



The Significance of Controlled Environments in Shaping the Future of Fruit Cultivation

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ABSTRACT

The escalating challenges presented by climate change, soil erosion, and a rising global population demand the adoption of innovative agricultural practices, especially within the realm of protected cultivation. This paper explores the significance and advancements in greenhouse and controlled cultivation techniques, focusing on fruit production. In fruit tree cultivation, employing greenhouse management science and implementing control and protection measures throughout the growth process can create ideal plant conditions. This approach facilitates the achievement of various objectives, producing fruit outside the primary environment, generating early-season fruit and off-season crops, and the potential to yield multiple harvests within a single growing season. Additionally, this approach effectively addresses numerous challenges fruit trees face, including drought, climate change, temperature stress, damage from hail, sunburn, and pest attacks, ultimately enhancing plant performance and quality. Despite these ongoing challenges, it improves production and increases efficiency. In this context, a specialist must constantly monitor the plants to control vegetative growth and enhance flowering through professional tree canopy and root pruning. Furthermore, a greenhouse specialist should be well-versed in the role of hormones in the physiological mechanisms of trees to induce flowering, accelerate the ripening process for off-season production, and meet chilling requirements and other needs. Actions such as controlling the atmospheric conditions within the greenhouse and monitoring the nutrient composition of the growing medium are also crucial for enhancing tree growth. Consequently, cultivating fruit trees in a greenhouse can increase yield and net profit while conserving water, soil resources, and solar energy.

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1. Introduction

Agriculture faces numerous challenges, including drought, climate change, soil erosion, and other environmental stressors, all while needing to support a growing global population. Given the challenges facing agriculture, proper planning can significantly reduce many threats. Agriculture is one of the pillars of national power and security for any country, as ensuring food security relies on sustainable agriculture. The agricultural sector is considered one of the most important economic areas of the country due to its role in providing the food needed by society. As a result, the development and expansion of protected cultivation methods have become essential (Khan, 2018). In recent years, the construction of greenhouses for agricultural product production has given a special status to this type of production, and controlled environmental agriculture (CEA) is expanding as a high-efficiency production method (Zarei, 2017). The leading countries in protected agriculture are Spain, Italy, China, the United States, and Germany. These findings confirm that Europe excels in greenhouse agriculture, representing more than 43% of the global greenhouse area. Spain, France, Greece, Italy, and the Netherlands are noted for their extensive protected cultivation, with Spain at the forefront, covering 71,783 hectares, particularly in agricultural areas like Almería province (Villagrán *et al.*, 2023). The greenhouse industry is growing due to technological advancements and increasing demand for controlled-environment crops. Iran is expanding its greenhouse sector to improve food security and water efficiency, with exports focused on regional markets. The area of existing greenhouse cultivation in Iran was nearly 16,000 hectares in 2024. This area was predicted to expand to about 48,000 hectares by 2025, but this did not occur (Reported YJC, 2025). Improving the productivity of fruit crops through technological advancements such as protected cultivation is of utmost necessity, and today, greenhouse cultivation of fruit products is rapidly increasing worldwide (Jat *et al.*, 2020).

The use of different methods for producing crops through protected cultivation is rapidly expanding (Bodiroga *et al.*, 2018). The advantages of protected cultivation, which are highly important, include increasing the cultivated area, overcoming unfavorable climatic conditions, mitigating the harmful effects of climate change, improving water management, enhancing fruit quality, and reducing postharvest losses (Yonemori, 2009). In general, the environmental benefits of protected cultivation extend beyond yield improvement. These systems contribute to water conservation and efficient nutrient management, critical to climate change. By minimizing excessive water use and reducing fertilizer runoff, protected cultivation promotes sustainable agricultural practices and enhances long-term food security (Naresh *et al.*, 2024). The most significant advantage of this cultivation is its ability to bring crops to market earlier and produce off-season products, which is associated with high pricing (Takakura, 1988).

However, despite these benefits, protected cultivation presents challenges such as high greenhouse construction costs, a shortage of trained and skilled labor for construction and maintenance, inadequate guidance for structures in various regions, the promotion of similar greenhouse designs and other protected structures without considering the specific needs of different climatic areas, the height of fruit trees, pollination issues, and the chilling and light requirements for plants. To promote protected cultivation, companies often recommend products without considering suitable climatic conditions and sometimes mislead farmers by claiming high profits for the products they endorse. Protective cultivation challenges are the lack of demand-driven practices and ineffective marketing strategies. Protected cultivation requires substantial resources, including water, energy, and labor (Singh, 2013).

Various structures are utilized in protected fruit cultivation, including shading systems, high tunnels, and modern greenhouses. Additionally, traditional methods like straw and soil can protect fruit trees in specific growing conditions. Shading techniques allow for cultivating a wide range of horticultural products across diverse regions, while high tunnels and

greenhouses contribute to increased yields and extended growing seasons. The success of any technological advancement in agriculture hinges on balancing lower production costs with higher yields, extending the lifespan of cultivation structures, reducing initial investment costs, maintaining product quality, and aligning with market demands (Lenka, 2020).

Expanding on the foundational knowledge of protected cultivation in agriculture, recent research has explored its diverse benefits and challenges in greater detail. A thorough review by Jain *et al.* (2023) reveals that protected cultivation not only improves yield and quality but also provides a sustainable approach to countering the negative impacts of climate change on horticultural production systems. The study highlights sustainable methods to address environmental challenges and support ecological balance to produce horticultural crops (Jain *et al.*, 2023). Thorat *et al.* (2023) reported that protected fruit cultivation has rapidly grown into a significant fruit farming sector, allowing for precise control over environmental factors that enhance growth and increase crop yields. This review discusses the introduction to protected cultivation, various methods for growing fruit crops, suitable fruit varieties, their outcomes, and other pertinent information (Thorat *et al.*, 2023).

Technological advancements in controlled environments, such as Artificial Intelligence (AI) and automation, have significantly improved the efficiency of protected cultivation. For example, Hosseinzadeh *et al.* (2024) discussed AI-driven innovations in greenhouse agriculture. They reported that AI significantly improves energy efficiency, and its benefits for CO₂ reduction, resource use, crop quality, and profitability remain limited. Furthermore, recent studies highlight the role of genetic advancements in protected cultivation. Researchers have been working on breeding horticulture cultivars suited explicitly for controlled environments and highlighting the role of advanced breeding tools such as genomics, marker-assisted selection, and high-throughput phenotyping to enhance crop profitability and industry growth (Bhattarai *et al.*, 2024).

As mentioned, controlled environment agriculture offers significant advantages for horticultural crop cultivation. However, challenges such as high costs, knowledge gaps, and the need for technological advancements must be addressed. Unlike other agricultural and horticultural crops, the challenges of cultivating fruit trees under controlled conditions have been less studied. Therefore, this paper aims to explore these challenges and identify practical solutions to optimize controlled fruit cultivation.

