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Protected Cultivation of Fruit Trees in Greenhouses: Advances, Benefits and Emerging Challenges

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Review Article

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ABSTRACT

Technological progress and evolving production methods have long influenced the trajectory of agriculture, steadily improving both crop performance and fruit quality. Within this continuum of innovation, cultivating fruit trees under greenhouse conditions has emerged as a significant development, offering a reliable means of producing marketable fruit throughout the year—even in regions where environmental conditions are normally unfavorable. As a distinct component of protected horticulture, these systems modify key microclimatic factors to create an environment in which fruit trees can grow efficiently and express their full genetic potential. The rapid adoption of greenhouse fruit systems underscores their relevance in confronting major agricultural constraints such as climate variability, shrinking arable land resources, deteriorating soil health, and the pressures of a growing global population. This review synthesizes current knowledge on fruit tree cultivation within greenhouse environments, examining agronomic advantages, physiological considerations, management practices, and research needs. Particular attention is given to how modern innovations such as automated climate control systems, renewable energy integration, and digital monitoring tools can elevate productivity and strengthen system resilience. Collectively, these advancements highlight the potential of protected fruit production to play an increasingly important role in sustainable horticulture and future food systems.

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1. Introduction

With projections by the United Nations, the world food demand by the year 2050 is bound to require around 42 percent increase in agricultural production and 120 percent increase in water resources relative to modern day production and water resource respectively. Against the current background of ever growing limitations like water scarcity, labor unavailability, and climatic unpredictability, the traditional open field agriculture is increasingly experiencing difficulties in maintaining its productivity. In turn, as a result, greenhouse agriculture and similar safeguarded farming have become an efficient approach to improve food security and farming performance (Sagheer *et al*., 2020). The space area under greenhouse cultivation has been approximated at over 623,000 hectares all around the world (Khan *et al*., 2018), which is a sign of increased greenhouse cultivation technology usage. Growing fruit trees in green-house conditions can be described as the great step forward in the development of the production system in horticulture. Greenhouses allow the tight control of the microclimatic parameters that include the temperature, humidity, light intensity, and ventilation, which leads to the production during the off-season and enhances the efficiency of resources use. Besides vegetables and ornamentals, many fruit species like orange, lemon, apple and pear have been grown successfully under the shelter in the protected conditions. This method helps not only to increase the yield and the quality of fruits but also reduce reliance on the unpredictable climatic conditions. The greenhouse-based fruit production is a contemporary approach to agriculture, and it provides the best environment to grow fruits, especially in areas with arid, semi-arid, or climatically hostile conditions. Because fruit trees are sensitive to ecological and physiological factors so that they would grow best and reach fruiting in greenhouses, the possibility of offering a fine control over the conditions in the environment gives an agronomic competitive edge. Protected agriculture has become an important part of sustainable agricultural systems with tremendous usefulness in high-value and export-oriented fruit production. It has helped in the promotion of production of organic fruits, decrease in pest and diseases, averting cracking of fruits, and ensuring year-long production (Aman *et al*., 2018). Over recent years, a significant amount of research work has been focused on the advancement of environmental-friendly technologies and enhancing the efficiency and sustainability of fruit trees farming (Chen and Boddu, 2022). The main goal of secured cultivation is to alter the natural environment in which a crop is growing to facilitate the season of crops, to enhance the stability of yield, and to facilitate in the improvement of the quality of fruits. Some of its many advantages include better efficiency in the management especially in irrigation, weeds control, pests control, and reduced postharvest losses attributed to unfavorable weather and higher profitability owing to earlier harvesting and supply to the market. Additionally, it is also due to the fact that in protected cultivation, a stable production base to sustain in the form of year-round propagation, full vegetation and reproductive growth and off-season cultivation is possible. It also reduces the harmful effects of the abiotic stresses including excessive rain, frost damage, wind damage, and even variation of temperatures thus ensuring a uniform growth and quality of fruits (Maier *et al*., 2022; Verteramo Chiu *et al*., 2024). Climatic limitations- weak access to sunlight, unpredictable weather conditions, unequal hurdling humidity, strata pressure, wind speed, and inappropriate atmospheric CO2 concentration are also significant limiting variables in fruit production. Protected systems have a positive impact on such challenges, as they will lead to a more controlled, resource-efficient and sustainable production system. The field of technologies that are classified as the protected cultivation includes the greenhouses, shade nets, windbreaks, drip irrigation networks, plastic tunnels (low and high), thermal exchanger (ETHE) of hot and humid areas, mulching practices, and fruit bagging systems (Aman *et al*., 2018). Taken together, these innovations will result in a robust and a high functioning agricultural model, which can serve the intricate needs of contemporary horticultural production.

2. Greenhouses and their significance to agriculture nowadays

Protected cultivation in greenhouse also known as a greenhouse crop refers to the deliberate and systematic cultivation of horticultural crops under controlled conditions, where clinically significant growth elements like a light, humidity, and temperature are monitored to satisfy species-specific physiological needs. The strategy of production has grown significantly over the last several decades and has become the basic element of the new system of fruit agriculture (Thakur *et al*., 2023). In Japan, however, shielded horticulture has been used strategically to boost the quality of fruits, and also minimize market dependency against the imported fruits in the off-season period (Iwagaki, 1990). Environmental regulation provided by greenhouse buildings also allows farmers to achieve high-quality crops that have stable growth and provide many fruits all year round (Thakur *et al*., 2023).

Traditional outdoor orchards are naturally susceptible to a broad combination of unfavorable factors, such as weather extremes, competition between the weeds, the pressure of pests and diseases, inconsistent weather patterns that tend to restrain the quality of the fruits and the uniformity of the market. Practical orchard systems tend to focus on large-scale production instead of maximizing the fruit quality, and thus to inconsistent fruit organoleptic properties and a lower level of market competitiveness. In comparison, a greenhouse production of fruits offers a platform to obtain better yields, quality of fruit, longer seasons of production, and broader export opportunities (Guvvali *et al*., 2017).

Pineapple is one of the best fruits that can be grown in a greenhouse, given that it has a moderate level of plant height, herbaceous, and growth pattern (Maneesha and Gupta, 2025). In a similar manner, stone fruit trees with short gestation periods like apricot and peach have proven highly adaptable to the greenhouse environment, and their benefits are extensive and comprise: (1) they mature sooner; (2) produce higher-quality fruit and a prolonged shelf life; and; (3) grow more healthily with an organic production system (Martinez-Gomez *et al*., 2021). They have enhanced the strategic value of the cultivation of the greenhouse fruits in temperate and sub-tropical areas.

The world continues to lose its agricultural productivity due to population increase, land fragmentation, and disturbance of natural resources (Maja and Ayano, 2021). The fact that the demand of consumers on the number of fruits in a short period begins to increase followed by higher prices and a lack of vegetables in certain seasons is an argument in favor of technological inventions that can stabilize supply levels. One of the most influential innovations in that regard is that of protected cultivation especially that of greenhouse systems. Greenhouse farming by changing the microenvironment around the crop enables fruit trees to realize their existing genetic capacities so that physiological processes like photosynthesis, nutrient upkeep and reproductive growth are maximized.

The advantages of greenhouse cultivation extend far beyond environmental buffering. They include:

- greater operational efficiency in irrigation, weed control, pest management, and harvesting;
- reduction of yield losses caused by climatic fluctuations;
- uninterrupted production across seasons;
- improved marketable yield and fruit uniformity; and
- earlier harvesting, which leads to higher profits and allows growers to access premium markets (Singh *et al*., 2013).

In addition, greenhouse farming is basically more sustainable since it is less reliant on climatic variables, resources are conserved and efficiency when it comes to using inputs is maximized. The green house systems in seasons when production cannot be done outdoors because of frost, heavy heat, rains or other climatic influences are guaranteed of fruit production and supply in the markets. Consequently, safe production of fruits is becoming a viable direction in the plans of realizing long-term food security, production of high value fruit and better resiliency to global horticultural systems.

