



Strawberry (*Fragaria × ananassa*) cultivation in India: A critical review of status, constraints and future directions

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Abstract

Strawberry (*Fragaria × ananassa* Duch.) is an economically important berry crop worldwide, due to its distinctive flavour, nutritional value and health benefits. In recent years, it has been cultivated not only in temperate regions, but also in subtropical and tropical regions. It has become one of the high-value horticultural crops in India, due to the growing consumer demand and good returns to farmers. This review critically examines the trends in yield, constraints and technological factors influencing strawberry cultivation across major strawberry producing states such as Maharashtra, Himachal Pradesh, Uttarakhand, Jammu and Kashmir and other emerging regions in India. Evidence from existing studies indicates that the adoption of improved cultivation practices such as balanced fertilisation, integrated pest management, mulching, protected cultivation and soilless systems has substantially improved fruit yield and quality compared to conventional open-field methods. Despite these advancements, productivity remains limited by climatic sensitivity, pest and disease factors, soil and nutrient management constraints and postharvest losses due to the highly perishable nature of the fruit. Moreover, disparities in technology adoption and the lack of cold-chain infrastructure continue to constrain sectoral growth. Emerging technologies such as precision agriculture and decision-support systems offer considerable potential to improve resource-use efficiency and sustainable production. The review discusses the status of strawberry production in India and its integration with production trends, challenges and future research in the field. It also points out gaps in the current knowledge and limited production systems and also outlines the future technological interventions needed to enhance the productivity, profitability and sustainability of strawberry production under Indian conditions.

Keywords: cold-chain infrastructure; postharvest management; production constraints; strawberry (*Fragaria × ananassa*); technological advances; yield trends

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1. Introduction

Strawberry (*Fragaria × ananassa* Duch.) belongs to the family of 'Rosaceae' and is an herbaceous octaploid ($2n = 8x = 56$) perennial plant. It originated from the interspecific hybridisation of two wild forms, *Fragaria virginiana* Duchesne and *Fragaria chiloensis* (L.) Mill. and is a crop of North American origin, valued for its aroma and flavour (1, 2). The plants are low-growing perennials with evergreen trifoliate leaves and bear entomophilous white actinomorphic flowers (3). Plants behave as perennial herbs in temperate climates, while they act like annuals in subtropical climates (4). Botanically, the fruit is an aggregate type, containing seeds or achenes embedded on the surface of a fleshy receptacle of red colour (5). It is a non-climacteric fruit that takes 28–30 days after anthesis to reach the full red colour (6). The fruits are vibrant red in colour and are

considered a rich source of vitamin C and antioxidants, such as ellagic acid, ellagitannins and pelargonidin-3-glucoside (7). A fully ripened strawberry fruit contains 90 % water and 10 % total soluble solids. The fresh fruits serve as a good source of potassium (K) (153 mg), vitamin C (58.8 mg), vitamin A (1 µg), niacin (0.386 mg), riboflavin (0.022 mg) and thiamine (0.024 mg) per 100 g (8). The fruits are also considered a good source of folate, which is involved in growth and development of cells in the human body, especially during pregnancy (9). The other health advantages include improvements in glucose metabolism, dyslipidaemia, total plasma antioxidant capacity, lipid peroxidation and low-density lipoprotein (LDL) oxidation (3). These functional and nutraceutical properties of strawberries have increased research interest in enhancing their yield and availability throughout the year in agro-climatic locations. In this regard, this review provides a comprehensive analysis

of the current status, production constraints and future prospects of strawberry production with particular emphasis on technological advancements and sustainable production strategies.

Global overview of strawberry production

The global strawberry production is estimated to be approximately 10.73 million tonnes with a total harvested area of approximately 436067 ha (10). The major producers are China, the USA, Mexico, Turkey and Spain, which consistently rank highest and together account for a large share (>70 %) of total production (11–14) (Table 1). The world market for strawberries is estimated to be USD 15.88 billion in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 4.1 % to reach USD 18.66 billion by 2033 (15, 16).

Table 1. Comparison of strawberry productivity in major producing countries, 2024 (10)

Country	Production (million tonnes)	Area (ha)	Yield (kg/ha)
China	4.1234	153651	26836.2
USA	1.4661	24767	59192.1
Mexico	0.6961	15858	43895.6
Spain	0.3235	7000	46220
Turkey	0.6063	19651	30851.1
India	0.0211	3031	6961.6

China is the leading producer with an estimated production of 4.12×10^6 tonnes. In comparison, India's production is relatively modest at approximately 21100.56 tonnes, indicating that the country contributes a small share to global production. The annual values exhibiting considerable year-to-year fluctuations likely reflect differences in climatic conditions, cultivation area, production practices and market dynamics, indicating that production has been variable rather than uniformly increasing in India (10) (Fig. 1). Thus, the country's modest share in global production not only shows existing constraints but also underscores a significant scope for expansion and competitiveness in the global strawberry sector.

Current status of strawberry cultivation in India

The cultivated strawberry was first introduced in India at the Indian Council of Agricultural Research-National Bureau of Plant Genetic Resources (ICAR-NBPGR) regional station in Shimla, Himachal Pradesh, in the early 1960s (17). Since then, its cultivation has gradually expanded across different agro-climatic regions. At present, strawberry is predominantly grown in states of Maharashtra, Himachal Pradesh, Jammu and Kashmir (J&K), Uttar Pradesh (UP), West Bengal, Punjab, Haryana, Rajasthan and the Nilgiri hills of Tamil Nadu. Among these, the Panchgani-Mahabaleshwar belt of Maharashtra leads in the country's total production (5).

