CrossRef](#)].
81. Ries J, Park Y. Far-red light in sole-source lighting can enhance the growth and fruit production of indoor strawberries. *HortScience.* 2024;59(6):799–805. [[CrossRef](#)].
82. Black BL, Swartz HJ, Deitzer GF, Butler B, Chandler CK. The effects of conditioning strawberry plug plants under altered red/far-red light environments. *HortScience.* 2005;40(5):1263–7. [[CrossRef](#)].
83. Takeda F, Glenn DM, Stutte GW. Red light affects flowering under long days in a short-day strawberry cultivar. *HortScience.* 2008;43(7):2245–7. [[CrossRef](#)].
84. Zahedi SM, Sarikhani H. Effect of far-red light, temperature, and plant age on morphological changes and induction of flowering of a ‘June-bearing’ strawberry. *Hortic Environ Biotechnol.* 2016;57(4):340–7. [[CrossRef](#)].
85. Smith BJ, Rezazadeh A, Stafne ET, Sakhanokho HF. Effect of light-emitting diodes, ultraviolet-B, and fluorescent supplemental greenhouse lights on strawberry plant growth and response to infection by the anthracnose pathogen *Colletotrichum gloeosporioides*. *HortScience.* 2022;57(8):856–63. [[CrossRef](#)].
86. Forges M, Vàsquez H, Charles F, Sari DC, Urban L, Lizzi Y, et al. Impact of UV-C radiation on the sensitivity of three strawberry plant cultivars (*Fragaria* × *ananassa*) against *Botrytis cinerea*. *Sci Hortic.* 2018;240:603–13. [[CrossRef](#)].
87. Darras AI, Demopoulos V, Bali I, Tiniakou C. Photomorphogenic reactions in geranium (*Pelargonium* × *hortotum*) plants stimulated by brief exposures of ultraviolet-C irradiation. *Plant Growth Regul.* 2012;68(3):343–50. [[CrossRef](#)].
88. Kim SK, Bae RN, Chun C. Changes in bioactive compounds contents of ‘Maehyang’ and ‘Seolhyang’ strawberry fruits by UV light illumination. *Hortic Sci Technol.* 2011;29(3):172–80.
89. Luo TQ, Zhao WZ, Zhang YZ, Xu SR, Xiao W, Li L. Effect of strong light on chlorophyll degradation in strawberry leaves. *Russ J Plant Physiol.* 2023;69(7):163. [[CrossRef](#)].
90. Pérez-Romero LF, Stirling PJ, Hancock RD. Light-Emitting Diodes improve yield, quality and inhibitory effects on digestive enzymes of strawberry. *Sci Hortic.* 2024;332:113192. [[CrossRef](#)].
91. Verma P, Singh G, Singh SK, Ahmad Mirza A, Bakshi M, Anmol, et al. Modulating productivity of strawberries (*Fragaria* × *ananassa* Duch.) through artificial full-spectrum light in indoor vertical farming. *J Soil Sci Plant Nutr.* 2025;25(1):1219–33. [[CrossRef](#)].
92. Nakayama M, Nakazawa Y. Effects of environmental control and LED supplemental lighting on strawberry growth and yield in a subtropical climate. *Sci Hortic.* 2023;321:112349. [[CrossRef](#)].
93. Tsuruyama J, Shibuya T. Effects of far-red light and photoperiod during early growth stages on flower bud development of seed-propagated strawberry seedlings. *Sci Hortic.* 2023;317:112051. [[CrossRef](#)].
94. Wang R, Eguchi M, Gui Y, Iwasaki Y. Evaluating the effect of light intensity on flower development uniformity in strawberry (*Fragaria* × *ananassa*) under early induction conditions in forcing culture. *HortScience.* 2020;55(5):670–5. [[CrossRef](#)].
95. Iatrou M, Papadopoulos A. Influence of nitrogen nutrition on nitrate levels of strawberry leaf blades and petioles. *J Plant Nutr.* 2016;39(8):1131–6. [[CrossRef](#)].
96. Wang J, He Q, Cao K, Zhou B, Niu X, Wang D, et al. Micro-nano bubble water with potassium fertigation improves strawberry yield and quality by changing soil bacterial community. *Rhizosphere.* 2023;28:100783. [[CrossRef](#)].