3. The significance of green house production of fruits

Protected cultivation refers to such a production system where the microclimate that envelops the plant is controlled to control its growth, development, and productivity (Pattnaik and Mohanty, 2021). Advanced types of the controlled-environment agriculture, greenhouses enable producers to regulate temperature, humidity, light, and ventilation to satisfy the specific physiological demands of the fruit crops. Against the backdrop of rapidly evolving climatic changes, an ever-growing lack of predictability in the natural climate, and escalating food demands in the world today, the idea of using green houses in the production of fruits has been viewed as a strategic approach in terms of stability and quality of the harvest. This production type is especially beneficial in the areas with harsh winters, great precipitation, or high temperatures, when the open fields production of fruits is highly limited. Greenhouse-based systems do not only stabilize productivity but go an extra mile to greatly decrease reliance on pesticides and chemical inputs thus making possible production of healthier, contaminant-free, and occasionally organic products. In addition, greenhouses allow year-round and off-season production of numerous fruit crops, which means destroying the reliance on seasonal imports and the rather strong food security of the country. Recent estimates of world greenhouse cover area by continent give an indirect but sound measure of world production rates, as generally greater area of land under cultivation represents greater production capacity. The geographical areas that have the highest concentration of green houses acreages, which are usually geographical areas with a developed horticultural business sector are possibly supplying the highest share of the world output. Such regions will usually have a developed infrastructure, availability of advanced technologies and robust commercial market to facilitate high-intensity production and production throughout the year. The distribution in the figure indicates that there are wide disparities in regions, some regions are running large scale green house based sectors as others are relatively small. This variation indicates a difference in the climate, level of investments, governmental assistance, and agricultural priorities. This results in the concentration of production levels in areas with the highest levels of green house footprint, where a high level of technology used and a high level of market demand ensures sustained and high volume of production (Table 1).

Table 1. lastest estimates of golbal area by region

	Total	Vegetables	Ornamentals	Low and mid tech	High tech
Europe	188,772	167,962	20,810	155,135	33,637
North America	71,155	57,683	13,472	60,785	10,370
South America	32,810	18,503	14,317	31,547	1,263
Asia (exuding China)	300,594	279,956	20,638	285,735	14,859
China	1,000,000-3,500,000	800,000-3,200,000	200,000-300,000	995,000-3,495,000	5,000
Africa	68,512	59,164	9,348	67,363	1,149
Oceania	2,509	1,132	1,377	1,385	1,124
Total (in hectares)	3,720,000	3,370,000	350,000	3,650,000	70,000

The distribution of global greenhouse area by crop type illustrates how production capacity is allocated among major horticultural categories. Crops occupying the largest greenhouse areas commonly vegetables such as tomatoes, cucumbers, and peppers represent the highest production rates globally due to their economic value, short growth cycles, and strong year-round market demand. These crops dominate protected cultivation because greenhouse systems significantly enhance yield, quality, and environmental control. Other categories, such as flowers and ornamentals, as well as certain fruit crops like berries, also hold notable but smaller shares, reflecting specialized production systems or market-driven segmentation. The figure therefore highlights the prioritization of crops that benefit most from controlled-environment agriculture, indicating that global production rates are strongly concentrated in high-value vegetable categories, followed by ornamentals and selected fruit crops. This distribution underscores the strategic role of greenhouses in optimizing productivity for commodities with the greatest commercial and resource-efficiency advantages (Table 2).

Table 2. latest estimates of golbal greenhouse area by crop

	Low-tech	Mid-tech	High-tech	Total
Tomatoes	35%	40%	50%	36%
Cucumbers	8%	8%	6%	8%
Peppers	5%	5%	5%	5%
Eggplants, Zucchinis, Melons	15%	10%	2%	14%
Leafy greens	20%	10%	8%	18%
Sof fruits	10%	10%	10%	10%
Ornamentals	7%	17%	15%	9%
Total (in hectares)	3,000,000	650,000	70,000	3,720,000

The growing number of extreme weather conditions combined with the growing needs to produce fruits of the premium quality have acted as an even stronger driver towards the internationalization of greenhouse production systems. Growers of greenhouse fruits have the capacity to overcome instability in yields, reduce the cycles of production, record earlier harvesting date, and enhance uniformity of the fruits. Additionally, it allows commercial use of the fruit crops; this is because once the production of the fruits is secured one will be able to conduct business in the markets where the fruit will be involved in the off-season, when prices are at their peak and where there is very little competition. Due to these reasons, the greenhouse fruit production is being viewed as a transformative production model to horticultural systems in the future as well as an adaptive alternative besides being seen as a strategy that has the potential of remaking world horticultural systems.

4. Rationale behind the use of greenhouses in production of fruits

Fruit tree greenhouse production is a highly specialized and rapidly expanding area in the contemporary horticulture industry, which provides producers of this sector with the capacity to lengthen their production span, produce a regular fruit output, and increase horticulture into areas where the climate has been previously hostile. Greenhouses are able to improve the main physiological functions, which leads to high productivity, quality of fruits and availability all year round because of the controlled environment. Conventional orchard control, in turn, can be constrained by invariable weather conditions, and productivity is usually rated solely on the basis of yield per acre (Orpet *et al*., 2020; Manfrini *et al*., 2020). However, despite this yield orientation as a core of the orchard efficiency, this traditional performance of orchard does not often consider the essential aspects of such parameters as environmental equilibrium, uniformity of microclimate, and the connection between and among the variables of production (Abasi *et al*., 2025). Subsequently, the key factors in determining the quality of fruits such as the health of the fruits, the size, flavor, appearance and pesticide residue levels get relatively less attention. There are several abiotic and biotic factors which limit open-field fruit production. Some of the strongest limiting factors include lack of enough sun radiations, fluctuating temperatures, assorted moisture content, and weed rivalry, wind stress, dwindled atmospheric concentration of CO_2 in certain areas, improper fruit pigmentation even in cold climates, pest and infection outbreaks and retarded fruit maturity. All these contribute towards limiting the growth of fruit trees to reach their genetic potential. Greenhouse growing represents a powerful solution to reduce most of these issues as they provide a superior and controllable growing environment, control the various environmental stresses, as well as allowing the growers to maximize the performance of the plants through the entire production process. Biological nature of fruit trees further explains the necessity to have controlled environment. Being perennial plants, the fruit trees are characterized by intricate physiological events, including those related to dormancy and chilling necessities, which are very receptive to environmental variations. Inability to fulfill the requirements of chilling, such as poor flowering, weak budbreak, and low fruit set may occur. Protected cultivation also allows managing these physiological processes more accurately, thus mitigating the risk of unpredictable winter temperatures and insufficient amounts of chilling. The production of fruits is highly dependent on both biotic and abiotic factors and the interactions between these factors are usually hard to control when working in the open-field conditions. Greenhouse at least provides a methodological way of controlling microclimatic variables, alleviating the pressure of pests, increasing the success of pollination, and stabilizing the growth and maturation of fruits. These reasons make protected cultivation a more and more accepted scientifically-based and economically feasible approach to producing fruit in the modern world, able to overcome the constraints of vintage orchard designs and help to achieve better yield stability, fruit quality, and Albedo (Martinez-Gomez *et al*., 2021).

5. Benefits of Greenhouse Farming of Fruits Trees

Protected cultivation is a highly regulated method of production, which lowers the stress levels to the environment along with providing optimum physiological functioning in fruit trees. This method has several agronomic and economic advantages, such as stabilized harvest, improved quality of fruits and possibility to produce fruit out of their natural growing periods. Greenhouse systems do not only insulate the plants against the unfavorable changes in the climate but also enable the accurate control of the environmental parameters that are of key to the growth and fruiting (Chimankare *et al*., 2023).