2. Fruit Production in Controlled Conditions

Fruit production has a direct impact on a country's gross domestic product. China is a leader in greenhouse fruit production, with the largest cultivation area. With 6.5 million hectares of land cultivated for fruit crops, India is the second-largest fruit-producing country after China, with a significant portion of land dedicated to protected cultivation. Strawberries are the only fruit crop that is commercially and profitably grown under protected cultivation in India (Lenka, 2020). Yields of various crops are higher in greenhouse production than in open-field production. For instance, the average yield of tomatoes in open-field production systems was 23.02 t/ha. In contrast, the average yield of tomatoes from greenhouse production systems reached 112.59 t/ha, nearly five times higher (Savvas *et al.*, 2015). It has also been reported that tomato production under greenhouse conditions can increase 15 times compared to open-field production (Padmanabhan *et al.*, 2016). Furthermore, tomatoes grown in open fields have a better flavor than those cultivated in greenhouses. However, the lycopene levels in mid- and late-season fruits may be lower due to the high temperatures encountered in open-field conditions (Singh *et al.*, 2021). Fruit crops with exceptional yield potential under protected cultivation include raspberries, papayas, loquats, grapes, bananas, apples, plums, peaches, strawberries, mangoes, etc. Benefits such as protection against wind, reduced water requirements, and protection against Sigatoka disease all contribute to yield advantages. By

using shading network techniques, better positioning can be achieved despite geographical weaknesses. For example, strawberry cultivation is generally carried out in the hilly regions of India. However, through protected cultivation, it can be grown in any condition (Lenka, 2020). Various fruits, such as strawberries (*Fragaria × ananassa*), grapes (*Vitis vinifera*), cherries (*Prunus avium*), apricots (*Prunus armeniaca*), citrus (*Citrus spp.*), plums (*Prunus domestica*), and peaches (*Prunus persica*), have proven successful for protected cultivation worldwide. Three major commercial crops—bananas (*Musa spp.*), pineapples (*Ananas comosus*), and papayas (*Carica papaya*)—are cultivated in greenhouses in subtropical regions. Greenhouse mango cultivation (*Mangifera indica*) is done in Japan (Jat *et al.*, 2020).

3. Greenhouse structure for fruit production

The protected cultivation should enhance performance, thereby increasing the profit-to-cost ratio. Various methods for producing fruit trees under protected cultivation include greenhouses, high and low-tunnel systems, and net houses (Chaurasia and Penumarthi, 2023). Higher marketable yields were achieved in the high tunnel and net house compared to the open field due to increased plant growth, a more extended harvest period, reduced pest presence, and a more significant proportion of marketable fruit (Kong *et al.*, 2020).

Greenhouses allow owners to control water and climate, nutrition, biological factors, and managing cultivation variables that affect crop growth and development. Thus achieving optimal conditions at various stages of crop growth. Additionally, they enable the production of off-season horticultural products (Rodríguez *et al.*, 2015). Greenhouses are framed structures covered with transparent materials large enough to grow crops under slightly or completely controlled environmental conditions for optimal growth and productivity. Leading farmers currently utilize protected commercial cultivation; generally, no greenhouse can be identified as the best. Various types of greenhouses have been designed to meet specific needs. Local climatic conditions and individual requirements play a significant role in model selection. For instance, in areas with high greenhouse heating costs, such as high latitudes in China, precision irrigation systems were utilized to decrease water usage and offset heating expenses while maintaining yield (Guo *et al.*, 2024). Depending on the type of greenhouse, crop, and environmental control facilities, the yield may be 10-12 times greater than that of open-field cultivation (Pandey and Pandey, 2015). Various types of greenhouses are used for cultivating fruit trees, but due to high costs, modern and well-equipped greenhouses are primarily reserved for high-value fruit trees (Chaurasia and Penumarthi, 2023). In Iran, modern greenhouse facilities produce strawberries, papayas, bananas, citrus fruits, and some tropical fruits (Fig. 1).



Fig. 1. Cultivating lemons in a modern greenhouse in Mazandaran, Ira

Although high tunnel systems resemble greenhouses, they typically lack precise environmental control systems. They are primarily used to extend the growing season, raise temperatures by a few degrees Celsius, and mitigate certain environmental limitations. These systems are particularly effective for extending the growing season, promoting early ripening, and enhancing the production of berries (Chaurasia and Penumarthi, 2023). The application of high tunnels at two Michigan State University experimental stations on sweet cherry (*Prunus avium*) improved fruit quality and product value, increased leaf size, and reduced chemical pesticide usage; the occurrences of cherry leaf spot (*Blumeriella jaapii*) and bacterial canker (*Pseudomonas syringae*) declined (Lang, 2009).

Net houses, covered with protective netting, shield crops from pests and diseases while allowing ventilation and natural light penetration. The effect of using shade nets on crops leads to various changes in microclimate and crop activity. Shading nets in horticulture are classified alongside greenhouse cultivation and fall under the category of protected horticulture, which includes multiple designs and types based on region, usage type, and application goals. The use of shade nets to protect various horticultural products from various abiotic factors such as intense radiation, excessive wind speed, and damage from birds and rodents, along with improving thermal climate (Kittas *et al.*, 2008) and viral diseases transmitted by insects, is being implemented (Teitel *et al.*, 2007). The difference in light intensity in shade nets compared to typical farm conditions is evident, and they can adjust various spectral qualities, which significantly affects plant growth and development. Shade net structures use various reduction materials such as plastic, wood, and galvanized iron (GI) pipes, with angled iron being a framed structure's components. This framed structure is primarily covered with plastic mesh, mainly made from polyethylene materials. Alternating the percentage of shade, which results from the reduction of light intensity and heating parameters, corrects the microclimates of the crops. Since different crops require varying light durations, this can be partially managed by shade net structures capable of controlling abiotic parameters. It is crucial that before constructing the structure, the shade nets should consider the type of crop being grown, local climatic conditions, and locally available materials (Figure 2). There should be sufficient facilities for future development, which is key to plans (Lenka, 2020).



Fig. 2. Cultivating apples under net house in Khorasan Razavi, Iran

The location of the shade structure is critical under current conditions. The distance between the shading network, market location, and essential communication routes is crucial. The prevailing wind direction and the intensity of sunlight are two key factors for orienting the shade house. A north-south orientation is more suitable for optimal solar radiation capture. On the other hand, shade structures act as windbreaks and should be positioned perpendicular to the prevailing wind direction. The main frame and the metal covering materials are two of the most essential components of shade structures. The frame of the shade structure serves as a base for the covering materials. It helps protect against natural forces and weather anomalies such as heavy rain, strong winds, hailstorms, and intense radiation. The design of shade house models depends on climatic conditions and the intensity of use (Lenka, 2020).

Different types of controlled cultivation manage the climate; southeastern Spain has a semi-tropical, semi-arid, and Mediterranean climate with hot, dry summers and mild winters. The high summer temperatures (above 40°C) and cold winters (sometimes below 10°C) are the main climatic challenges. In these conditions, the successful cultivation of tropical fruits like mangoes is possible in open fields. In contrast, papayas require protected cultivation, at least during the cooler months from November to March, although they gain clear advantages from more extended protection. Papaya cultivation in Spain is carried out in parallel greenhouses with low technology, at a height of 3.5 to 4 meters, in a covered manner. The upper part of the greenhouse plastic is known as raspa and is supported by galvanized beams and woven wire tubes or wire strands. The lower part of the greenhouse roof (amagado) is connected to the structure by iron forks attached to the greenhouse base. The plastic covering is made of high-density polyethylene with a thickness of 200 micrometers.