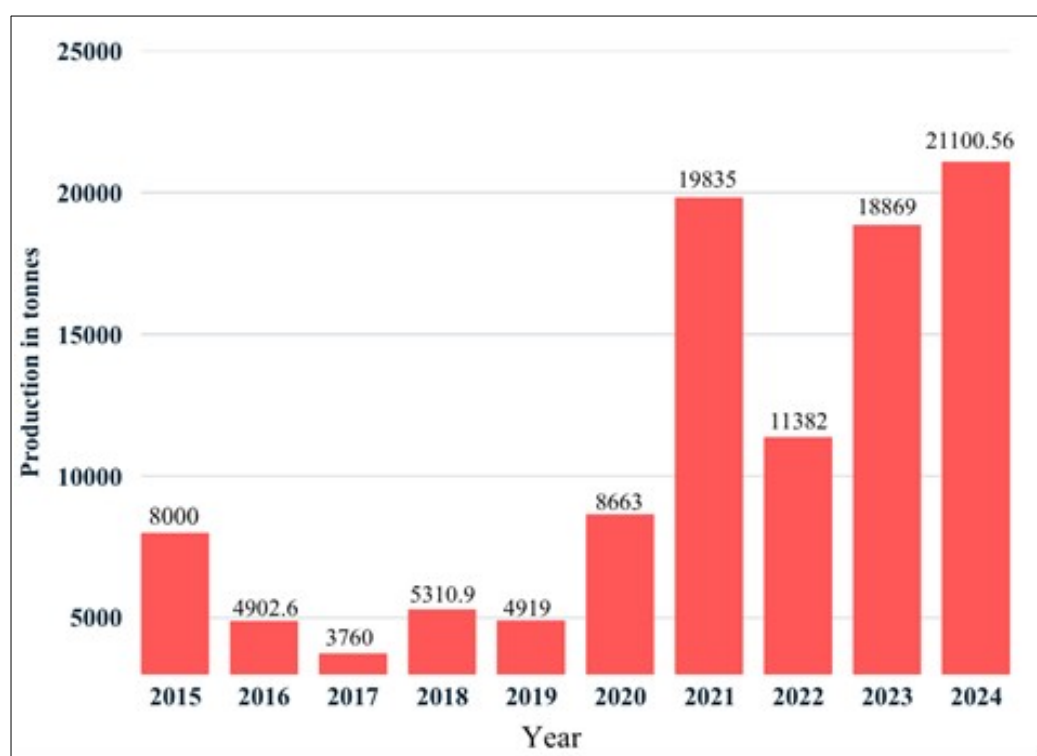


Fig. 1. Production trends of strawberry in India.

In addition to the traditional temperate regions, Srinagar (J&K) and the hills of Darjeeling, strawberry cultivation has also extended to sub-tropical and tropical regions, including Gurgaon (Haryana), Meerut, Muzaffarnagar and Saharanpur (UP), Pune and Mahabaleshwar (Maharashtra), Jalandhar and Gurdaspur (Punjab) and Bangalore (Karnataka) (18). Despite the growing demand, cultivation in South India remains relatively limited (19). In India, the total harvested area under strawberry cultivation is about 3031 ha and the country exported approximately 48.04 tonnes of fresh strawberries in 2024, according to Food and Agriculture Organization of the United Nations (FAO) statistics (10). Depending on the variety, temperature and location, strawberries may be planted at any time of the year. In northern India, planting typically occurs during the second week of October (20), whereas in sub-tropical and tropical areas, cultivation is successfully undertaken during the winter months (21). However, the overall cultivated area in tropical and sub-tropical zones remains very low and the price of the fruit is still very high (22).

Two classes of strawberries are currently grown commercially in India, namely day-neutral and short-day plants, depending on how each variety reacts to photoperiod (Table 2). Commercial cultivation utilises cultivars such as Tioga, Camarosa, Sweet Charlie, Winter Dawn, Chandler and other varieties including Sensation, Brilliance and Nabila (34). Among these, Chandler remains the most widely used cultivar in the plains of northern India, due to its excellent fruit colour, superior flavour and high dessert grade. It is appropriate for fresh marketing and processing, exhibits resistance to infections and rain-induced physical damage. Camarosa has recently emerged as a promising strawberry variety, due to its larger and firmer fruits, while 'Winter Dawn', introduced from Florida, is valued for its early maturity and high-yielding potential (35). A wild species, *Fragaria nubicola* Lindl. (commonly known as the Himalayan strawberry), is a perennial herb found growing naturally at altitudes between 2100 and 4000 m above sea level in shaded spots along forest borders. This species is distributed across regions from Afghanistan to India (3). Conventional breeding in strawberries faced

difficulties due to the complicated octaploid genome; however, this has now been overcome by advances in recombinant DNA technology. The successful genetic transformation of strawberries through *Agrobacterium tumefaciens* has been a major breakthrough. Since then, it continues to be the most preferred method, although several direct-gene transfer techniques have also been documented (36).

Mulching is also considered an important management practice in strawberry cultivation. Various mulching materials used include black polyethylene, transparent plastic, coloured plastics, hay, paddy straw, wheat straw and pine needles (20). The application of black polyethylene mulch significantly enhanced fruit yield (19.45 q/ha) compared to the control (6.70 q/ha), representing an increase of approximately 190 %, likely due to improved soil moisture retention and weed suppression (37). Techniques like glasshouses, polyethylene bags, low tunnels, soilless media, raised beds, cement pots, flat beds and ridges are used worldwide to cultivate strawberries. High and low tunnels are favoured in Asia and the Mediterranean region because they can prolong the harvest season and improve fruit quality (38).