5.1. Environmental Control

The advantage that is most unique of the greenhouse-based cultivation is the ability of the practice to impose strict environmental control. Atmospheric constituents, temperature, humidity, light intensity and reproduction can be precisely controlled in order to maintain the optimum growth, photosynthesis and reproductive maturation.

- ✓ Temperature Control: Fruit trees are mostly researchers of optimum vegetative and reproductive development of 22 °C-25°C. This variety is provided with integrated heating and cooling systems which allows keeping of the required range throughout the year and the standardized productivity even in areas where frost or excessive heat may arise (Yu *et al*., 2025).
- ✓ Humidity Control: Relative humidity has a great impact on the rate of transpiration, intake of nutrients and the vulnerability to disease. A humidity of 50-70 percent reduces the presence of fungal pathogens and eliminates water stress factor and stomatal closure that may cause carbon assimilation inhibition (Hamidane *et al*., 2024).
- ✓ Light Management: At the short-day or low-light phases, artificial lighting systems (especially the light-emitting diodes (LEDs) with variable spectra) have the potential to supplement solar radiation, increasing photosynthetic efficiency, and enabling even canopies. The greenhouse effect, which allows shortwave radiations into the covering material and traps longwave radiations that are emitted by internal surfaces, helps in increasing the internal temperatures and enhancing the photosynthetic ability (Soufi *et al*., 2024).

A combination of these environmental controls enables growers to develop microclimates that match species-specific physiological needs and hence increase the length of the growing season and improve the uniformity of fruits.

5.2. Yield Improvement on Controlled Environment

The combination of heating, cooling system and artificial lighting systems make it possible to keep the fruit trees in the year all the year round regardless of climatic limitations that occur outside. The given method is especially beneficial in areas that experience severe weather conditions of either cold winters or sweltering summers, as it enables several and foreseeable picks. In control-environment schemes, citrus, strawberry, fig and apricot can undergo two to three growth-dollar round each year, when compared to conventional open-field orchard which bears at least once per year (Zhao *et al*., 2024). By controlling the photoperiod and photon temperature, one can synchronise the stages of the phenological conditions (bud break, flowering, and fruit development) facilitating harvesting throughout all seasons of the year (Ampim *et al*., 2022). Regulated light and accurate thermal regulation hasten changes in vegetative to reproductive growth, which enhances productivity per unit area. In the urban areas where there are a small land area and use of pesticides is restricted, the alternative that can be used to replace the use of open fields as rural orchards is the use of greenhouse fruit cultivation. Also, the larger yield to input ratio and improved uniformity of fruits and other crops makes the use of greenhouse systems an economical remedy to high-value crops (Yuan *et al*., 2025).

5.3. Pests and Diseases Control

One of the key benefits of the protected cultivation is the pest and disease control (Martinez-Gomez *et al*., 2021). The physical and biological barrier of the enclosed greenhouse environment is characterized by lowering the introduction and distribution of pathogens, arthropod pests. Monitoring of the temperature, humidity and ventilation conditions inhibits the growth of fungal diseases, and other biological control methods, such as the introduction of useful insects (*Encarsia formosa*, *Aphytis melinus*) or fungal pathogens (*Beauveria bassiana*), can be used to adequately control the pest population with no use of chemical pesticides. This Integrated Pest Management (IPM) model does not just provide an ecological balance but also results in avoiding the accumulation of pesticide residual organic agents on the surfaces of the fruits. Isolated production areas allow early production infestations to be detected, thus allowing localized and prompt interventions. Therefore, greenhouse fruit production is in line with sustainability and residue-free production provisions (Koti *et al*., 2025).

5.4. Water-Use Efficiency

Growing fruits in green houses has been found to greatly enhance efficiency in the use of water due to the accuracy of irrigation technologies most commonly drip and micro-irrigation systems. Such techniques provide water to the rhizosphere and ensure that wastages such as evaporation or percolation are minimized. Research suggests that the systems that are equipped with protection have a potential to decrease total water usage by 50-70 percent compared to more traditional open-field systems (Nicola *et al*., 2020). Furthermore, the fertigation, which is the conglomeration of water and nutrients, can provide accurate delivery of nutrients in accordance with the demand of the plants. The strategy will avoid loss of nutrients, reduce efficiency of fertilizer use and environmental pollution. These measures of water saving are of great importance, especially in arid or semi-arid lands, where the value of freshwater is low (Nakachew *et al*., 2024; Sood *et al*., 2025).

5.5. Growing Techniques and Cultural closely relates to cultivation Techniques and Cultural Practices

The efficacy of greenhouse fruit production is associated with the combination of culture methods depending on the cultivated crop plant and the design. Espalier, Y-training, or slender spindle are all forms of training that promote evenness of light interception and circulation of air, which is essential in the world of photosynthesis and the fruit. Similarly, there are cultural practices such as regulated deficit irrigation, restriction of roots, and targeted management of the canopy that has been used to regulate vegetative growth with reproductive performance (Ragaveena *et al*., 2021).

5.6. Rootstock and Cultivar Selection

The choice of rootstock and cultivar are crucial factors of both productivity and adaptability in greenhouse fruit production (Leonardi and Maggio, 2013). Dwarfing/semi dwarfing rootstocks are also desirable to manage the height of the canopy and to be in a position to manage with limited vertical space. To a great extent, self-compatible or parthenocarpic cultivar is what should be selected, as natural pollinators may have a very limited presence in closed spaces (Folta, 2019). Alternatively, self-incompatibility problems can be reduced by using mechanical pollinators or controlled insect colonies of bees. High-market-value and early-maturing cultivars are the most preferable type of plants since it will provide a high turnover and be economically viable (Bhattarai *et al*., 2025). Greenhouse buildings of lower heights (below 3 m) can be used with species that have been domesticated to be utilized in less pronounced training systems, like fig and pomegranate.

5.7. Dormancy and Chilling Control

Meeting the chilling needs of the temperate fruit species will be necessary to ensure natural uniformity of bud break and flowering. Two techniques that are used in green houses to control the artificial dormancy are temperature control and regulated ventilation (Campoy *et al*., 2011). The typical requirements between 2 °C and

12 °C and 6-8 weeks are considered sufficient to trigger dormancy in the apricot species, but the conditions differ among the cultivars and seasons (Yang *et al*., 2021). Natural changes in diurnal temperatures can be used by growers to open the green houses at night and use covers at other times of the day to reduce excessive heat buildup. In the case of cultivars with a low chilling requirement, a greenhouse system allows production in warmer climates to achieve sufficient satisfactory levels of dormancy thus allowing production to achieve earlier flowering and fruit set. Adaptability and competitiveness in the market are further improved by genotypes of low-chill, or early-ripening (Sabir *et al*., 2025).

5.8. Pollination Management Pollination is also a requirement to achieve the optimum fruit set and fruit yield

Manmade or controlled pollination systems are also required in closed environments due to the low number of natural pollinators. The honeybee colonies (Apis mellifera) or the bumblebees (Bombus spp.) are commonly introduced to achieve successful pollen deliveries, especially to those species that do not pollinate each other like in apricot and cherry (Lee *et al*., 2020; Wu *et al*., 2022). In areas where a temperature or light limitation limits pollinator activity, industry pollination techniques can be used as an addition to fruit set. Other measures can include planting congruent cultivars at the right proportions (1:4 pollinator to main cultivar) or self-fertil genotypes (Saez *et al*., 2020). The management of pollination in greenhouse systems should therefore be in line with the floral biology and environmental parameters (He *et al*., 2025).

5.9. Pruning, Girdling and Growth Regulation

Pruning, girdling and root control all help in maintaining effective regulation of growth of vegetation and relation of the reproductive development to the vegetative vigor and structure. Girdling (ringing)- Because the process lacks translocation in phloem, initiating flower bud differentiation and enhancing the size and quality of fruits is facilitated (Sharma *et al*., 2024). Stress-free measures like regulated deficit irrigation, root pruning and application of growth retardants also contribute to improvement of canopy control and yield stability (Hota and Chander, 2025).