Increasing the greenhouse height has been observed to meet the needs of some plants, such as papaya, as some cultivars easily exceed 5 meters at the end of the crop cycle. The greenhouse climate must be managed to prevent overheating in the summer. Most greenhouses are equipped with natural ventilation and windows on the sides. The plastic covering is also partially separated from the primary columns to improve ventilation and reduce internal temperatures in the summer. Various techniques used for protected cultivation include whitening the roof to lower the internal temperature of the greenhouse, as well as radiation, or using small ponds created between plant rows that evaporate water and increase relative humidity. Most advanced greenhouses also have roof ventilation and automatic opening and closing windows. The structure of advanced greenhouses allows for better climate control, but their costs are high. Various nebulization systems (pressure reduction and water-air) are being evaluated to improve temperature and relative humidity inside greenhouses. Heating systems for winter are also being studied. A new greenhouse structure with a climate control system designed explicitly for papaya cultivation on the Mediterranean coast in southeastern Spain has recently been constructed as part of a project called EUROPAPAYA, which is funded by European funding (FEDER-INTERCONECTA) (Hueso *et al.*, 2017).

4. Factors involved in fruit production under controlled conditions

Key factors influencing fruit tree cultivation in controlled conditions (Fig. 3) include 1) environmental management (regulating temperature, humidity, light, and CO₂ concentration), 2) water and edaphic management (selecting planting substrates, managing soil physical and chemical properties, ensuring proper nutrient supply, and maintaining water quality), 3) plant material (choosing suitable cultivars and rootstocks), and 4) tree management (optimizing planting systems, pollination, pruning, and the application of plant growth regulators (Martínez-Gómez *et al.*, 2021)). The following outlines key factors that significantly influence the cultivation of fruit trees in controlled environments. These factors are crucial for cultivating peaches (*Prunus persica*) and apricots (*Prunus armeniaca*) in greenhouse

environments. The unique characteristics of particular fruit trees, including their perennial nature, size, and the requirement to accumulate chilling hours to sprout, have posed new challenges in countries such as Japan (Shizuoka and Niigata prefectures), Korea (Wanju County), China (in the Provinces of Henan and Shandong), Italy (Region of Naples and Sicilia) and Spain (in the Province of Huelva, Southwest of Spain) (Martínez-Gómez *et al.*, 2021).

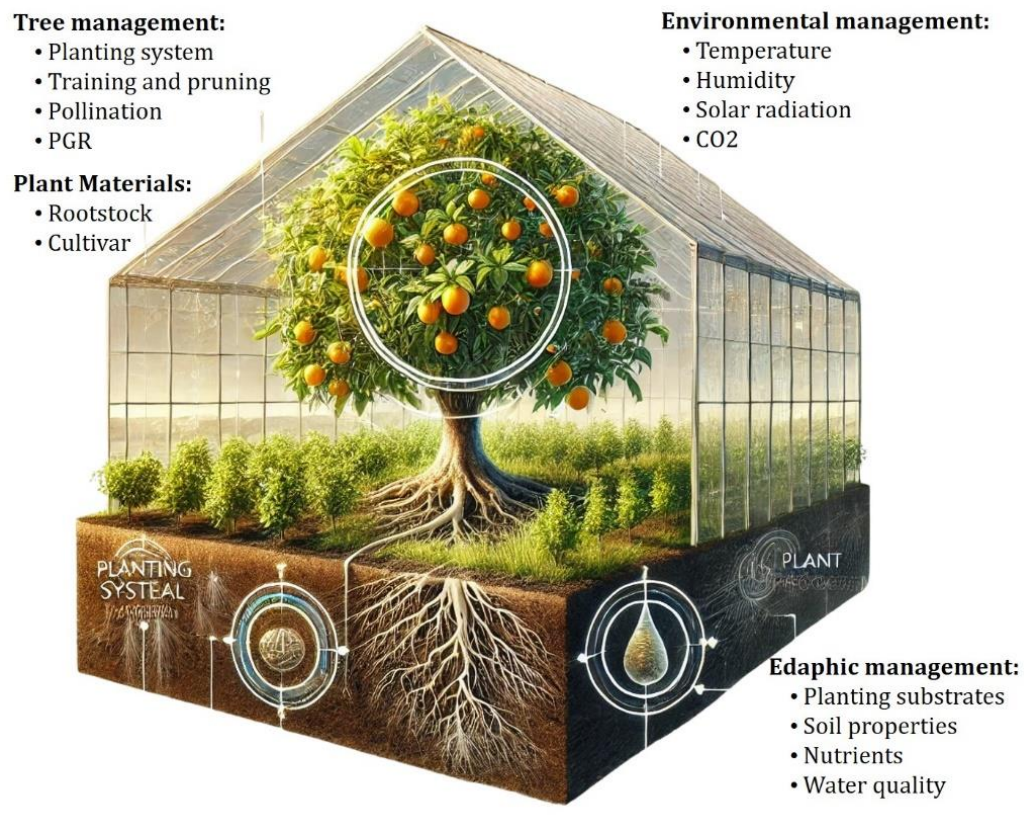


Fig. 3. Main factors involved in cultivating fruit trees in a greenhouse (Adapted from Martínez-Gómez *et al.*, 2021).

5. Management of Fruit Trees in Controlled Conditions

5.1. Environmental condition

Consumer demand for valuable food and societal concerns about sustainability and energy optimization make controlling greenhouse operations essential (Van Straten and Van Henten, 2010). Protected cultivation provides a controlled environment optimized to enhance various physiological processes in plants (Yamanaka *et al.*, 2021). A greenhouse that reduces or does not open windows is called a semi-closed or closed greenhouse. Maintaining ideal temperatures for enzymatic activities and metabolic processes is essential. Temperature extremes are minimized in protected environments, ensuring consistent growth conditions. Proper humidity levels reduce transpiration rates, prevent water stress, and facilitate efficient nutrient uptake. Evaporative cooling methods, such as misting, lower temperatures, and increased humidity, create a favorable microclimate for plant growth. Utilizing shading materials and adjustable shading systems helps regulate light intensity, prevents light inhibition, and maximizes photosynthesis (Yamanaka *et al.*, 2021). In a protected greenhouse cultivation, the concentration of CO₂ must be controlled. The concentration of CO₂ in the environment is crucial for producing the plant's photoassimilate. CO₂ is one of the natural

gases that make up the air and is vital for the life of plants and animals, playing a significant role in regulating air temperature. One of the fundamental issues in performance physiology is comparing the capacity for producing photosynthetic materials and the capacity for sink acceptance as limiting factors for further performance increase. The growth and development of plants are usually limited by photosynthetic sources, meaning the source is limited. Low sink demand typically reduces leaf photosynthesis, and a sink, like a fruit, delays leaf senescence. Several sinks can compete with each other for photosynthate absorption. After fruit removal, i.e., harvesting, the roots become the dominant sink. In apples, fruit removal led to starch accumulation in leaf chloroplasts, while soluble carbohydrates remained largely unaffected. A water potential gradient allows water to flow into the fruit. In general, fruit or sink regulates leaf photosynthesis, increases photosynthesis, Rubisco activity, dark respiration, stomatal conductance, transpiration, and water use efficiency (WUE), and prevents or delays leaf senescence, which is modified by environmental conditions (Blanke, 2007). In the greenhouse, the concentration of CO₂ is high in the early morning due to the respiration of plants within the greenhouse (Wang *et al.*, 2019). The "source" may be recognized in a plant as a tissue or organ that photosynthesizes with carbon skeleton export. The "sink" is recognized as something that requires carbon import, and the strength of the sink is defined as the ability of a tissue or organ to move photosynthate.