A high degree of variation was observed in the performance of cultivars in different agro-climatic zones (Table 3). In sub-tropical humid zones, the highest yield was recorded for 'Winter Dawn' and in sub-tropical hills for 'Nabila'. In temperate zones, 'Chandler' recorded a good yield (996.3 g/plant), suggesting its suitability in cold-hardy regions. By contrast, other cultivars, like 'Camarosa', showed inconsistent performance in sub-tropical plains, with relatively lower yields in some areas. In tropical regions, the performance of 'Nabila' was moderate, indicating broader adaptability. These findings suggest that the performance of cultivars is site-specific and sensitive to agro-climatic zones.

Economic and market opportunities

Strawberries are in demand, both locally and globally, due to their nutritional value and palatability. Strawberry cultivation has a number of significant advantages, one of which is that it yields higher and earlier economic returns per unit area than many conventional fruit crops

Table 2. Classification of strawberry cultivars based on photoperiodic responses, traits and cultivation relevance

Type of cultivar	Key traits	Common examples	Suitability	Reference
Short day (June bearing)	Flower when days are short and temperatures cool; usually give one main crop per year. (winter–spring in Indian plains). Dominant type in India	Chandler (most widely grown), Camarosa, Festival, Sweet Charlie, Winter Dawn, Nabila, Sabrina, Fortuna, Tudla, Sweet Sensation, Capri, Winter Star	Open field, Winter cultivation	(6, 23–29)
Day neutral	Less sensitive to daylength; can fruit over a longer period if temperatures are suitable; useful for extended seasons and protected cultivation.	Albion, San Andreas, Monterey, Portola	Protected cultivation, hydroponics	(30–33)
Recurrent/ everbearing	Multiple flushes of flowers and fruits; behaviour controlled by interaction of photoperiod and temperature, especially under Indian subtropical conditions. Often overlap with day neutral group in practice.	Tristar	Vertical farming, Off-season production	(32, 33)



Table 3. A zone wise synthesis of cultivar performance across different agro-climatic regions of India

Agro-climatic zone	States	Top cultivars	Yield (g/plant)	Reference
Temperate	Himachal Pradesh	Chandler	996.3	(18)
Sub-tropical (Humid)	West Bengal	Winter Dawn	1305.7	(39)
Sub-tropical (Hill)	TamilNadu-Upper Pulney hills	Nabila	1290	(19)
Sub-tropical (Hill)	Mahabaleshwar	Winter Dawn	820	(40)
Sub-tropical	Uttar Pradesh	Chandler	591.17	(41)
Sub-tropical	Maharashtra	Sweet Sensation	440	(26)
Sub-tropical	Ludhiana	Camarosa	262.4	(42)
Sub-tropical	Punjab	Camarosa	710	(43)
Sub-tropical (High-rainfall)	Meghalaya	Camarosa	248.2	(44)
Sub-tropical	Punjab	Winter Dawn	238.5	(45)
Tropical	Chhattisgarh	Nabila	655.06	(6)
Tropical (sub-humid)	Chhattisgarh	Nabila	420	(46)

(47). According to the FAO most recent report for the year 2024, the worldwide strawberry market is continuously expanding, reflecting increasing consumer demand and trade potential (48).

Studies carried out on the national level in the Indian context reveal that processed fruit exports are expanding vigorously, particularly in products such as jams, jellies, marmalades and dried fruits, with a compound annual growth rate (CAGR) ranging between 12 % and 17 %. This category contains canned berries, indicating that there is a great potential for strawberry-based products from India (49).

The Hisar and Bhiwani districts of Haryana have become major centres of strawberry production in Northern India, emerging as the second-largest producing region of exotic fruit after Mahabaleshwar in Maharashtra. Due to their proximity to major markets in Delhi, rapid financial returns and high nutritional value, strawberry cultivation has expanded in this region (50).

Strawberries also have great potential in processing and value addition. Processing technologies are used to increase their shelf life, reduce postharvest losses and increase the variety of value-added products in the form of powders, jams, purees and freeze-dried foods. Despite its growth, the Indian strawberry industry continues to face several challenges such as limited cold storage facilities, poor supply chain management and a lack of awareness among farmers regarding advanced processing techniques. However, the increasing demand for processed and functional foods in India provides significant opportunities for investment in strawberry processing industries. Additionally, new processing techniques, such as freeze-drying and high-pressure processing (HPP), have created new marketing opportunities through the creation of strawberry-based functional foods and nutraceuticals (51). In general, the growing domestic demand, increasing export possibilities and technological improvements in processing technologies make the strawberry industry a high-value and economically promising part of India's horticultural industry.

Challenges

Climatic constraints

Climate change is emerging as a major challenge to strawberry cultivation in India. Rising temperatures, erratic rainfall, prolonged dry spells and the increasing frequency of extreme weather events are expected to adversely affect overall productivity. Strawberries need to be planted at a particular time to partition assimilates, which exerts a direct effect on fruit growth and yield (52). A study from Kerala reported significant variation in yield based on planting date, where planting on 30 September resulted in the highest yield (190 kg/ha) compared to 30 October (160 kg/ha) and 1 September (85 kg/ha), indicating that delayed or early planting can reduce productivity, which varies across regions (53). Under diverse agro-climatic conditions, genes determining plant height exhibit variable expression levels across locations (6). This indicates that there is a high genotype-environment interaction that influences strawberry performance.