5.10. Administering Systems and Spacing

Due to the high cost of construction of protective structures, the planting systems used in the cultivation of greenhouse fruits should be capable of proper utilization of space, early fruits bearing, and quality yield. The close spacing of plants has been found to be among the most effective methods. Since the root volume and the vigor of the shoot have a high correlation, the limitation of root space constrains vegetative and encourages the early attainment of fruit (Tripathi *et al*. 2020). In peaches, Y-training system where there is a spacing of 4.5 ± 0.5 m and spacing of trees 1.2 ± 0.1 m, the planting density of the peach is increased to 5000 trees per ha-1 and the system still has no effect on the color and quality of the fruits. The light distribution and increased fruit coloration are the benefits of pre-harvest pruning that is conducted three weeks before harvest (Gruda *et al*., 2013). The medium of growth is also significant; it should have adequate aeration, water retention, and design in order to facilitate the root activity (Gruda *et al*., 2013). Hydroponic and semi-hydroponic systems recently become significant due to the possibility of active regulation of nutrients, pH, and water and their effects on the decrease of the yield as well as fruit quality (Fussy and Papenbrock, 2022). Automated fertigation systems also increase the efficiency by regulating the concentration of fertilizer as well as irrigation based on the demand of the plant (Aziz *et al*., 2022; Imbernon-Mulero *et al*., 2023).

5.11. The Microclimatic Control of temperature and humidity in greenhouse fruits

To control the growth of plants, fruit development and disease occurrence in greenhouse fruit farming, it is necessary to maintain appropriate levels of temperature and humidity (Yusuf *et al*., 2025). This can be done using environmental control materials such as retractable films, ventilation systems, and temporary shading structures, which might be yet an expensive means of production (Maraveas, 2019). It is essential to constantly monitor the internal microclimate temperature, humidity, light, and air flow and to research it to avoid physiological stress and provide equal maturation of fruits (Salagovic *et al*., 2024). Transparent exterior films may increase the rate of solar radiations and using reflective ground films, which increases light reflectance inside the canopy structure, elevating the homogeneity of the photosynthetic environment (Martinez-Gomez *et al*., 2021). Poper temperature control in the process of flowering and ripening may speed up the fruit maturity by between 10 to 50 days which enhances early harvest and better marketability (Banjare *et al*., 2023).

5.12. Solar Radiation maximization to generate photosynthetic and juice-fruit quality

Greenhouse architecture automatically lowers the intensity of light that is sufficient to nearly 60-70 percent when compared to the energy present in open field settings. In addition, light distribution within the structure is not even at around 85 percent in the south and central areas and at the 44 percent in the north with possible variations in color and quality of fruits (Sethi *et al*., 2025). To overcome this shortcoming, clean and transparent greenhouse cover has to be kept and reflective materials or additional light systems used to provide equal light penetration. Optimization of the sun radiation does not only enhance the photosynthetic efficiency but adds to the fruit size and sweetness as well as the use of the skin pigments important features in commercial quality (Vishwakarma *et al*., 2025).

5.13. Optimization of Photosynthetic Activity and CO_2 Employments

Coupling the greenhouse allows extending the photosynthetically active time of plants by maintaining optimal temperatures and avoiding abiotic stress on leaves and hence preserving a high photosynthetic activity (Chimankare *et al*., 2023). In the normal circumstances, the level will be approximately 300 mL m^{-3} of CO_2 which is sufficient to drive normal growth in plants. Nevertheless, ventilation, and CO_2 consumption as in the morning hours may cause temporary depletion (Weidner *et al*., 2021). The research has proved the enrichment with CO_2 to be a drastic detector of photosynthetic performance and biomass expansion when the enrichment is associated with sufficient lighting and ample food provision (Pan *et al*., 2019). The increased levels of CO_2 can improve the yield by an average of 15 percent due to the increase in carbon uptake and nutrient uptake. Sustaining high CO_2 levels, however, is not an easy task because of the leakage in structures that are poorly sealed. It can be partially balanced with the use of organic fertilizers that, to a certain degree, emit CO_2 when their application is low and, therefore, can be seen as a practical and cost-effective solution (Badagliacca *et al*., 2024).

5.14. Smart Controlled Growing Systems of Fruits on Sustainable Bases

The combination of soilless and hybrid production technology of fruits has transformed the production of fruit trees that use the facility of protected production systems due to the enhancement of resource utilization and the consistency of yield (Lakhiar *et al*., 2025). Such innovative approaches include hydroponics, aeroponics, aquaponics, and geoponics to enable the supply of water, nutrients, and oxygen to be controlled more precisely and eliminate environmental stress and dependence on soil quality (Fuentes-Penailillo *et al*., 2024).

5.14.1. Hydroponic Systems

Hydroponics Hydroponics is the culture of plants in a liquid medium of nutrients without soil. It was first coined by Dr. W.F. Gericke (1936) who created the first commercial system of hydroponics in the United States in 1930. In the production of hydroponic fruits, water and soluble nutrients are provided at a constant to the root zone, which makes plants undergo the minimum stress and the highest metabolic rates (Khan *et al*., 2018). This will mean that the use of the limited land resource can be effectively utilized and even the growth of plants can be uniform as there is even distribution of light in the green houses. Moreover, the most recent innovations have been directed at the creation of organic and renewable materials such as coconut coire, composted bark, or biochar to diminish use of non-renewable and non-recyclable minerals like peat, rock wool, and perlite (Gajc-Wolska *et al*., 2014). These technologies enhance sustainability without compromising productivity and quality of fruits.

5.14.2. Aeroponic Systems

Aeroponics is a high technology type of hydroponics whereby plant roots are suspended in air and sprinkled with fine spray of nutrient-enriched solution -periodically (Murali Mugundhan *et al*., 2011; Agina Effat *et al*., 2018). Excessive aeration and availability of oxygen to the roots due to the absence of a solid growing medium means that aeroponic systems have the highest possible level of growth which can access nutrients and grow fast. Automated systems adhere to and maintain environmental factors such as temperature, pH, humidity, concentration of nutrients, length of misting and repetition interval. Aeroponics comes in especially handy where soil pH will compromise the soil. It has been proven that compounding empirical evidence suggests that this system decreases water usage by up to 98 percent, decreases fertilizer usage by 60 percent, decreases pesticide and herbicide usage by 100 percent, and increases total plant productivity by 4575 percent of soil-based systems (Lakkireddy *et al*., 2012; Thakur *et al*., 2023). Its rapid level of diffusion of oxygen and constant pH render the system ideal when it comes to intensive production of greenhouse.

5.14.3. Aquaponic Systems

Aquaponics is an interdisciplinary approach that combines aquaculture and hydroponics in a closed-loop process where the wastewater in fish tanks is rich and turned into useful nutrients by biologically converting and using it to grow vegetables. Microbial nitrification converts fish waste into nitrogenous materials, which act as plant nutrients, whereas the plants, in their turn, clean the water, and it is again recirculated to the fish tanks (Agina Effat *et al*., 2018). This symbiotic connection deteriorates the necessity in the use of synthetic fertilizers and saves the use of water resources, which develops an ecologically balanced production cycle. Most of the crucial nutrients needed to sustain the growth of plants are found in fish feed, and therefore, aquaponics is one of the most sustainable models of integrated food production with a minimal environmental impact (Shaw *et al*., 2022).

5.14.4. Geoponic Systems

The ancient basis of horticulture is geoponics or soil-based cultivation. The soil-borne diseases, weed pressure, unreliable and unpredictable nutrient substances, and poor usage of water limit its production, however (Murali Mugundhan *et al*., 2011). Geoponics involves a lot of frequent and labour-intensive nutrient management interventions, and the performance of plants is prone to variation as a result of the spatial and time heterogeneity of the soil conditions. Although geoponic systems have been widely adopted as a result of their simplicity and low cost to install, a shift to soilless/semi-soilless systems is crucial in attaining greater productivity, quality, and environmental sustainability in the practice of the production of fruits under protection (Syed *et al*., 2021).