The sink capacity is defined as the capacity of a tissue or organ to absorb and store compounds from the source(s), and the activity of the sink is based on the respiration rate (Blanke, 2007). Photosynthesis is vital for controlling crop growth variables, and exposing C3 plants to CO₂ generally increases photosynthesis (Ainsworth and Long, 2005). The increase in photosynthesis due to CO₂ leads to increased carbohydrate production, which indirectly alters many physiological processes, mainly through the pathways that measure the plant's carbon and nitrogen metabolism. Aside from this direct effect on photosynthesis, carbohydrate and signaling regulation occur. Carbohydrates are recognized for their use as energy sources and building blocks of organic materials, and they also influence gene expression (Price *et al.*, 2004), germination (Dekkers *et al.*, 2004), and hormonal interactions (Mishra *et al.*, 2009), among other functions in plants. Despite the initial stimulation of photosynthesis observed due to CO₂, prolonged exposure to CO₂ decreases photosynthesis (Ainsworth and Long, 2005; Warren *et al.*, 2015).

Controlling temperature during the plant growth period is an important parameter that prevents the occurrence of temperature stress, such as frost and high-temperature burns in trees, while also meeting their chilling requirements. Extremely high or low temperatures often limit plant growth and crop production (Żróbek-Sokolnik, 2012). The plant response to heat stress is generally indicated by changes in the lipid composition of the cell membrane and the activation of endogenous detoxification mechanisms (Yancey, 2020). Excessive solar radiation, often associated with global warming and climate change, can significantly increase the fruit surface's temperature, resulting in sunburn and a complete loss of fruit quality (Racsko and Schrader, 2012). Various studies have reported that inoculation with plant growth-promoting rhizobacteria (PGPR) can enhance the tolerance of grapevines to low temperatures (Ait Barka *et al.*, 2006; Fernandez *et al.*, 2012; Theocharis *et al.*, 2012). Using biostimulant compounds based on animal-derived amino acids in the growing medium has increased growth and resistance to frost damage in strawberry plants (Marfà *et al.*, 2008). Many temperate fruit plants require a specific amount of cold exposure, known as the "chilling requirement," to break dormancy and ensure proper flowering and fruit set. Inadequate cold can result in delayed leafing, irregular flowering, and decreased fruit yield and quality. Protective cultivation systems can artificially fulfill these requirements in regions with insufficient natural cold. Techniques such as evaporative cooling, including misting systems, help maintain optimal temperatures in greenhouses and satisfy the chilling

requirement (Rabbi *et al.*, 2019). In the use of shading nets during winter, the low temperature meets the chilling requirements of trees. However, in greenhouse cultivation, due to the enclosed environment, there is a possibility that the chilling requirements of the trees may not be met. In this case, using compounds such as potassium nitrate (KNO₃), 2-methyl-3,5-dinitrophenol, hydrogen cyanamide (2N₂CH), and a combination of benzyl adenine and promaline can somewhat alleviate the symptoms of unmet chilling requirements in trees.

5.2. Pruning

For fruit tree cultivation in controlled greenhouse conditions, the size of the trees is significant, and the use of dwarf and low-vigor cultivars is recommended. However, for better control, it is necessary to prune the trees to manage their size regularly. Pruning trees immediately after planting restores the balance between the root system and the shoot. Young trees are usually pruned to establish a strong framework accessible for other activities. Fully grown fruit trees are pruned to maintain the height of the canopy, the spread, and the density required for easy spraying, thinning of fruit, and harvesting. However, the main reason for pruning mature trees is to produce high-quality fruit. Pruning prevents excessive fruiting, increases fruit size, and facilitates light penetration into the tree canopy, which improves fruit color. Pruning fruit trees is usually a severe operation that directly or indirectly affects many physiological processes. A careful examination of the effects of pruning shows that they arise from a communication system with good yield in the tree. For example, if the tip of the stem is cut off, the remaining part of the tree is informed that the lost organ must be rebuilt to restore balance between the parts of the tree. Plant growth regulators likely play a key role in the functioning of communication systems by turning specific genes on and off. When the stem tip is removed, the hormonal status between the meristems changes. These changes in plant growth regulatory levels stimulate lateral buds to grow, produce abundant branching, and increase leaf photosynthesis. They alter dry matter partitioning in such a way that the tree can rapidly regenerate lost parts. Thus, increased trunk and new root growth is reduced by directing photoassimilates and mineral uptake to the regenerating branches. In addition, a transport system is established for the growing meristems, and flower bud formation is inhibited because reproductive growth depends on vegetative growth (Mika, 2011).

The results of winter pruning experiments with apples at the East Malling Research Station indicated that pruning affects characteristics such as the size, height, and spread of the stem, tree shape and thorniness, precocity, number of blooms, number and percentage of fruit, fruit quality (mainly size and color), and control of susceptibility to diseases (such as scab, canker, mildew, and leaf blight) (Grubb, 1939).

The effects of pruning on stem growth depend on the type and timing of the pruning. Types of pruning fruit trees include topping, thinning branches, and wound pruning, while types of pruning in terms of timing include winter pruning or black pruning, summer pruning or green pruning, and fruiting pruning of fruit trees. During the dormant season, pruning techniques like heading or tipping involve shortening stems or branches. Heading refers to cutting a shoot or stem back to a bud, typically on a branch less than a year old. Stubbing, or heading of branches, involves shortening the branches themselves. Summer pruning shortens the tree, increases the formation of fruit buds, and improves fruit quality (Swarbrick and Berry, 1937). Today, summer pruning is mainly recommended for high-density orchards to limit tree size and improve fruit quality (Mika, 1982). Winter and summer pruning affect the branches' surface and leaves, leaf structure, and light penetration, directly and indirectly impacting photosynthesis. Heavy winter pruning reduces leaf area at the beginning of the growing season, but later, due to the rapid growth of new shoots, the leaf area increases (Mika *et al.*, 1977). Pruning blackberries (*Rubus* subgenus *Rubus* Watson) in high tunnels at the Oregon State University–North Willamette Research and Extension Center in Aurora, OR, resulted in

increased yields and an extended growing season compared to open fields (Thompson *et al.*, 2009).