97. Zhang Z, Yu S, Zhang Z, Zhang J, Li H. Comparative characterization of fruit volatiles and volatile-related genes expression of ‘benihoppe’ strawberry and its somaclonal mutant. *Plants.* 2023;12(5):1109. [[CrossRef](#)].
98. Liu L, Xiao W, Ji ML, Yang C, Li L, Gao DS, et al. Effects of molybdenum on nutrition, quality, and flavour compounds of strawberry (*Fragaria* × *ananassa* Duch. cv. Akihime) fruit. *J Integr Agric.* 2017;16(7):1502–12. [[CrossRef](#)].
99. Yang L, Niu Y, Zheng C, Fan R, Xiao W, Li L. Study on the fruit development and cell wall metabolism of high-hardness strawberry ‘Dongyang Hong 5’. *J Berry Res.* 2026;16(1):79–85. [[CrossRef](#)].

100. McKee GJ. Coordinated pest management decisions in the presence of management externalities: The case of greenhouse whitefly in California-grown strawberries. *Agric Syst.* 2011;104(1):94–103. [[CrossRef](#)].
101. Dara SK, Dara SR, Dara SS. Endophytic colonization and pest management potential of *Beauveria bassiana* in strawberries. *J Berry Res.* 2013;3(4):203–11. [[CrossRef](#)].
102. Carlile WR, Cattivello C, Zaccheo P. Organic growing media: Constituents and properties. *Vadose Zone J.* 2015;14(6):1–13. [[CrossRef](#)].
103. López-Medina J, Peralbo A, Flores F. Closed soilless growing system: A sustainable solution for strawberry crop in Huelva (Spain). *Acta Hortic.* 2004;649:213–6. [[CrossRef](#)].
104. Wortman SE, Douglass MS, Kindhart JD. Cultivar, growing media, and nutrient source influence strawberry yield in a vertical, hydroponic, high tunnel system. *HortTechnology.* 2016;26(4):466–73. [[CrossRef](#)].
105. Wang D, Gabriel MZ, Legard D, Sjulín T. Characteristics of growing media mixes and application for open-field production of strawberry (*Fragaria ananassa*). *Sci Hortic.* 2016;198:294–303. [[CrossRef](#)].
106. Zhang X. Screening of nutrient solution formulas for hydroponic cultivation of strawberries and optimization by orthogonal experiment [master's thesis]. Hefei, China: Anhui Agricultural University; 2020. (In Chinese). [[CrossRef](#)].
107. Guan Q. Establishment of strawberry tissue culture system and research on factors affecting hydroponic growth [master's thesis]. Yanji, China: Yanbian University; 2020. (In Chinese). [[CrossRef](#)].
108. Asaduzzaman M, Kobayashi Y, Mondal MF, Ban T, Matsubara H, Adachi F, et al. Growing carrots hydroponically using perlite substrates. *Sci Hortic.* 2013;159:113–21. [[CrossRef](#)].
109. Sandhu RK, Boyd NS, Sharpe S, Guan Z, Qiu Q, Luo T, et al. Management of relay-cropped strawberry and eggplant to maximize yield and economic return. *HortScience.* 2020;55(7):1083–9. [[CrossRef](#)].
110. Torres-Quezada EA, Zotarelli L, Whitaker VM, Darnell RL, Morgan K, Santos BM. Production techniques for strawberry plugs in west-central Florida. *HortTechnology.* 2020;30(2):238–47. [[CrossRef](#)].
111. Bottoms TG, Hartz TK, Cahn MD, Farrara BF. Crop and soil nitrogen dynamics in annual strawberry production in California. *HortScience.* 2013;48(8):1034–9. [[CrossRef](#)].
112. Wang B, Lai T, Huang QW, Yang XM, Shen QR. Effect of N fertilizers on root growth and endogenous hormones in strawberry. *Pedosphere.* 2009;19(1):86–95. [[CrossRef](#)].
113. Kilic N, Burgut A, Ali Gündesli M, Nogay G, Ercisli S, Kafkas NE, et al. The effect of organic, inorganic fertilizers and their combinations on fruit quality parameters in strawberry. *Horticulturae.* 2021;7(10):354. [[CrossRef](#)].