6. Benefits of Greenhouse Cultivation of Fruits with Protection

The creation of fruit orchards in the greenhouse is one of the greatest innovations in the contemporary fruit farming that provides highly accurate environment regulation that amplifies the yield, quality and production uniformity of fruits (Argento *et al*., 2024). Guarded systems counteract abiotic disorders like frost, heat, wind, and hail besides enhancing microclimatic conditions in photosynthesis and formation of fruit. Additionally, the fruiting carried out in greenhouses will lower the levels of pests and diseases, allow us to manage the weeds, and provide us with an endless supply of fruits ready to be sold in this market with high prices and product quality (Martinez-Gomez *et al*., 2021).

6.1. Improved of Fruit Quality

Such tight control of the greenhouse environment as temperature, humidity, light intensity and irrigation can be tuned so that ones can directly manipulate all the parameters of fruit development and quality. Fruits grown in the greenhouse have better external and internal parameters in comparison to open-field systems, such as bigger size, homogeneous coloring, and better shape (Thakur *et al*., 2023). Environmental factors can be manipulated to make producers increase biochemical properties including sugar-acid balance, pigmental levels, and firmness to guarantee greater nutritional and commercial value (Nie *et al*., 2024).

6.2. Prematurely Born and Prolonged Harvest

Phenological stages are significantly shortened in green house production especially flowering and the maturation of fruits. Indicatively, the apricot trees grown in controlled environments take some 50-60 days to mature compared to those planted in open field settings (which occur between mid-April and mid-May) (Galan, 2002). On the same note, when grown in greenhouses, satsuma mandarins exhibit a boost in photosynthetic activity and yield (Martinez-Gomez *et al*., 2021). Early ripening enhances better market timing in addition to food safety and traceability by using standard production practices (Allara *et al*., 2013). Complete harvest times are also longer in controlled environments- grapevines (*Vitis vinifera* L.) can be harvested several days at a time between the first of April and the end of August as compared to mid-to late-August in an open-field system (Alonso *et al*., 2003). Similar progress has been made with respect to apricot and peach species (Wang *et al*., 1999; Zhang *et al*., 2005).

6.3. Fruits Shelf Life and Market Quality

The nature of light distribution in greenhouses is that it is heterogeneous by nature and, therefore, the fruit characteristics of the different canopy layers vary. The nature of fruits in the upper canopy region normally suggests that their soluble solids and coloration are greater, as they are more likely to experience higher levels of photosynthetically active radiation (PAR), even as they end up having a smaller diameter as compared to those found in the middle canopy layers (Kishore *et al*., 2023). Nevertheless, shade does not affect the weight of peach fruit significantly, indicating that the shading of canopy has no effect on quality traits regardless of the intensity of PAR light (Anthony and Minas, 2021). The use of hydroponic and semi-hydroponic methods in green houses favors high production fruits which have good organoleptic characteristics of texture, taste, aroma, and appearance. Research also suggests that paradoxical nutrient solutions based on manure can enhance biochemical properties of organic hydroponic systems, including the level of lycopene and antioxidant effects (Mowa *et al*., 2018). Similarly, plastic film coatings placed some weeks prior to crop harvesting increases the yield of apricots along with the postharvest time, but protracted covering might outweigh the color of fruits (Wurm and Urschler, 2008). In sweet cherry (*Prunus avium* L.), fungus and cracking caused by rainfalls are prevented by the use of pre-harvest protective covers, which means that the shelf life is extended in a Northern European climate (Borve *et al*., 2008).

6.4. Pest Control, Suppression of Disease and Organic Production

Physically, greenhouses can be used to repel pests, pathogens and poor weather to provide the basis of organic and low-input horticultural operations. Bird predation, cracking of cherry caused by rain, hail, and frost damage are a big threat to the cherry production that is highly mitigated to boost production (Lang, 2014). Environmental impact is decreased by the decreased use of chemical pesticides, especially fungicides, which provide favorable conditions to sustainability in the agricultural context. As an example, it is known that the incidence of anthracnose is significantly reduced in greenhouse growing plants compared to open-field vineyards (Guvvali *et al*., 2017). Moreover, a controlled environment offers a suitable platform on which to determine resistance of fruits to diseases. The resistance to the viral and viroid pathogens in Prunus spp has been studied under the greenhouse (Rubio *et al*., 2009; Garcia-Ibarra *et al*., 2012; Rubio *et al*., 2016), whereas tolerance of the nematode infestation has been studied (Okie *et al*., 1986, 1987; Culver *et al*., 1989). Ultimately, protected cultivation supports more precise pest monitoring and rapid intervention (Thakur *et al*., 2023).

6.5. Optimal Land Resource use

The reason protected cultivation maximizes land productivity is due to the fact that it allows the production of fruits throughout the year and that very little crop rotation or fallow time is required. This system is mainly advantageous to smallholder farmers in places that have scarcity of arable land (Thakur *et al*., 2023). Studies of a wide range of fruit species have demonstrated that the application of protective systems promotes not only increased economic returns but also the yield of the fruit production but also decreases the variability of the environment surrounding them, such as strawberries (Ambad *et al*., 2007; Choi *et al*., 2015), pineapples and bananas (Sauco, 2002), papayas (Kaur and Kaur, 2017; Salinas *et al*., 2021), peaches (Martinez-Gomez et 6.6. Significant constraints of growing fruits in Greenhouses. Although the greenhouse systems have their benefits, they have a number of limitations. The most notable constraints are a decrease in the level of light, inadequate chilling to start releases, high temperatures during hot seasons, and the inability to produce aromatic components under variable diurnal temperatures (Engler and Krarti, 2021). Besides, there are high costs of operation and infrastructure that require better energy efficiency and automation. High interiors temperatures could also cause a heat burden to laborers when flowering and picking (Castronuovo *et al*., 2017).

6.7. Light Deprivation in areas with high latitude

In colder latitudes, greenhouse fruit trees can be affected by light limitations, which is a reason of thick canopies and unfavourable sun angles (Trepanier, 2024). Summer pruning is necessary under these circumstances to ensure sufficient light levels especially when the peach fruit is at the third stage of development (Musacchi, 2018). Lower irradiance changes the pigment reduction of leaves, lowering the chlorophyll a/b ratios, and the performances of Photosystem I and Photosystem II, as observed in nectarines and apricots (Wang *et al*., 2007; Sun *et al*., 2008). Hence, canopy architecture and light control optimization are of much importance in high latitude secured systems.

6.8. Getting over the Dormancy and Chilling Requirements

Chilling of the fruit is a crucial problem in the production of greenhouse fruit, with temperatures above 19 deg C blocking the release of dormancy (Salama *et al*., 2021). Evaporatively cooled artificial chilling systems and micro-sprinklers may be useful in reducing the temperatures of buds (Martinez-Gomez *et al*., 2021; Erez *et al*., 1998). Also, to achieve a successful adaptation to the greenhouse, it is crucial to select cultivars that have low chilling violations (Campoy *et al*., 2011; Rodriguez *et al*., 2021). Although chemical agents are used, they include mineral oils, calcium cyanamide ($CaCN_2$), hydrogen cyanamide (H_2CN_2), and dinitro-ortho-cresol and are used to artificially induce budbreak (Petri *et al*., 2013). Other biostimulants that are eco-friendly like garlic extracts with diallyl disulfide have demonstrated potential effects as biostimulants that are non-toxic in granting dormancy breakage in grapes and apples (Wang *et al*., 2007; Kubota *et al*., 2000). Both the timing and method of applying such treatments are important, as timely action may cause a phytotoxic effect, or the release of dormancy may require an excessive amount of time (Erez, 1995; Erez *et al*., 2008, Sabir *et al*., 2025). In recent studies, the authors note that biostimulant application should be matched with the physiological condition of the buds in order to enhance uniformity of flowering and fruit set (Prudencio *et al*., 2018, 2019).