Temperature: The availability of day and night-time temperature greatly influences the fruit composition (4). The optimum temperature needed to grow strawberries ranges from 22–24 °C during the day and 7–13 °C at night (54). Below 7 °C, the temperature may negatively influence the colour and size of the fruit, while higher temperature affects the soluble sugar content (55). For strawberry cultivation, temperatures up to 30 °C are generally tolerated. Exposure to temperatures exceeding 35 °C impairs quality and reproductive development, significantly reducing growth and yield. Increased temperatures can disturb cellular homeostasis by overloading antioxidant defence and induce oxidative damage to the cells as a result of the build-up of toxic reactive oxygen species (ROS). Microscopic analyses also indicate that there was a decrease in leaf thickness, palisade mesophyll cell layers and epidermal cell size caused by extreme heat, leading to a reduction in the photosynthetic area (56).

Assimilate allocation and the duration of plant development are also affected by temperature. Elevated temperatures induce plants to allocate more energy toward vegetative growth, thereby decreasing fruit yield. The final fruit weight is highly related to floral development time. As the interval of anthesis-fruiting time is prolonged, the fresh weight of the strawberries increases; day-night temperature affects this process. This phase is prolonged under cooler conditions, resulting in higher yields. This indicates a negative correlation between temperature and yield in nonoptimal thermal conditions (53). The number of malformed berries also increases as a result of hot and dry weather (57). Thus, the plants are drought sensitive. Moreover, the flowering among varieties can be different because of their chilling requirements (6). Research reported that exposure to low temperature and low illumination (6 °C and 100 units of light intensity) significantly reduced the chlorophyll content, with chlorophyll a decreasing to 2.96 mg/g (approximately 8.1 % lower than natural light) and chlorophyll b declining to 0.84 mg/g (approximately 25.7 % lower than natural light conditions) (58). Therefore, sustaining favourable temperature regimes and the use of temperature-resilient cultivars are critical in maintaining yield and quality of fruit in strawberry farming.

Relative humidity: Strawberry crops are usually favoured by a higher relative humidity, so they produce higher yields, larger fruit size and enhanced photosynthesis and leaf development. However, it frequently amplifies the chances of illness, resulting in fruit malformation. Prolonged exposure to excessive humidity may induce physiological disorders like tip burn, which adversely affect fruit yield (53). The occurrence of diseases could also increase as a result of mild weather and excessive rainfall (57).

Light: Flowering is greatly influenced by photo period and light quality in strawberries. They are classified into short-day, long-day and day-neutral types based on their photoperiodic flowering behaviour and fruiting pattern. For the induction of flower buds, a minimum of 7–24 photoinductive cycles is needed, depending on cultivar and environmental conditions (59). Reduced light exposure along with high temperatures during the developmental stage alters the carbon balance, which leads to smaller fruits and lower yields (53). Seasonal flowering cultivars produce only a single flush of flowers and require exposure to short days for flower initiation. In contrast, long-day conditions promote vegetative development but prevent blossom initiation (60).

Soil and nutrient management constraints

Strawberries grow in sandy loam to loamy soils with a pH range of 5.7–6.5 (55). They require specialised feeding and management techniques due to their shallow root system, with the majority of the plant's roots (primary and secondary roots), being confined within the top six inches of soil (61). This characteristic makes the crop highly sensitive to nutrient deficiencies as well as moisture stress. Additionally, continuous monocropping

can increase the crop's vulnerability to soil-borne pathogens like *Fusarium oxysporum* f. sp. *fragariae*, *Phytophthora cactorum*, *Colletotrichum* spp. and *Pythium* spp. (54).

Planting material and propagation constraints

Strawberries can be grown across a wide range of agroclimatic conditions and there is significant diversity in how different strawberry cultivars respond to specific environments. Therefore, choosing an appropriate cultivar is crucial for successful production (35). One of the major limiting factors in commercial strawberry farming is the lack of quality and healthy planting material, which occurs primarily due to soil-borne diseases, nematodes and unfavourable soil conditions, which hinder the development of elite planting stock. In strawberry cultivation, soil-borne infections are frequently linked to significant yield losses (23). The propagation of nursery vegetative plants is increasingly challenged by soil-borne pathogens such as *Colletotrichum* spp., *Phytophthora fragariae* and *Neopestalotiopsis* spp., which adversely affect plant health and establishment (62).

Pest and disease problems

A temperature around 25 °C is highly favourable in promoting mycelial growth, whereas temperatures below 15 °C do not support the pathogen's growth (63). Fungal pathogens like *Botrytis cinerea*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Colletotrichum* spp., *Verticillium dahliae*, viruses like strawberry mottle virus (SMoV), *Fragaria chiloensis* cryptic virus (FCICV), strawberry necrotic shock virus (SNSV) and strawberry mild yellow edge virus (SMYEV) and others pose serious threats to strawberry production. Among the diseases, grey mould caused by *Botrytis cinerea* is considered one of the most economically important because it results in substantial losses during flowering, fruit development and post-harvest storage. A bacterial infection caused by *Xanthomonas fragariae*, which spreads through stolons, further complicates cultivation and disease management (64). Soil fumigants, such as 1,3-dichloropropene, dazomet, metam sodium and chloropicrin, are often necessary in the control of soil-borne diseases. However, excessive dependence on chemical control has raised concerns regarding the development of fungicide-resistant pathogen populations. Therefore, integrated disease management, biocontrol agents and judicious fungicide use are increasingly recommended for sustainable disease management. The combined application of the biocontrol strain *Chaetomium globosum* Cg-40 along with vesicular-arbuscular mycorrhiza (VAM) resulted in a substantial reduction in wilt incidence (84.94 % over control) and significantly improved plant growth, indicating a synergistic effect (65). Along with biotic stress, physiological disorders (albinism) can also exist, most likely due to unfavourable climatic conditions and extremes in nutrition (66). Furthermore, nepoviruses transmitted by nematodes are known to cause huge losses in strawberry cultivation (67).