Summer pruning is performed early in the season, and the leaf area removed is partially compensated by the regrowth of leaves (Taylor and Ferree, 1981). Another type of pruning effective in training seedlings and creating the tree's overall shape is pyramidal, vase-shaped, or trained on a trellis. Thinning is regularly performed on stone fruit species such as peaches and nectarines, but it is rarely done on apricots, plums, sweet cherries, or sour cherries. The response and effectiveness of thinning depend not only on the species and cultivar but also on climatic and soil conditions and agricultural treatments, especially pruning. Yield and vegetative growth are related to the intensity and timing of thinning (Costa *et al.*, 2018). Fruit trees produce numerous flowers that cannot all develop into fruit. The number of flowers on a tree is very high, depending on the species and size of the tree. For example, there may be 50,000 flowers on a sweet cherry and up to 20,000 flowers on a peach. To obtain a marketable crop of good quality, it is sufficient for about ten percent of the flowers to set fruit (Costa *et al.*, 2012). When 7 percent of the blossoms turn to fruit, apple trees perform well. Stonefruit plants require improved pollination. A sufficient yield in peaches is attained when 25% of the blooms set fruit (Costa *et al.*, 2012). Meanwhile, sweet cherries do well with a fruit set ratio of 25% to 40% (Beyhan and Karakaş, 2009; Wojcik and Wojcik, 2006).

5.3. Planting System

Due to the high costs of protective structures, it is crucial to choose planting methods that consider the size of the trees and allow for rapid production and good fruit yield in cultivating greenhouse fruit trees. One of the most efficient agricultural solutions has been reducing the spacing between trees. Given the correlation between the growth of shoots and root organs in fruit trees, root space limitations in small areas gradually reduce the vegetative vigor in the tree canopy (Caruso *et al.*, 1999).

Various methods of growing fruit trees in controlled conditions. The first commonly used method is soil cultivation. Although cultivating the soil is traditional, it remains the most widely used method in agricultural production. In general, factors such as soil pH and porosity impact plant growth. Plants' uptake of minerals is controlled by soil pH. For instance, most plants utilize iron through the ferrous ion (Fe^{2+}), but in higher pH environments, they may experience iron deficiency as ferric iron (Fe^{3+}) becomes the dominant form (Du *et al.*, 2022). The following method is pot cultivation, which is significant in managing tree growth and pruning and is recommended for better control over plant growth management. Small plants can be grown in plastic pots, making them easily transferable (Continella *et al.*, 1992). The production of potted citrus nursery plants has significantly increased in recent years and is a potential solution to soil-related issues. Potted citrus nurseries have advantages over field-grown nurseries (Maxwell and Lyons, 1979), which include the following:

1. Sterilizing soil-less potting mixtures can be done annually in one location for disinfection.
2. Nematodes, harmful weeds, and soil-borne diseases are not transferred to new growing areas.
3. Less equipment is needed in potting systems than in fields.
4. Operations are concentrated in a greenhouse or indoor setting, allowing for fine control of microclimates and protection against cold and heat.
5. Citrus plants grown in pots grow faster because they have an intact root system than field-grown ones.

On the other hand, as a modern planting technology, hydroponics is widely used in agriculture. Hydroponics often uses recycled irrigation water and nutrients to improve water resource efficiency. Additionally, hydroponics can prevent the transmission of pests and diseases from growing environments to the crops (Du *et al.*, 2022). Hydroponics is very effective in growing strawberries and can be used for other fruit trees if a support system is created for planting. Another planting method is aeroponics, which is applied to strawberries and is used for research purposes in fruit trees. Aeroponics, or soil-less farming, is a new technique where plants grow without soil while nutrient-rich water is sprayed onto the hanging roots through a system of atoms or fine particles. Spray nozzles are used mainly to supply water and fertilizer directly to the roots and hair roots of the desired plant (Narasegowda and Kumar, 2022).

5.4. Growing media

In managing fruit trees in controlled conditions, it is essential not only to control the atmospheric environment but also to monitor the growing medium and root conditions, as the placement of nutrients in the growing medium affects the mechanisms of the trees. The use of fertilizers for the plant's needs is crucial. The application of biostimulants at low concentrations can stimulate a range of biochemical, physiological, and molecular responses in plants, including improved flowering, growth, and performance; enhanced nutritional and practical quality of edible products; and their shelf life (Basile *et al.*, 2020). For instance, using 2 g/L of humic acid combined with 0.5-1 g/L of zinc sulfate on *Physalis alkekengi* significantly improved the uptake of micronutrients and the alkaloid content (Kazemi *et al.*, 2023, 2024). Biostimulants can also stimulate carbon and nitrogen metabolism by activating key enzymes, enhancing the antioxidant defense system and secondary metabolite production, improving photosynthetic activity and water relations in plants, and strengthening the chemical and physical properties of the soil. Also, biostimulants can stimulate the activity of hormones such as auxins, cytokinins, and gibberellins and increase the populations of epiphytic and rhizosphere microbes around the roots, affecting root hair, density, diameter, length, and soil volume in the cultivated substrate (Bulgari *et al.*, 2017; Calvo *et al.*, 2014; Odhong' *et al.*, 2019; Rouphael *et al.*, 2017a; Rouphael and Colla, 2018; Rouphael *et al.*, 2017b; Rouphael *et al.*, 2018a; Rouphael *et al.*, 2018b; Souri and Hatamian, 2019; Yang *et al.*, 2004).

Growing media comes in various types, with animal manure being the primary source of organic matter to supply the essential minerals plants need. Organic materials are crucial for successfully producing fruits and vegetables (Goh and Haynes, 1977). New and advanced root zone media are being tested as substitutes for natural soils in greenhouse and hydroponic agriculture. These environments must ensure better rooting conditions, provide anchorage for the root system, supply water and nutrients to the plants, and ensure adequate aeration for the roots (Savvas *et al.*, 2013). There is a wide selection of growing media available, and the choice of each depends on the financial and technical implications for the grower (Gruda *et al.*, 2013). The medium can be filled with organic materials, including animal manure, leaf mold, and various types of peat (such as cocopeat, moss, etc.) or mineral substances. Among mineral materials, the soil is the most commonly used medium. In contrast, other materials suitable for hydroponic cultivation include vermiculite, zeolite, pumice, perlite, rock wool, synthetic media like sponges, expanded plastic, polyurethane, and urea-formaldehyde. Fruit trees are primarily grown in soil or cocopeat-perlite or leaf mold-perlite mixtures. Most growers use locally available media because they are cheap and reliable (Gruda *et al.*, 2013). In a potting environment containing sand, animal manure, loamy clay, and sawdust, the healthy growth of Troyer citrange was effectively supported (Anvari *et al.*, 1992). Similarly, maximum growth in nursery-grown *Citrus limonia* Osbeck plants was observed in animal manure, lignite, and two commercial products, Agrohumus 51 and 61 (Grassi Filho *et al.*,

1999). The growth medium with different mixes of loam, sand, and cow manure significantly impacted the growth of sour orange and Troyer citrange seedlings (Nasir *et al.*, 1990).