6.9. Stress at High Temperature and Thermal Management

In greenhouse production, temperature control is a requisite to a successful fruit production (Kawasaki and Yoneda, 2019). Prolonged high temperatures (above 35°C) have the ability to affect reproductive development, yield less fruit set, and it leads to premature drop of fruits (Erez *et al*., 1998; 2000). Ideal temperatures of peaches are about 23°C when blooming, 25°C when budbreak and 30°C when fruit swell (Bielenberg and Gasic, 2022). Going past these patterns causes over vegetative growth and loss of color formation (Koshita, 2014). In order to reduce the impact of thermal stress, shading nets, ventilation lights, or removable plastic nets have been widely applied, although they add up to higher costs of operations and exposure to pests (Wang *et al*., 1999). Abundance of heat may also reduce chlorophyll a/b ratios and lead to root hypoxia among nectarines (Wang *et al*., 2007).

6.10. CO_2 Enrichment and Photosynthetic Efficiency

Since CO_2 is the major energy source in photosynthesis the level of concentration directly influences the growth and yield (Idso and Kimball, 1992). CO_2 concentrations in greenhouses tend to increase at night during respiration and decrease to below 200 ppm on bright days (10:00-14:00), which restricts photosynthesis. Enrichment with supplemental CO_2 has effectively been used on a variety of horticultural crops- grapes, peaches, strawberries and tomatoes and it has led to the enhancement of growth and productivity (Castilla, 2013). Increases in CO_2 level augment photosynthetic rates and fruit size of peach and orange trees (Xi *et al*., 2014).

6.11. Aroma Composition and Fruit Quality

The UV-absorbing compounds incorporated in the light-filtering polyethylene films enhance the look and pigmentation of fruits at different temperature conditions (Erez *et al*., 1998). Strong diurnal change of temperature intensifies synthesis of anthocyanin and coloration of the skin (Layne *et al*., 2013). Relative analysis of volatile compounds in Cavendish bananas showed that bananas produced in the open-field had a marginally larger overall amount of aroma compounds (80 vs. 76 compounds) that were largely esters and aldehydes in composition (Selli *et al*., 2012). However, the bananas cultivated in greenhouses had similar aromatic richness and better visual quality, thus proving the prospects of the guarded farming in the balancing of the sensorial competence and environmental managing.

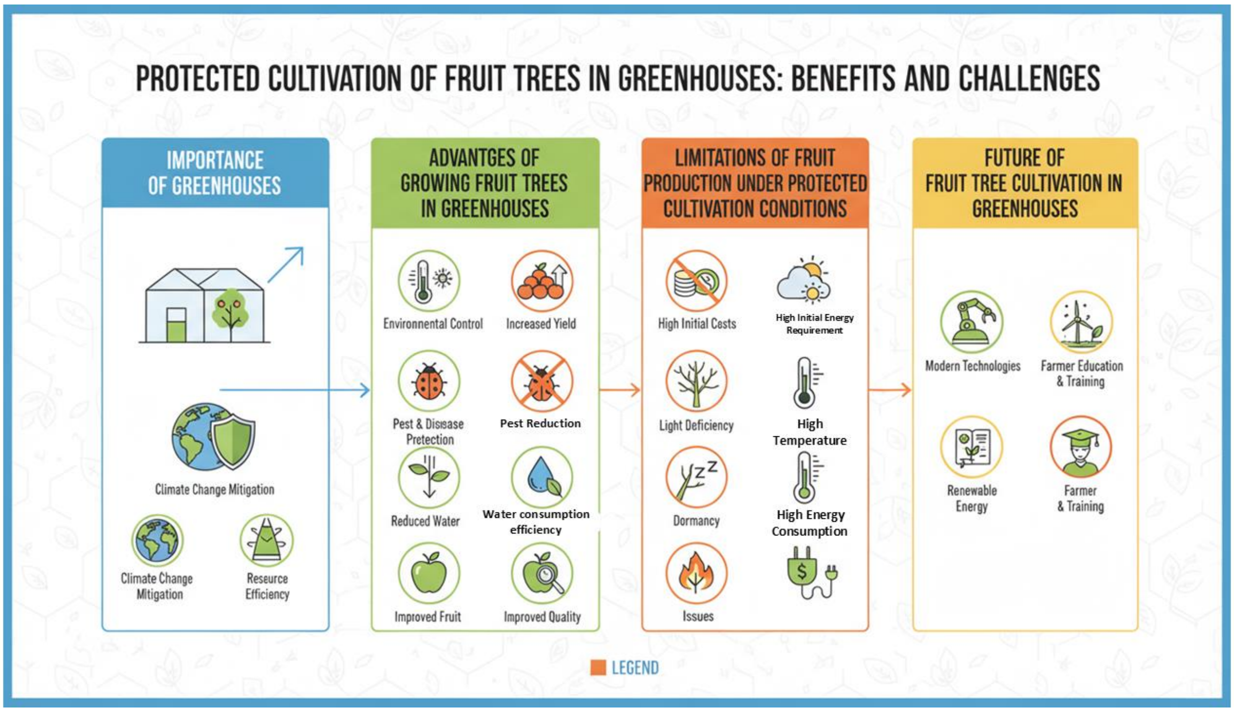

Figure 1. Conceptual framework summarizing the importance, advantages, limitations, and future perspectives of fruit tree cultivation under protected greenhouse conditions.

7. Limitations of Fruit Production Under Protected Cultivation Conditions

Despite the substantial advantages of protected cultivation, fruit production under greenhouse conditions is subject to several biophysical and phytosanitary constraints. Inadequate solar radiation, suboptimal or highly fluctuating temperatures, imbalanced humidity (either deficient or excessive), weed interference, wind dynamics, and variability in atmospheric CO_2 collectively limit the physiological performance of fruit trees (Aman *et al*., 2018). These factors are all directly or indirectly governed by climatic conditions; protected cultivation moderates but does not completely eliminate their impact.

Moreover, greenhouses cannot be considered hermetically sealed systems. While they provide a physical barrier, complete exclusion of pests and pathogens is unrealistic. Airborne spores and bacteria-laden particles can enter through doors, vents, and structural gaps. Dust carried by wind can introduce soil-borne microorganisms via footwear, tools, and machinery. Insects that penetrate greenhouse openings act as vectors for viruses, bacteria, and fungi, and irrigation water itself may serve as a reservoir for aquatic or water-dispersed pathogens (Singh *et al*., 2019). Once established inside a protected structure, these organisms may proliferate rapidly due to the favorable microclimate, making eradication technically challenging and often economically costly. Consequently, fruit production under protected conditions requires continuous implementation of rigorous integrated pest and disease management strategies rather than relying solely on physical exclusion.

8. Strategies for Increasing Productivity in Greenhouse Fruit Systems

8.1. Integration of Modern Digital Technologies

The adoption of digital agriculture tools, particularly artificial intelligence (AI) and Internet of Things (IoT) technologies, is transforming greenhouse fruit production. Networked sensors, actuators, and decision-support algorithms enable precise and real-time control of environmental variables such as temperature, relative humidity, light, and soil/substrate moisture.

- **Smart irrigation systems** use soil and air moisture sensors to determine optimal irrigation timing and volume, minimizing both water wastage and the risk of waterlogging or nutrient leaching.
- **Automated climate control** systems respond dynamically to sensor feedback, adjusting ventilation, heating, cooling, and humidification/dehumidification devices to maintain target microclimatic set-points.

Such technologies improve resource-use efficiency, reduce labor requirements, and decrease human error, thereby increasing productivity and stabilizing fruit yield and quality.