Post-harvest and storage problems

Post-harvest management remains a significant constraint in the Indian strawberry sector due to high fruit perishability and lack of infrastructure. Strawberries possess soft tissues, high respiration rates, rapid softening and high-water loss, leading to a short marketable life of only 5–7 days with no stringent cold-chain management (68). Furthermore, the fruits are highly susceptible to mechanical damage. Care must be taken to avoid cuts that may give the fungi a portal to deteriorate (69). Post-harvest infections in strawberries are traditionally handled with the help of sanitising solutions, e.g. hydrogen peroxide, chlorine and synthetic fungicides. However, these chemical treatments pose potential environmental and human health risks (70). Major postharvest fungal pathogens are *B. cinerea*, *Penicillium* spp., *Mucor* spp., *Rhizopus stolonifer*, *Colletotrichum* spp. and others. These pathogens lead to postharvest spoilage, not only resulting in financial losses but also generating mycotoxins (e.g., those produced by *Penicillium*) that are harmful to human health if eaten (71). Among these, the fruit rot caused by grey mould (*B. cinerea*) is the most destructive and accounts for the majority of post-harvest losses in India. The incidence of rot is further increased by warm temperatures and high humidity during late-season storage and transportation. In total, post-harvest fruit rot can cause 25–40 % losses where storage and transport are inadequate (72).

Collectively, these constraints continue to limit productivity, quality and profitability in strawberry cultivation. Addressing these challenges effectively is required to ensure widespread strawberry cultivation in India.

Technological interventions improving the Indian strawberry sector

The increasing demand for strawberries in India, particularly driven by developing industries in the Punjab state and adjoining areas, has encouraged farmers to adopt both open-field and protected cultivation systems. While open-field strawberry cultivation is largely seasonal, the crop can be produced year-round under protected conditions by following specific cultivation practices (30).

The use of soilless growth material is becoming important and gaining popularity due to its ability to enhance root zone conditions and overall plant performance. The most popular media for strawberries are peat moss, cocopeat, rockwool and perlite, as they improve root zone aeration, water retention and nutrient availability, which have led to better blooming and berry set than in soil (23). Hydroponic systems are gaining more popularity, due to their efficient utilisation of space, improved disease control and accuracy in control of environmental conditions and resource distribution (16). Hydroponic systems facilitate year-round production, faster growth and produce a good harvest with minimal insect pest and disease infestation, nutrient deficiency symptoms and soil-related diseases. Among hydroponic

techniques, production through a closed system under the nutrient film technique (NFT) has shown superior performance (73). Additionally, maintaining an optimal electrical conductivity (EC) formulation of 2, 2.41 mS cm⁻¹, has been shown to increase plant height and growth under hydroponic conditions. Under semi-hydroponic conditions, using a vermiculite + vermicompost (50 : 50) medium showed a 2.04-fold increase in the fresh weight of fruits compared to soil-grown plants, indicating the superiority of soilless media in enhancing strawberry productivity (1).

Strawberry production indoors and in vertical farming systems is emerging as a means to maximise space, light, water and nutrients. In such systems, the light spectrum plays a critical role in influencing plant morphology and developmental processes in strawberries. In comparison to conventional light sources, artificial-full-spectrum light dramatically boosts the strawberry plant growth and yield. The exposure of indoor strawberry plants to artificial full spectrum light (AFSL) for 6–8 hr significantly enhanced plant growth, flowering and fruiting, resulting in yields of up to 220–240 g per plant, demonstrating the effectiveness of supplemental lighting. Besides productivity, indoor vertical strawberry production provides a sustainable solution to issues like climate change, land shortages and the necessity of resilient agricultural systems. It is also a promising source of urban agriculture (Fig. 2). Furthermore, spectral quality influences physiological responses, as studies indicate that blue and far-red light



spectra postpone flowering and promote runner formation. Red light seems to be more significant for the vegetative growth of strawberry runner plants, compared to other light spectra (74, 75).

Fig. 2. Adoption of vertical farming technology for strawberry in Mahabaleshwar, Maharashtra, India.

Effective control of irrigation further contributes to productivity enhancement. Drip irrigation combined with polythene mulch recorded a significantly higher yield (50.10 q/ha) compared to surface irrigation under unmulched conditions (40.15 q/ha), representing an increase of approximately 24.8 % (76).

The Indian strawberry sector is being transformed by these technological interventions, through improving productivity, resource-use efficiency and sustainability, thereby positioning it for future climate-resilient and high-value horticultural production. Although these technologies have considerable potential to enhance productivity, their adoption under Indian conditions should be supported through financial incentives, farmer training programmes and region-specific cost-benefit analyses to ensure long-term sustainability and wider acceptance.