5.5. Root Management

In many parts of the world, a shortage of arable land is a serious problem. However, the greenhouse cultivation of trees is suitable for growing the desired plant that fits the local climate. This type of cultivation allows for various growing mediums, which mitigates the issue of land scarcity. Nevertheless, providing these mediums for the large roots of certain trees can be challenging, and controlling the volume and size of the roots to the minor possible scale without hindering plant performance is crucial. Water and nutrient uptake can be reduced by manipulating fruit trees' root systems. Root pruning can reduce resource uptake or create a hormonal imbalance in the plant, negatively impacting shoot growth. Pruning root systems in some fruits has been successful but less effective for others (Sharma *et al.*, 2009). Pruning the roots of young and mature apple trees reduces shoot growth and consequently helps control tree size (Ferree, 1989; Schupp and Ferree, 1988). The timing of root pruning is an important factor, and pruning during dormancy or at full bloom was more effective in reducing stem length than pruning in June (Schupp and Ferree, 1987). Similar results were observed in peaches, where root pruning in April was more effective in reducing stem length than in June (Santos *et al.*, 1991). This limitation is applied by minimizing the root growth space and soil depth. In a study investigating the effects of root pruning on red raspberries produced in the off-season under plastic tunnels in the United States, researchers found that root pruning significantly reduced root carbohydrates, growth, flowering, and fruiting. They suggested that increasing plant density could offset the reduction in yield until light became a limiting factor (Darnell *et al.*, 2008). Root restriction is suitable for high-density, high-yield, and efficient cultivation. Root restriction adjusts vegetative growth by reducing the volume of the root system, which in turn regulates water and nutrient uptake. This reduction in root volume can be considered a stress condition. The extent of root volume reduction varies among trees and should be assessed in research to find the best performance for each tree with the least root volume. In peaches, excessive root restriction causes physiological changes based on phenotype and stimulates root exudation, which contains high levels of autotoxins and allelochemicals that can lead to reduced plant growth (Brady and Weil, 2013; Zhu *et al.*, 2017). Reducing the root volume decreases the secretion of autotoxins in the rhizosphere. In general, the relative amount of identified compounds significantly increases with reduced root volume (Wang *et al.*, 2019). In peaches, the aim of lowering root volume is to create a stable range of root constraints that can modify the vegetative growth of the peach tree, such as trunk diameter, length of one-year-old branches, and photosynthesis-related elements, while also preventing the accumulation of autotoxic compounds released by the roots (Wang *et al.*, 2019). Vegetative and reproductive growth and size control are important aspects of high-density orchard cultivation (Williamson *et al.*, 1992). Root constraints considerably limit root exploration in the soil, which is consequently associated with suppressed vegetative growth (Williamson *et al.*, 1992). Under root constraint conditions, water supply is limited due to the small root range. Evaluating photosynthetic stomatal conductance has shown that decreased stomatal conductance with reduced root volume is a specific response of drought-resistant plants (Romero *et al.*, 2004). Stomatal conductance relates to the movement of CO₂ into the leaf, controlled by stomatal regulatory processes, and a decrease in stomatal conductance is an adaptive mechanism that plants use to reduce water loss (Karimi *et al.*, 2015). Researchers have found that root restriction increases the number, area, and lateral volume of roots, as well as boosting lateral roots (Wang *et al.*, 2019). Overall performance and photosynthesis are also affected by root-restraining treatments, which can induce changes in the soil environment, such as nutrition, enzymes, etc., and improve production in greenhouses of unusable land (Wang *et al.*, 2019).

In addition to using space restriction methods to control root volume, pruning can help create the desired volume. In a plant like Mandarin, it was observed that root pruning led to a decrease in leaf nitrogen and an increase in leaf carbon, which in turn increased the C/N ratio in trees with pruned roots compared to those with untouched roots. The physiological responses in flowering and fruiting, fruit size, fresh fruit weight, and soluble solids content (SSC) in trees with pruned roots were significantly greater than in trees with healthy roots. Moreover, pruning the roots of trees enhanced the overall fruit yield compared to mandarin trees without pruning root hair. Overall, the results indicated that root pruning minimizes issues like low yield and poor fruit quality (Kang *et al.*, 2019). Root pruning has been widely used in fruit trees to enhance fruit production and quality management systems (Kang *et al.*, 2019).

Root pruning improves the performance of tree roots and branches and their physiological responses (Geisler and Ferree, 2011). Therefore, the growth responses of trees and fruit quality are significantly influenced by root pruning in apples (Yoon *et al.*, 2005), black poplar (Smith and Greenwood, 1995), grapes (Poni *et al.*, 1992), peaches (Choi, 2004), pears (Wang *et al.*, 2014), pecans (McCraw and Smith, 1998), persimmons (Choi *et al.*, 2005), raspberries (Darnell *et al.*, 2008), plums, and cherries (Symeonidou and Buckley, 1999). Additionally, the depth and distance of soil from the trunk for root pruning were closely associated with tree performance in ten-year-old peach trees (Choi, 2004). It is, therefore, assumed that the main reason for using root pruning methods should be to control tree vigor (Dry *et al.*, 1995); thus, managing the growth and development of trees leads to sustainable fruit yield and quality (Ferree, 1992). Doing these things helps control tree growth and achieve relatively high yields in greenhouse-grown tree crops. Root growth inhibitors under the term chemical pruning are also used. High concentrations of IAA inhibit underground organs (Mashamaite *et al.*, 2020). All concentrations used led to a decrease in root dry weight. As a result, IAA has reduced root growth and promoted shoot growth (Mashamaite *et al.*, 2020).

5.6. Plant growth regulators

Plant growth regulators (PGRs) are compounds that can significantly regulate all physiological processes in plants through their signaling role. Greenhouse fruit producers use signaling substances, such as PGR, to manage growth and flowering, improve fruit quality and harvesting, and increase yield under specific greenhouse and controlled conditions. PGR networks and interactions exist among PGRs during fruit growth, ripening, and other aspects (Kumar *et al.*, 2013). Fruit ripening is a complex, genetically programmed process (Liu, 2019) in which many physiological and biochemical changes occur. The pigment change process during fruit ripening is a completely controlled phenomenon that is regulated by PGR, various transcription factors, gene families, enzymes involved in the biosynthetic pathways of pigments, and environmental stimuli (Wang *et al.*, 2020). In climacteric fruits, the physiological changes, including color, texture, aroma, and flavor, which contribute to the overall quality of the fruit, are somewhat coordinated with changes in ethylene biosynthesis and its receptors (Begheldo *et al.*, 2008). Besides ethylene, there are other PGRs involved in regulating the ripening process (Ziosi *et al.*, 2008). Auxins also appear to play an important role. Most reports on PGR processes involving indole acetic acid (IAA), including biosynthesis, synthesis, perception, and transport, come from the model plant *Arabidopsis* (Delker *et al.*, 2008; Woodward and Bartel, 2005). However, much less is known about the potential role of IAA in the growth of fleshy fruits (Liu, 2019). In peaches, auxin can stimulate ethylene synthesis by enhancing signaling pathways (Tatsuki *et al.*, 2013). In addition, several genes involved in auxin biosynthesis, transport, and signaling have been identified (Liu, 2019). The expression of these genes significantly increases during peach ripening, indicating a notable relationship between auxin and ethylene, meaning that they influence each other. As a result, increased auxin concentration in peaches before ripening has