8.2. Use of Renewable Energy in Protected Systems

Energy consumption is a major cost component in greenhouse fruit production (Taki *et al*., 2012). Integrating renewable energy sources, particularly solar photovoltaics and wind energy, can partially or fully offset the demand for fossil fuel–based electricity and heating (Mohammed, 2021). Solar-powered systems can supply energy for climate control, fertigation pumps, and automation units, thereby reducing operational costs and carbon footprints over the long term (Abdelhamid *et al*., 2025). Although the initial capital investment is substantial, the medium- to long-term economic and environmental benefits make renewable energy integration a strategic component of sustainable protected horticulture.

8.3. Farmer Education, Training, and Extension Services

The effectiveness of protected fruit cultivation critically depends on the technical capacity of growers. Training programs and extension services are essential to develop competencies in greenhouse design and management, climate regulation, irrigation and fertigation scheduling, pest and disease control, and the use of digital and renewable technologies. Targeted capacity-building programs for orchardists and greenhouse managers enhance adoption of best practices, reduce management mistakes, and facilitate the diffusion of innovative technologies from research institutions to commercial production settings (Kalogiannidis and Syndoukas, 2024).

9. Challenges and Issues in Fruit Production in Greenhouses

Although greenhouse fruit production is a promising pathway for intensification and climate resilience, it is accompanied by several structural, economic, and technical challenges.

9.1. High Construction and Establishment Costs

The installation of high-quality greenhouses for fruit trees requires substantial capital investment. Costs include structural components (frames, glazing materials, anchors), climate-control systems (ventilation, heaters, cooling systems), irrigation and fertigation infrastructure, and automation hardware (Raju *et al*., 2025). For many small and medium-scale growers, these upfront costs constitute a major barrier to adoption and necessitate access to credit or governmental subsidy schemes.

9.2. Need for Technical Knowledge and Specialized Expertise

Greenhouse fruit production is inherently more complex than conventional open-field cultivation. Successful management requires a multidisciplinary understanding of horticulture, greenhouse engineering, plant nutrition, irrigation science, and plant protection. Farmers with limited experience in controlled-environment agriculture may face a steep learning curve, increasing the risk of suboptimal management and economic loss if appropriate training and technical support are not available (Weser, 2025).

9.3. High Energy Consumption and Associated Costs

In regions with cold winters or hot summers, the energy required to maintain suitable temperatures inside greenhouses can be considerable. Heating during cold periods and cooling during heat waves increase production costs and may reduce the economic viability of greenhouse systems, particularly where energy prices are high or energy infrastructure is unreliable. Improving insulation, adopting energy-efficient technologies, and integrating renewable energy sources are therefore critical for long-term economic sustainability (Soussi *et al*., 2022).

9.4. Selecting the Right Plant Cultivars for Greenhouse Conditions

The choice of fruit species and cultivars is a key determinant of success in protected systems. Cultivars must be compatible with the microclimatic conditions and cultural practices typical of greenhouse environments such as altered light regimes, restricted root volumes, and potential limitations in natural pollination. Some species or cultivars may have specific chilling, light, or pollination requirements that are difficult to reproduce under all greenhouse configurations, necessitating breeding and selection for greenhouse-adapted genotypes.

9.5. Energy Planning and Management

Beyond total energy consumption, the temporal distribution and reliability of energy supply are critical. In regions where artificial lighting, heating, or cooling are indispensable, inadequate energy management may lead to microclimatic instability, plant stress, and yield loss. The integration of solar or other renewable sources can reduce long-term dependence on conventional energy, but their deployment requires careful planning, significant initial investment, and technical capacity for maintenance. In cold climates, the continuous demand for heating may remain high even when renewables are used, underscoring the importance of structural insulation and climate-smart greenhouse design.

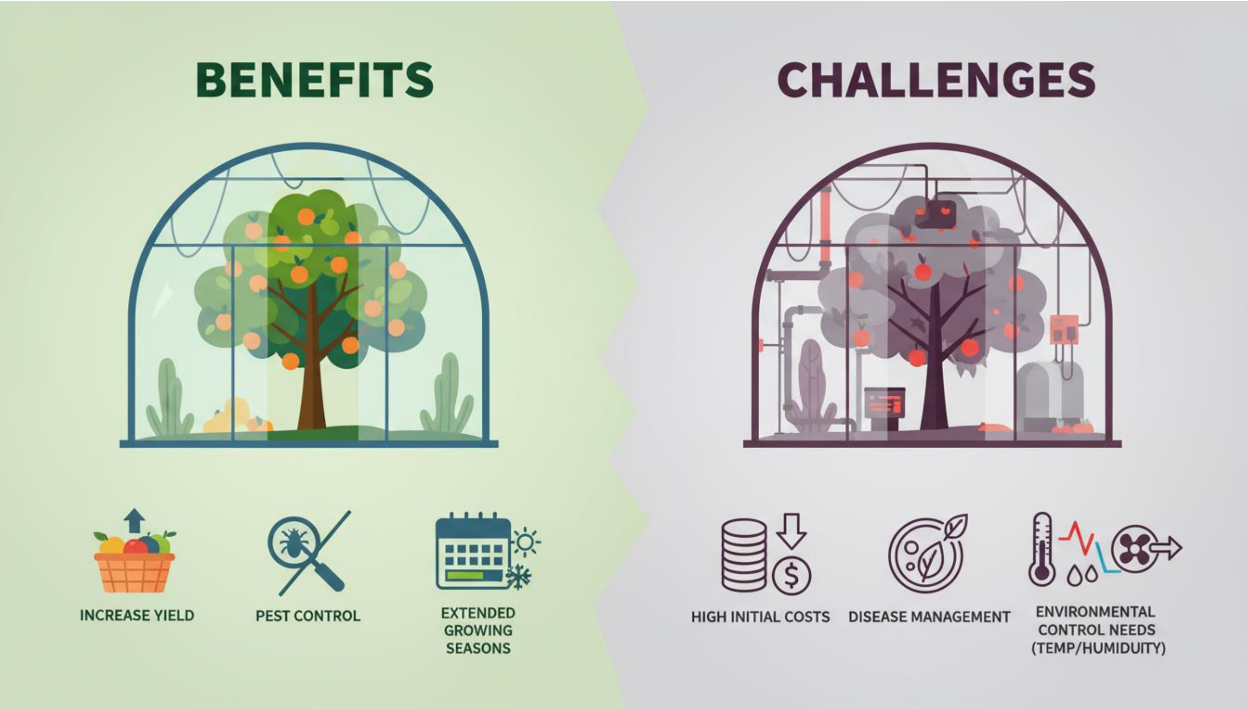

Figure 2. Comparative summary illustrating the major benefits and challenges associated with greenhouse-based fruit tree cultivation.

9.6. Pollination

Pollination is one of the most critical yet challenging aspects of fruit tree cultivation in greenhouses. Many temperate and subtropical fruit species rely on insect-mediated pollination, and the enclosed environment can restrict the activity of natural pollinators such as honeybees and bumblebees. Limited air movement and reduced floral scent dispersion may further hinder pollen transfer. To overcome these limitations, growers often rely on managed pollinators introduced into the greenhouse, mechanical vibration techniques, hand pollination, or the use of parthenocarpic cultivars. Each method has advantages and constraints. For example, while bumblebees perform well in protected environments, their efficiency can be reduced under high temperatures or artificial lighting. Moreover, variations in floral biology among fruit tree species such as flower size, anther dehiscence, and stigma receptivity require species-specific pollination strategies. Thus, successful pollination in greenhouse orchards depends on optimizing both biological and environmental factors to ensure adequate fruit set (Halder *et al*., 2019).

9.7. Chilling Requirement

Many deciduous fruit trees, including cherries, peaches, apples, and apricots, require a specific amount of winter chilling to break dormancy and ensure synchronized flowering (Fadón *et al*., 2020). In controlled-environment agriculture (CEA), fulfilling chilling requirements becomes complex, especially in mild or warm regions where natural cold accumulation is insufficient. Greenhouses can inadvertently reduce natural chilling due to heat retention, making endodormancy release even more difficult. To address this issue, growers may adopt artificial cooling techniques, such as nighttime ventilation, evaporative cooling, shading, or the use of growth regulators that partially substitute for natural chilling. However, these approaches may be costly or inconsistent in their effects. Failure to meet chilling requirements can result in uneven bud break, reduced flower quality, poor fruit set, and lower yields, making it essential to integrate chilling management into greenhouse design and production planning.