Future prospects

Strawberries were once considered a temperate crop; however, with improvements in their growing practices, they can now be successfully grown across a wider range of climates, including subtropical and tropical regions (Fig. 3). At present, they are commercially farmed in several Indian states, including Maharashtra, Jammu and Kashmir, Karnataka and Madhya Pradesh (64). It is easy to grow them in nutri-gardens, rooftop gardens, pots, tiny containers, etc., due to their herbaceous annual habit and adaptability to small spaces (30). The promotion of high-value horticultural crops like strawberries may be strategically encouraged to increase the income and livelihood security of fruit-growing farmers (77). Innovative processing techniques like HPP have opened up new opportunities for industries in the development of products from strawberries. Government initiatives, including Operation Greens and the PM Formalisation of Micro Food Processing Enterprises (PMFME) scheme, along with subsidies for cold storage infrastructure, among other measures, have played a significant role in expanding India's food processing sector. In addition,

there is an increase in demand for frozen strawberries both domestically and in export markets (51). Organic cultivation is receiving increasing attention in India owing to growing consumer preference for chemical-free fruits and the expanding domestic market for organic produce.

The expanding fruit industry has inspired nurseries to invest in a variety of clonally propagated plants, including fresh plants (vegetative, bare-root, or rooted tips) and frigo plants (type A-, A, waiting bed and tray plants). These planting systems, together with everbearing cultivars, have enabled off-season production, including autumn harvesting, both in soil and soilless cultivation systems (62). Additionally, the integration of cover crops can further enhance strawberry farming by boosting soil nitrogen (N) availability, lowering soil-borne pest pressure, enhancing soil physical characteristics and decreasing soil erosion (69).

Advances in propagation techniques

Conventionally, runners are used as the propagating material for strawberries, which remain the primary planting material in commercial cultivation (50). Although strawberries can be multiplied both asexually via runner plants and sexually by seeds, asexual propagation is usually preferred due to low rates of seed germination and high heterozygosity, which leads to genetic segregation in seed-propagated progeny. Thus, to maintain clonal purity and needed maternal qualities, commercial production relies on the propagation of runners and the number of runners can vary according to cultivar (74). It also helps in the transmission of viral infections, especially in cases where the parent material has been affected (50). A study reported that the growth and yield characteristics of runners treated with 30 Gy of ^{60}Co were significantly improved by about 15 % (plant height) and 10.5 % (fruit number) over the control, showing the beneficial effect of irradiation (78).



Fig. 3. Strawberry cultivation in tropical region under shade-net conditions at Horticultural College and Research Institute, Periyakulam, Tamil Nadu, India.

To avoid most of the diseases that can be transmitted by plants and soil, the introduction of micropropagated strawberry plants has been undertaken (79). Micropropagation through tissue culture offers a rapid and efficient multiplication system, where proper sterilisation is essential to avoid microbial contamination and ensure plant survival. Among the sterilisation treatments evaluated, 0.1 % sodium hypochlorite (NaOCl) for 4 min recorded the highest percentage establishment (73.3 %) of contamination-free explants, whereas shorter exposure durations were less effective in controlling contamination. During acclimatisation, the choice of hardening media significantly influences plant survival. Pure cocopeat recorded the highest survival rate (70 %), whereas cocopeat-vermiculite mixtures (1 : 1 and 2 : 1) resulted in survival rates of 60 % (64). Tissue culture has proven effective for producing disease-free planting material, but its commercial scalability is constrained by higher production costs and the need for efficient acclimatisation protocols. Emerging approaches involving nanotechnology, like silver nanoparticles for reduced disease and pathogen infestation and silicon nanoparticles for the improved development and biomass of strawberry roots, have also shown promising results (80). Half-strength Murashige and Skoog (MS) medium with indole-3-acetic acid (IAA) at 1.5 mg/L gave the highest rooting percentage and best rooting results, while successful hardening is supported by substrates like pure coco peat or simpler combinations (64). Additionally, perlite has proven effective in producing virus-free plants by limiting nematode transmission (67). Although advancements have been made in propagation techniques, limited research exists on large-scale standardisation, cost-effectiveness and field-level validation of micropropagation under diverse agro-climatic conditions.

Improved cultivation practices

Nutrient management

Integrated nutrient management (INM) practices promote plant growth through enhanced organic carbon, improved nitrogen, phosphorus and potassium (NPK) levels, microbial biomass and dehydrogenase activity. As a foliar pre-harvest spray, chitosan and calcium chloride play a dynamic role in reducing the percentage of spoilage in strawberries. The combined application of chitosan (6 g/L) and CaCl_2 (1.00 %) was found to be the most effective treatment, as it improved biochemical attributes and extended storage life up to seven days, whereas control fruits showed complete spoilage by the 4th day (81). In addition, studies indicate that the biostimulant *Ascophyllum nodosum* extracts have demonstrated a remarkable potential in improving plant growth, yield and drought resistance in strawberries (16). Hence, promoting INM, biostimulant-based approaches, sensor-based fertigation and nano-enabled nutrient delivery systems should be prioritised as a key future strategy for sustainable strawberry cultivation.

Plant growth regulators

Biofertilisers are directly involved in N fixation and P mobilisation, thereby improving nutrient availability. In terms of strawberry vegetative development, gibberellic acid (GA_3) was shown to be the most effective. It is involved in increasing the endogenous level of auxins, thus increasing plant growth. Applying GA_3 to one-year-old strawberry plants reduces flowering, encourages runner development and vegetative growth (77). Nano zinc (Zn) particles have been shown to markedly enhance strawberry performance by promoting vegetative growth, flowering and facilitating greater nutrient acquisition (54). The application of cycocel (CCC) induces early flowering, enhances fruit bud growth and increases the number of flowers per plant. Specifically, CCC at 500 ppm has been reported to increase yield, specific gravity, total sugar content, total soluble solids and the number of flowers and fruits per plant (82). Methyl jasmonic acid (MeJA) has been reported to suppress postharvest decay in strawberry fruits and suppress gray mold during storage, with an optimal concentration of 230 μM promoting the maturation of fruits (83). Despite advances, significant research gaps remain in the development of nano-formulations, controlled-release plant growth regulator (PGR) mechanisms and molecular-level mechanisms governing growth regulation in strawberries.