been reported alongside increased ethylene production (Trainotti *et al.*, 2007). Abscisic acid (ABA) 's role in fruit ripening is still unknown. However, it appears that ABA accumulation is important in regulating the ripening process in both climacteric and non-climacteric fruits (Liu, 2019). In non-climacteric fruits, like cherries and grapes, ABA is thought to play a significant role in fruit ripening (Kondo and Gemma, 1993; Lara and Vendrell, 2000; Zhang *et al.*, 2009a; Zhang *et al.*, 2009b; Zhang *et al.*, 2009c). Several studies have shown that using ABA exogenously accelerates ripening by increasing anthocyanin content, sugar accumulation, and softening while also reducing titratable acidity in strawberries and grapes (Guo *et al.*, 2018; Hou *et al.*, 2018; Jeong *et al.*, 2004). In climacteric fruits, like apples, peaches, and tomatoes, where ethylene concentration is mainly coordinated with the expression of ripening-related genes, ABA accumulation either precedes or co-occurs with ethylene production and may be associated with increased ethylene levels (Sun *et al.*, 2011; Torrigiani *et al.*, 2012). The increase in maturity has been attributed to the rise in ethylene production caused by ABA (Sun *et al.*, 2017). IAA plays a significant role in the coloring of immature fruit, consistent with the accumulation of anthocyanins after treatment with IAA and ABA (Liu, 2019). IAA leads to chlorophyll degradation in fruit, while ABA does not reduce the chlorophyll content and follows with chlorophyll degradation after the accumulation of anthocyanins (Liu, 2019). Increasing soluble carbohydrate content and decreasing titratable acid content are also key indicators of the fruit ripening process, which IAA improves by increasing fruit sucrose, glucose, fructose, and total sugars (Liu, 2019). Thus, based on previous research, auxins can activate the ethylene biosynthesis pathway and enhance the expression of related genes while reducing the expression of the ABA biosynthesis gene. These actions can cause immature fruit to ripen earlier than their typical season. In sweet cherries, the regulated concentration of ABA, along with the expression of ACO1, led to higher ethylene production (Ren *et al.*, 2010). ABA stimulates ethylene production and the ripening process in lychee and grape, and these two hormones display synergistic effects (Jiang and Joyce, 2003; Sun *et al.*, 2010; Zhang *et al.*, 2009a; Zhang *et al.*, 2009b; Zhang *et al.*, 2009c). ABA can diminish or enhance ethylene activity in various fruit species (Liu, 2019). The small size of tangerines has always posed a serious problem for producers, significantly reducing the market appeal of the fruit. Research has shown that using auxins like 2,4-D and naphthalene acetic acid (NAA) effectively influences the size and quality of tangerines, transforming them from unsaleable to market-friendly with an appealing appearance, which is economically very important (Arzani and Akhlaghi-Amiri, 2001). Brassinosteroids are a key hormone that interacts with auxins and gibberellins to regulate plant growth and development (Zheng *et al.*, 2019). The growth of apple trees is regulated through the interaction of brassinosteroids, auxins, and gibberellins (Zheng *et al.*, 2019).

In enclosed environments, pollination gets disrupted since there is no wind, and high humidity slightly affects insect movement. The proposed solution is to use trained pollinating bees. When we want to produce fruit outside its growth season, we must first induce flowering in the plant. Inducing flowering requires endogenous signals (LDS), and plant hormones are likely candidates for LDS. Given their importance in plant physiology, they also receive special attention in studying flowering induction (Bangerth, 2009). Gibberellins (GA) and polar IAA transfer are proposed as potential inhibitors, while cytokinins (CK) are explored as potential stimulators for inducing flowering in angiosperm trees (Bangerth, 2009). Flowering induction (FI) in mature fruit trees means activating and transcribing many genes (Boss *et al.*, 2004). Practically, inducing flowering is critically important, especially for angiosperm fruit trees, as it significantly determines the success rate of commercial orchards (Buban and Faust, 1982; Forshey and Elfving, 1989). For some subtropical fruit trees, the possibility of starting FI and producing fruit outside of season (in some cases, even more than once a year) is also highly significant (Manochai *et al.*, 2005; Tongumpai *et al.*, 1988). In recent years, remarkable advancements have been made in decoding their role in transitioning plant

products to the reproductive stage (Bernier and Périlleux, 2005; Corbesier *et al.*, 2007; Tan and Swain, 2006). Considering the grafting method (grafting a mature cutting onto a stem) used to propagate almost all orchard trees, these plants are mature from the time of planting (Bangerth, 2009). Therefore, the implications of changes at the late stage for fruit production from the FI regulatory mechanisms in mature trees are less significant (Bangerth, 2009). Regulating FI in perennial plants requires more advanced techniques and knowledge than annual and biennial plants (Bangerth, 2009). In perennial plants, even if the inducing substance might be saturated (Davenport *et al.*, 2006), the upper parts of the meristems are always vegetative (Bangerth, 2009). Most evidence among all hormones shows that cytokinins (CKs) directly promote the flowering process of annual/biennial and perennial plants (Bangerth, 2009).

6. An example of fruit trees in greenhouse cultivation

6.1. Papaya

The Pusa Nanha, a dwarf variety of papaya, in greenhouse cultivation showed early flowering (67 days), a more significant number of leaves at flowering (33), petiole length (32.84), prolonged fruiting (46.171), and fruit set (23.46%) compared to open-air conditions (Prakash *et al.*, 2015). Similarly, greenhouse plants reported early flowering (69.84 days), with the highest number of flowers produced per plant (88.48) and maximum fruit set (38.74%). In contrast, late flowering was recorded in open-field plants (69.95 days) (Reddy and Gowda, 2011). A report evaluated the yield of papaya, noting that the fruit length (68.22 cm), width (93.11 cm), weight (874.32 g), and volume (895.16 cm³) of the plants in the net house increased (Kaur and Kaur, 2017). Papaya plants were observed in the greenhouse without the papaya ring spot virus (PRSV) till the end of the study. At the same time, the occurrence of PRSV in open cultivation started at 163.23 days with a 100 percent incidence (Reddy and Gowda, 2011).

6.2. Mango

The effect of plastic covering on the microclimate of greenhouse mango canopies was studied. Results show that the light intensity under the plastic cover exceeded 1600 $\mu\text{mol PPF m}^{-2}\text{s}^{-1}$, 26 percent less than in natural conditions but still considered sufficient for net photosynthesis (Juntamanee *et al.*, 2008). A study was conducted on the suitability of white greenhouse net covers for mango growth, revealing that maximum temperatures under these covers were 2°C lower. The impact of white net covering on the vegetative growth of mango trees was assessed, showing that plant height, leaf number, branch number per plant, and primary stem diameter in the greenhouse with the white net were significantly greater than in open-field conditions across both seasons (Medany *et al.*, 2009).

6.3. Bananas

A report from a banana greenhouse revealed that the temperature difference between the top and bottom of the canopy reached 9 °C. Considering the cooling of the greenhouse in summer, the best effect was achieved when ventilation was opened and the cooling system was turned on during the hottest part of the day. The plants were 34% taller inside the greenhouse, and the pseudostem diameter at flowering was 4% greater than those grown outside. They also produced 3 to 4 leaves before flowering in the open environment, extending the planting-to-flowering interval by 2.8 months. The plants inside the greenhouse showed a 28% higher yield than those outside (71 tonnes per hectare versus 56 tonnes per hectare). This higher yield potential in the greenhouse can be explained by a more favorable microclimate (higher temperature and humidity), leading to increased capacity and photosynthetic efficiency (larger leaf area and higher photosynthesis rate) (Eckstein *et al.*, 1997). In another report, the average pseudostem diameter of bananas in open-field cultivation

was 68.5 cm, while in protected cultivation, it was 78.3 cm. The average pseudostem height in open fields was 1.7 meters compared to 1.8 meters in protected cultivation. In protected cultivation, the total number of leaves was higher (28.2) than in open fields (20.8) (Gubbuk and Pekmezci, 2004). Similar results were reported where, at flowering, the plants inside the greenhouse were 34% taller and had a pseudostem circumference that was 4% greater compared to those grown outside (Eckstein *et al.*, 1997). The growing period until harvest was shorter by 41.4 days in protected cultivation (Gubbuk and Pekmezci, 2004).