9.8. Energy Costs

Energy consumption represents one of the most significant constraints in greenhouse fruit tree production. Heating, cooling, ventilation, supplemental lighting, and automated irrigation systems all contribute to substantial operational costs. Energy demands become particularly high in climates requiring intensive heating during winter or cooling during summer. For perennial fruit crops, which remain in the structure year-round and have large biomass, maintaining optimal temperatures is more challenging and energy-intensive than for short-cycle vegetable crops. To mitigate costs, modern systems incorporate renewable energy sources, such as geothermal heating, solar panels, heat pumps, and thermal storage units. Improving insulation, using energy curtains, and optimizing climate-control algorithms can also enhance energy efficiency. Despite these advancements, high energy consumption remains a primary barrier to large-scale adoption of greenhouse fruit orchards, especially in regions with high energy prices (Soussi *et al*., 2022).

9.9. Fruit Quality Changes

Controlled environments can significantly influence fruit quality, leading to both improvements and challenges. Greenhouses allow precise regulation of temperature, humidity, and light, which can enhance fruit size, uniformity, color development, sugar accumulation, and overall marketable quality. Stress factors common in open-field cultivation—such as wind, excessive rain, and extreme temperatures—are minimized, reducing cosmetic defects and improving shelf life. However, some fruit species may show altered flavor profiles or reduced secondary metabolite accumulation when grown under highly controlled conditions, especially if light spectra or intensity are suboptimal. Limited UV exposure may decrease the synthesis of pigments, antioxidants, and aromatic compounds in certain fruits. Additionally, rapid growth under high relative humidity can make fruits more susceptible to softening or postharvest disorders. Achieving optimal fruit quality therefore requires a careful balance between environmental control, cultivar selection, and tailored management practices (Zhao *et al*., 2024).

10. Future Prospects for Fruit Tree Cultivation in Greenhouses

Protected horticulture is evolving rapidly and is poised to play an increasingly central role in meeting global fruit demand under conditions of climate uncertainty and resource scarcity.

10.1. Advanced Technologies and Automation

Future greenhouse fruit systems are expected to rely heavily on intelligent control technologies, including robotics, machine vision, big-data analytics, and AI-based decision support. These tools can optimize canopy management, targeted harvesting, pest detection, and input application at fine spatial and temporal scales. Data-driven management will enable more precise control of microclimate and resource allocation, improving both productivity and environmental performance.

10.2. Supportive Policy and Financial Incentives

Public policies will be crucial in scaling up greenhouse fruit cultivation. Financial incentives—such as low-interest loans, investment subsidies, tax relief, and risk-sharing schemes—can help offset high initial establishment costs. Educational and advisory programs can support farmers in adopting and optimizing protected systems. Such measures have the potential to reduce dependency on fruit imports, strengthen domestic production capacities, and improve national food security.

10.3. Mitigating and Adapting to Climate Change

Greenhouse's systems offer a practical tool for climate change adaptation, enabling growers to buffer crops against extreme weather events, erratic rainfall, and temperature anomalies. When combined with efficient energy use and renewables, protected cultivation can also contribute to climate mitigation by improving input-use efficiency and reducing wastage. Intelligent climate management, water-saving technologies, and resilient cultivar choice will make greenhouse fruit systems pivotal in sustaining production under future climate scenarios.

11. Discussion

Meeting the rising global demand for nutritious food hinges on substantially increasing fruit production, especially as population numbers climb and consumer habits shift toward healthier diets (Ruel *et al*., 2017). However, expanding the land area available for fruit orchards is becoming increasingly difficult due to rapid urban growth, industrial development, and competition for agricultural land (Knorr *et al*., 2018). Under these limitations, improving productivity through intensive, technology-driven systems offers a more realistic path than expanding cultivation area. Among the available approaches, greenhouse-based fruit production has emerged as a promising option. Protected fruit cultivation has grown across many regions of the world because it allows farmers to deliver premium-quality fruits outside their natural harvest seasons and shields production from erratic weather (Uma and Kumar, 2025). Although greenhouse systems for fruit crops are less mature than those for vegetables, several species such as citrus, grapes, cherries, lychees, peaches, and mangoes perform remarkably well under controlled conditions (Jat *et al*., 2020). These systems help growers secure off-season markets and access export channels that increasingly prioritize produce with minimal chemical residues. To capitalize on these opportunities, there is a strong need to design protected structures that are tailored to local climates and economies, relying on affordable, durable materials and region-specific engineering solutions (Paroda, 2014). Policy support is especially vital for perennial crops, which require considerable initial investment and have longer economic cycles than short-term horticultural crops (Scott *et al*., 2022). Well-designed subsidies, credit programs, and risk-sharing mechanisms can significantly reduce financial pressures on growers (Li *et al*., 2025). Greenhouse technology also opens pathways for cultivating fruit crops in regions previously considered unsuitable for orchard development, thereby broadening production zones (Ahmed *et al*., 2024). Progress in this sector will depend on collaboration among government agencies, research institutions, and private enterprises. Strengthening technical capacity through demonstration farms, training initiatives, and extension services led by universities and research organizations will be essential for encouraging grower adoption. Incentive programs that improve profitability and reduce financial risk can stimulate employment creation, nurture local entrepreneurship, and support rural and peri-urban economic development. In this light, greenhouse fruit farming should not be treated as a specialized or marginal practice, but as an important component of future horticultural systems capable of responding simultaneously to land scarcity, climatic instability, and evolving market expectations.

Conclusion

Cultivating fruit crops in greenhouses represents an important shift in contemporary horticulture, offering producers the ability to manage crop environments with precision and deliver high-quality fruits consistently. Advances in automated irrigation, environmental sensors, and artificial lighting have substantially strengthened growers' capacity to manage plant growth, enhance yields, and stabilize fruit characteristics. Beyond productivity benefits, protected cultivation contributes to more efficient water use, reduces vulnerability to pests and diseases, and mitigates the effects of unpredictable weather. Successful greenhouse fruit production relies on multiple interconnected factors, including thoughtful system design, appropriate growing substrates, careful selection of cultivars and rootstocks, dependable pollination strategies, and fine-tuned environmental control. When integrated effectively, these elements enable productive cultivation even in areas with harsh or unfavorable climates, supporting broader goals for food security and sustainable agricultural development. Despite these advantages, several challenges continue to slow adoption. The high cost of establishing greenhouse infrastructure, substantial energy requirements, and the need for specialized technical expertise remain significant barriers. Overcoming these obstacles will require coordinated solutions—ranging from technological improvements and supportive financial frameworks to comprehensive training programs for growers. Further scientific research is also needed, especially on adapting greenhouse designs, refining climate-smart management practices, and understanding fruit crop physiology under protected conditions. Given increasing climate uncertainty, the pressures of urbanization, and the need for stable food supplies, the expansion of greenhouse fruit production is becoming not only beneficial but increasingly essential. Perennial fruit species, despite occupying relatively limited land areas, offer consistent, nutrient-dense harvests that align with year-round consumer expectations, making them particularly suitable for protected cultivation. Strengthening financial assistance for growers and creating targeted training programs especially for unemployed or highly educated youth—can help build a robust workforce and stimulate entrepreneurship in protected horticulture. Maximizing the benefits of greenhouse fruit production will ultimately depend on sustained investment in infrastructure, scientific innovation, and human capacity. With adequate support, protected fruit systems can become a cornerstone of long-term food security, improved diet quality, and environmentally responsible horticultural development.

Conflict of Interest

The author declares that there is no conflict of interest, whether commercial, non-commercial, or personal, either directly or indirectly related to the published work.

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