Deep learning and digital innovations

Internet of Things (IoT)-based systems automate irrigation and climate control, thereby reducing labour requirements and improving resource use efficiency. It has been reported that computer vision imaging techniques can be successfully used in early plant disease detection (84). Recently, plant disease detection systems have been increasingly using machine learning or deep learning models as modern solutions. Many studies suggest the use of CNNs or advanced variants (YOLO, Faster R-CNN, ViT) to detect multiple strawberry diseases (e.g., gray mold, anthracnose, powdery mildew) on leaves and fruits, achieving accuracy levels of more than 90–98 % (85, 86). In addition, digital twins of strawberry farms and greenhouses have been shown to accelerate the development of vision-based and robotic harvesting systems without the need for constant field access (87).

Post-harvest treatments

Rapid removal of field heat is critical; it has been reported that delays of even 1 hr at high field temperatures can shorten storage life by approximately 24 hr. Experimental studies have demonstrated that forced-air precooling can extend shelf life up to 15 days at 4 °C compared with other precooling methods (Table 4). The underlying physiological responses to temperature and moisture management are broadly applicable to Indian strawberry supply chains (88). By modifying the gaseous environment surrounding the fruit, controlled atmosphere (CA) storage or modified atmosphere packaging (MAP) significantly increases the shelf life of strawberries. One of the main causes of post-harvest strawberry

degradation is fungal growth, which can be effectively inhibited by high CO₂ levels (e.g., 15–20 %). Besides, ozone treatment, electrolysed water and plasma technology are being investigated as surface disinfection methods for decreasing the microbial load without leaving any dangerous residues. Breeding projects are becoming more focused on the development of cultivars with better post-harvest features, such as delayed ripening, increased resistance to bruising and natural resistance to usual post-harvest diseases. Likewise, edible coatings composed of polysaccharides (like chitosan, starch and cellulose) and other natural polymer derivatives; proteins (whey protein and soy protein) or lipids (waxes and fatty acids) have been shown to extend the shelf life of strawberries (68). Studies have also shown that the application of chitosan at 6 g/L combined with CaCl₂ at 1.00 % can extend the storage period up to seven days at 7 °C (70). Farmer education and proper knowledge regarding the significance of the cold chain, pre-cooling and appropriate handling are essential for minimising post-harvest losses.

According to *in vitro* research, the application of the antagonistic yeast *Debaryomyces hansenii* considerably reduced the incidence of the pathogen *R. stolonifer* by approximately 22.5 % compared to the control. It has also been observed that grey mold on strawberry fruits can be controlled when *Bacillus amyloliquefaciens*, *Aureobasidium pullulans* and *Beauveria bassiana* are applied together. Furthermore, postharvest application of *Trichoderma harzianum*, *Trichoderma viride*, *Gliocladium roseum* and *Paecilomyces variotii* results in better control of *Botrytis* rot in strawberries. *Trichoderma harzianum* and *Bacillus* have been reported to successfully suppress *B. cinerea*, the pathogen that causes grey mould (70). Future developments in non-chemical preservation technologies, smart packaging and real-time monitoring of storage conditions are expected to further enhance shelf life and reduce post-harvest losses.

Protected cultivation

Growing in greenhouses, as well as low and high tunnels, helps to prolong the berry season and significantly reduce the effects of unfavourable weather

conditions. Such systems can reduce water usage by up to 90 % while also minimising disease risks. However, in these structures, yields are observed to be higher in winter and spring months than in other seasons (89). Under protected cultivation in Karnataka, the cultivar 'Winter Dawn' recorded a yield of 618.28 g/plant, indicating its suitability for high-input production systems in tropical regions (90).

Protected cultivation resulted in a yield increase across cultivars. However, variations in responses across locations indicate that the yield improvement may be affected by the growing environment and more multi-location research is needed for generalisation (Table 5).

The morphology of the strawberry plant renders it one of the most preferable fruit crops for vertical farms, allowing crops to grow year-round and be located close to urban consumers (92). Light-emitting diodes (LEDs) may be adapted in vertical farming to provide particular light wavelengths that enhance the growth rate of plants, with blue (approximately 450 nm) and red (approximately 660 nm) light being the best spectra and playing an important role (93).

Strawberries can be produced in hydroponic or greenhouse systems in controlled settings in tropical and subtropical areas, thus lengthening their production period beyond the typical growth period. Precision farming practices, such as the use of sensors, IoT devices and data analytics, are also finding their way into contemporary farming activities to monitor and track performance (29). The genotypes 'Rania', 'Nabila', 'Winter Dawn', 'Sweet Charlie', 'Camarosa' and 'Winter Star' showed the best agromorphological characteristics in hydroponic cultivation, suggesting their suitability for growth in controlled environments (94).

The implementation of integrated technologies and precision-based interventions is worldwide, scaling up production systems of strawberries, whereas in India, their strategic combination is vital to fill the current gaps. Greater emphasis on region-specific adaptation and large-scale implementation of protected cultivation systems is essential to fully exploit their potential under diverse agro-climatic conditions.