6.4. Cherrymoya

The leaves and stem growth morphology were evaluated under three shade levels in a greenhouse. The stem length and the number of leaves in light shade (64% sunlight) were more significant than in the other shade levels. Internode length and specific stem length increased with shade. Stem diameter and dry weight of leaves and stems were higher in light shade conditions. Although dry weight was suppressed under high shade conditions (10% sunlight), the dry weight of stems was less affected by shade than the dry weight of leaves. High shade increased the leaf area per leaf, while the total leaf area per branch decreased. As the shade level increased, specific leaf area increased, indicating that reduced leaf thickness was reduced by increasing shade percentage (Higuchi *et al.*, 2001).

6.5. Peach

Leaf area in peach trees (*Prunus persica*) and nectarine (*Prunus persica* var. *nucipersica*) were significantly higher under red nets compared to trees under control conditions (Vuković *et al.*, 2016). Similarly, a report indicated that the average leaf size of nectarine trees under red nets was more significant than under white nets (Giaccone *et al.*, 2009). Furthermore, trunk area and stem length (6.8 cm² and 30.5 cm, respectively) were greater under red nets and then under blue nets than outdoor ones (Schettini *et al.*, 2009). This is because red netting, which has lower R/FR and B/FR ratios than typical outdoor radiation parameters, stimulates vegetative behavior, directly affecting photomorphogenic receptors (Young *et al.*, 1994).

6.6. Grapes

In a study conducted in the rainiest regions of China, grape diseases and phenolic compounds in the grape skin were analyzed by comparing cultivated-covered grapes with open-field cultivation. Growing grapes under rain shelters significantly reduced the incidence of grape diseases. Regarding most of the identified phenolic compounds in this study, their content in the covered cultivation samples was lower than that of open-field cultivation. As a result, vineyards using a plastic cover in rain shelters were deemed suitable (Meng *et al.*, 2012). In a report based on a 2-year average, the growth of the aerial parts of plants in protected cultivation was higher than that of plants grown in open fields. Phenological periods occurred earlier in protected plants than in open lands (Kamiloğlu *et al.*, 2011). Compared to open-field production, protected production resulted in an earlier harvest by 15-18 days (Kamiloğlu *et al.*, 2011).

6.7. Raspberries

The quality and yield of raspberries in high tunnels improved compared to open-field cultivation. Additionally, the fruit size in this study averaged 2.8 g per berry compared to 1.7 g in the first year of the external (Weber *et al.*, 2004).

6.8. Strawberries

A report evaluated the effect of different growing environments on the morphological characteristics of strawberries. The produce grown in a naturally ventilated greenhouse showed maximum branch crown, more leaves per plant, and greater plant spread, while the minimum was observed in plants grown in agricultural shade nets. However, based on fresh

weight, the plant weight was maximized at 115 g in the naturally ventilated greenhouse, while it was 30.88 g in open conditions based on dry weight (Pandey *et al.*, 2015).

6.9. Japanese Medlar

An experiment using high-density planting (3×3 m) and protected cultivation was conducted. It showed that protected cultivation resulted in an earlier harvest by 13 to 20 days compared to an open field (Polat *et al.*, 2005). It was also observed that growing in a greenhouse with a plastic cover led to earlier harvesting (Lorente *et al.*, 2003).

Table 1. Key advantages of different fruits in protected cultivation

| Fruit | Key Benefits in a Controlled Environment | References |
|-----------------|---|---|
| Papaya | Early flowering (67-69.84 days), higher fruit set (23.46%-38.74%), larger fruit size, and virus-free plants. | Prakash <i>et al.</i> (2015), Reddy and Gowda (2011), Kaur and Kaur (2017) |
| Mango | Improved vegetative growth, lower temperatures (by 2°C), and sufficient light intensity for photosynthesis. | Juntamanee <i>et al.</i> (2008), Medany <i>et al.</i> (2009) |
| Banana | 28% higher yield, taller plants (34% increase), faster maturity (by 41.4 days), and larger pseudostem diameter. | Eckstein <i>et al.</i> (1997), Gubbuk and Pekmezci (2004) |
| Cherrymoya | Increased leaf area, stem length, and biomass under light shade conditions (64% sunlight). | Higuchi <i>et al.</i> (2001) |
| Peach/Nectarine | Increased leaf area, larger trunk and stem size, and stimulated vegetative growth under red nets. | Vuković <i>et al.</i> (2016), Giaccone <i>et al.</i> (2009), Schettini <i>et al.</i> (2009) |
| Grapes | Reduced disease incidence, earlier harvest (15-18 days), and improved vegetative growth. | Meng <i>et al.</i> (2012), Kamiloğlu <i>et al.</i> (2011) |
| Raspberries | Larger fruit size (2.8g vs. 1.7g in open field) and improved yield in high tunnels. | Weber <i>et al.</i> (2004) |
| Strawberries | Greater plant spread, higher crown branches, and larger fresh weight (115g vs. 30.88g in open field). | Pandey <i>et al.</i> (2015) |
| Japanese Medlar | Earlier harvest by 13-20 days in protected cultivation with high-density planting. | Polat <i>et al.</i> (2005), Lorente <i>et al.</i> (2003) |

7. Conclusion

Protected cultivation is a groundbreaking method for fruit production, enhancing yields, quality, and sustainability. Protected cultivation reduces climate-related pressures, maximizes resource use, and supports off-season production, vital to food security. The future of fruit cultivation in protected environments brings both obstacles and prospects. Significant initial investments, the necessity for skilled workers, and the intricacies of managing pollination, chilling requirements, and pest control present substantial challenges. Additionally, ensuring energy and resource efficiency is an ongoing concern. Nonetheless, Artificial Intelligence, automation, and precision agriculture advancements provide promising solutions for enhancing environmental conditions and boosting yields. Creating greenhouse-specific cultivars, adopting sustainable water and nutrient management techniques, and expanding high-value off-season fruit production pave the way for new economic possibilities. With ongoing innovation and targeted investments, protected cultivation can be vital in promoting sustainable and resilient fruit production. Future research in protected fruit cultivation should focus on sustainable practices, including biostimulants, organic substrates, and integrated pest management strategies, that can reduce reliance on chemical inputs while maintaining high yields. In addition, research into energy-efficient greenhouse designs, alternative renewable

energy sources, and automation in pruning and harvesting can improve scalability and sustainability. Finally, market-based studies will be essential to examine consumer preferences and economic viability to expand the production of high-value, off-season fruits and ensure profitability in this sector. In summary, combining scientific insight with creative strategies will shape the future of sustainable fruit production in controlled environments.

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