114. Li Q, Zhang D, Song Z, Ren L, Jin X, Fang W, et al. Organic fertilizer activates soil beneficial microorganisms to promote strawberry growth and soil health after fumigation. *Environ Pollut.* 2022;295:118653. [[CrossRef](#)].
115. Zheng Z, He Y, He Y, Zhan J, Shi C, Xu Y, et al. Micro-nano bubble water subsurface drip irrigation affects strawberry yield and quality by modulation of microbial communities. *Agric Water Manag.* 2025;307:109228. [[CrossRef](#)].
116. Udekwe D, Seyyedhasani H. Virtual Reality-Enabled remote Human-Robot interaction for strawberry cultivation in greenhouses. *Comput Electron Agric.* 2025;237:110567. [[CrossRef](#)].
117. Huang Z, Wu Z, Luo Z, Gong H, Li W, Jin P, et al. Development of temperature-sensitive and controlled-release PLA-based film for strawberry preservation. *Food Packag Shelf Life.* 2025;50:101561. [[CrossRef](#)].
118. Khammayom N, Maruyama N, Chaichana C, Hirota M. Impact of environmental factors on energy balance of greenhouse for strawberry cultivation. *Case Stud Therm Eng.* 2022;33:101945. [[CrossRef](#)].
119. Blanch M, Alvarez I, Sanchez-Ballesta MT, Escribano MI, Merodio C. Increasing catechin and procyanidin accumulation in high-CO<sub>2</sub>-treated *Fragaria vesca* strawberries. *J Agric Food Chem.* 2012;60(30):7489–96. [[CrossRef](#)].
120. Li D, Zhang X, Li L, Aghdam MS, Wei X, Liu J, et al. Elevated CO<sub>2</sub> delayed the chlorophyll degradation and anthocyanin accumulation in postharvest strawberry fruit. *Food Chem.* 2019;285:163–70. [[CrossRef](#)].
121. MacInnis G, Forrest JRK. Pollination by wild bees yields larger strawberries than pollination by honey bees. *J Appl Ecol.* 2019;56(4):824–32. [[CrossRef](#)].
122. Jaboor SK, da Silva CRB, Kellermann V. The effect of environmental temperature on bee activity at strawberry farms. *Austral Ecol.* 2022;47(7):1470–9. [[CrossRef](#)].

123. Teixeira MA, Martins RMS, Vieira RF, Aguilar Vildoso CI, Adami AAV, Ferreira AC. *In vitro* identification and control of *Pestalotiopsis longisetula* fungus, pathogens strawberry crop. Rev Agrogeoambiental. 2015;7(3):61–7. [[CrossRef](#)].
124. Mazzola M, Agostini A, Cohen MF. Incorporation of *Brassica seed meal* soil amendment and wheat cultivation for control of *Macrophomina phaseolina* in strawberry. Eur J Plant Pathol. 2017;149(1):57–71. [[CrossRef](#)].
125. Shilomboleni H, De Plaen R. Scaling up research-for-development innovations in food and agricultural systems. Dev Pract. 2019;29(6):723–34. [[CrossRef](#)].
126. Lin YB, Liu CY, Chen WL, Chang CH, Ng FL, Yang K, et al. IoT-based strawberry disease detection with wall-mounted monitoring cameras. IEEE Internet Things J. 2024;11(1):1439–51. [[CrossRef](#)].
127. Cruz M, Mafra S, Teixeira E, Figueiredo F. Smart strawberry farming using edge computing and IoT. Sensors. 2022;22(15):5866. [[CrossRef](#)].
128. Chen Y, Lee WS, Gan H, Peres N, Fraisse C, Zhang Y, et al. Strawberry yield prediction based on a deep neural network using high-resolution aerial orthoimages. Remote Sens. 2019;11(13):1584. [[CrossRef](#)].
129. Zhou X, Lee WS, Ampatzidis Y, Chen Y, Peres N, Fraisse C. Strawberry maturity classification from UAV and near-ground imaging using deep learning. Smart Agric Technol. 2021;1:100001. [[CrossRef](#)].