Table 4. Comparative effect of precooling methods on post-harvest quality of strawberry (88)

Pre-cooling method	Shelf-life (days at 4 °C)	Effect on fruit quality	Key limitation
Forced-air precooling (FAPC)	15	Excellent retention of firmness, colour, antioxidants; low microbial growth	Higher energy requirement
Cold room precooling (CRPC)	15	Moderate quality retention	Time-consuming
Cold-water precooling (CWPC)	~12	Risk of decay	Surface moisture leads to microbial growth
Electrolysed water precooling (EWPC)	~12	Slight microbial control but quality decline over time	Residual moisture
Fluidized ice precooling (FIPC)	~12	Tissue damage; increased browning	Chilling injury

Table 5. Comparative yield response of strawberry cultivars under open and protected cultivation in subtropical conditions

Cultivar	Agro-climatic condition	Open-field (g/plant)	Protected structure (g/plant)	Yield (%) increase under protected condition	Reference
Camarosa	Sub-tropical (Punjab)	689.86	730.99	+5.96 %	(43)
Nabila	Sub-tropical (Punjab)	625.64	737.31	+17.85 %	(43)
Winter Dawn	Sub-tropical (Rajasthan)	218.89	242.77	+10.91 %	(91)

Research gaps

Despite significant research advancements in strawberry production, several research gaps persist across production, breeding, post-harvest management and emerging technologies. In the area of biostimulants, the lack of nutrient-balanced, non-biostimulant controls in existing studies makes it difficult to clearly distinguish nutritional effects from biostimulant-induced responses. Moreover, it is not well understood how molecular processes and signalling pathways mediate biostimulant-mediated plant resilience, especially concerning how these mechanisms and pathways interact with plant metabolic and stress-response systems (16).

The application of IoT and artificial intelligence (AI)-based predictive models in smart agriculture is constrained by insufficient datasets and limited validation in a variety of production systems. Existing synthetic data generation models fail to capture extreme weather variability, reducing the reliability of yield forecasting systems. Additionally, the transferability of such models across cultivars and cultivation systems remains underexplored (48).

Vertical farming systems are promising solutions to urban agriculture, but their economic and environmental sustainability remains uncertain. Commercial adoption is restricted by limited cost-benefit analysis, especially in the case of small- and medium-scale growers. The high energy consumption of artificial lighting is still one of the major limitations and research concerning the integration of renewable energy sources into vertical farming systems is limited (55).

A lack of knowledge about the genotype-environment interaction limits breeding and genetic improvement initiatives and the subsequent development of location-specific cultivars (19). Genomic selection and marker-assisted techniques are not fully exploited and promising genotypes are sparsely tested under commercial hydroponic systems (94). Also, the molecular pathways that regulate the formation of runners, such as gene regulatory networks and differentiation of the axillary bud, are not completely understood (74).

Propagation methods need to be further validated, since micropropagated plants are not adequately evaluated to assess their yield stability, morphological uniformity and fruit quality (62). Similarly, there are no standardised protocols for effective genetic transformation to enhance the reproducibility across genotypes (64).

The functions of phytohormones in the context of plant physiology and fruit quality are not well understood. There is a lack of research examining the cross-talk of phytohormones in the formation of aroma compounds (83).

Limited knowledge exists regarding consumer acceptance and market demand for processed strawberry products. Additionally, innovation in small-scale processing technologies and value-added products remains insufficient (51). The combined effect of chemical treatments and packaging technologies on shelf-life and fruit quality is also underexplored (81).

Finally, plant health management requires attention, especially the development of rapid, field-deployable diagnostic devices to detect viruses that are transmitted by nematodes. The interaction between virus, vector and host is not well studied and this limits effective disease control measures (67). Collectively, strawberry research in India has been mainly focused on the productivity aspects through cultivar assessment and agronomic management, while comparatively little research has been conducted on long-term climate resilience, precision farming, economic viability, consumer behaviour and integrated production systems. In addition, the vast majority of the studies were carried out in specific locations with a limited number of multi-location trials, which limits the ability to generalise the recommendations to different agro-climatic areas. Therefore, more comprehensive studies should be conducted in the future, taking a multidisciplinary approach that incorporates breeding, genomics, digital agriculture, climate adaptation and post-harvest technology and socio-economic analyses, to create resilient and commercially viable strawberry production systems in India.

4. Conclusion

Strawberry cultivation in India has experienced rapid growth over the past decade, owing to the increase in demand, increased economic returns and its adaptability to a variety of agro-climatic conditions. Currently, production is still centralised in selected areas that have improved production practices; nevertheless, the general productivity and sector growth remain to be constrained by the problems of low productivity, high perishability and inadequate market systems and infrastructure. Addressing these limitations through targeted research in breeding, development of varieties that are resistant to climate change and wider

incorporation of protected and organic cultivation techniques are vital to enhance the productivity of fruits. The reinforcement is also important in post-harvest care and market connections to minimise losses and enhance returns. With a coordinated approach that is a combination of technology, policy support and farmer adoption, strawberry cultivation can be turned into a high-value horticultural crop offering sustainable incomes to smallholder and peri-urban farmers in India.

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Authors' contributions

AD conceptualised the review article, designed the methodology for the literature search and prepared the manuscript. CR guided throughout the review work and revised the final manuscript. SM critically reviewed and approved the final manuscript. SS guided in summarising and editing the manuscript. DL involved in correcting and revising the final manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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