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Current Status of Protected Cultivation Practices of Horticultural Crops: Future Prospects and Sustainability

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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Abstract

Protected cultivation of horticultural crops has emerged as an essential component of modern agricultural systems, offering substantial advantages in terms of improved crop quality, enhanced productivity, efficient resource utilisation, and protection against pests, diseases, and unfavourable environmental conditions. In recent decades, the adoption of protected cultivation technologies has increased considerably owing to the growing demand for high-quality horticultural produce, coupled with the challenges posed by climate variability, diminishing arable land, and increasing population pressure. This comprehensive review seeks to examine the current status of protected cultivation practices in horticulture and to evaluate their future prospects within sustainable agricultural production systems. The review has been conducted using secondary data obtained from existing scholarly literature, including peer-reviewed journal articles, academic books, technical reports, and conference proceedings. Relevant literature was critically analysed to synthesise contemporary developments, technological advancements, and emerging trends associated with protected horticultural production systems. The discussion initially provides an overview of the principal types of

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protected cultivation structures, including greenhouses, shade houses, polyhouses, low tunnels, and high tunnels, together with their respective advantages, limitations, and suitability for different agro-climatic conditions. Particular emphasis is placed on the role of environmental modification in optimising plant growth and improving crop performance. In addition, the review examines the contribution of protected cultivation towards enhancing water-use efficiency, minimising production risks, and facilitating precision crop management practices. Furthermore, the study highlights the increasingly important role of protected cultivation in addressing global food security concerns through the promotion of year-round crop production, stabilisation of yield, and reduction in dependence on seasonal climatic variability. The integration of advanced technologies, such as automated climate control systems, fertigation, and precision monitoring tools, is also discussed as a promising avenue for improving the economic and environmental sustainability of protected horticulture. Collectively, these developments indicate that protected cultivation is likely to play a pivotal role in the future of high-value horticultural crop production and sustainable agricultural intensification. It also examines the impact of protected cultivation techniques on crop growth and development, particularly in terms of improved morphogenesis, efficient precipitation management, and optimisation of key environmental parameters such as temperature, humidity, and carbon dioxide levels. In addition, the review explores the integration of advanced technologies—such as hydroponics, aeroponics, and vertical farming—within protected cultivation systems, emphasising their potential to maximise productivity while minimising resource use. The challenges and constraints associated with the adoption of protected cultivation, including high initial investment, energy requirements, and dependence on external inputs, are also discussed. Moreover, the paper considers sustainable and eco-friendly strategies to mitigate these challenges, including the use of renewable energy sources and the adoption of organic farming practices to maintain ecological balance. Eventually, the review outlines emerging trends in protected cultivation, focusing on the operation of artificial intelligence, perfection husbandry, and smart husbandry technologies. These innovations are expected to further enhance resource efficiency, automation, and crop monitoring, ultimately leading to improved yield and quality in horticultural production.

Keywords: Food security; sustainable agriculture; eco-friendly practices; hydroponics; greenhouse technology; protected cultivation.

1. Introduction

Protected cultivation refers to the practice of growing crops within fully or partially enclosed structures, such as greenhouses, shade houses, polyhouses, and high tunnels, with the objective of creating a controlled microenvironment conducive to optimal plant growth (Lamichhane et al., 2023; Singh & Sabir, 2022; Trivedi et al., 2018a,b). The principal aim of protected cultivation is to safeguard crops from adverse climatic conditions, pests, and diseases while simultaneously regulating environmental parameters such as temperature, humidity, light intensity, and carbon dioxide concentration (Jain et al., 2023; Aditya et al., 2023; D'antonio et al., 2002). This system employs specialised structures, covering materials, and advanced management technologies to facilitate environmental modification and improve crop performance (Jewett & Jarvis, 2001; Trivedi & Gautam, 2017). In addition to enhancing crop productivity and quality, protected cultivation contributes significantly to the diversification of agricultural systems by enabling the cultivation of exotic and climate-sensitive crops that are difficult to grow under open-field conditions. The technology also plays a crucial role in promoting climate-resilient agriculture through the mitigation of risks associated with erratic weather events, including unseasonal rainfall, temperature fluctuations, hailstorms, and prolonged dry periods (Jalwania et al., 2025; Gautam et al., 2023; Jiang et al., 2004). A wide range of horticultural crops, including vegetables, fruits, flowers, herbs, and nursery plants, are commonly produced under protected cultivation systems (Tüzel & Kacira, 2021). Protected cultivation techniques have been widely recognised as effective strategies for overcoming production constraints, particularly in regions characterised by harsh climatic conditions and limited agricultural resources (Trivedi, 2019). These systems facilitate year-round and off-season crop production, extend the cropping period, improve produce quality, and increase yield potential while reducing dependence on external environmental factors. Furthermore, protected cultivation supports the efficient use of land and water resources and enhances the profitability of growers by ensuring a consistent supply of fresh produce, especially in peri-urban and urban markets where transportation time and post-harvest losses can be minimised (Lee et al., 2019; Nordey et al., 2017; Suman et al., 2020; Tiwari et al., 2025). The adoption of protected cultivation has become increasingly important for maximising vegetable crop productivity and ensuring the continuous availability of high-value horticultural commodities throughout the year (Gruda & Tanny, 2014; Biswas et al., 2010). Improved agronomic practices, including closer spacing, higher planting density, and precision nutrient and irrigation management, further contribute to enhanced productivity under protected environments (Jain et al., 2025; Paradiso & Proietti, 2022). In recent years, multistorey crop cultivation within greenhouse systems has gained considerable importance in peri-urban regions for meeting the growing demand for fresh vegetables, strawberries, flowers, and fruit tree nurseries (De Gelder et al., 2012; Campana et al., 2025). Horticultural production in northern India is frequently constrained by several environmental and biological stresses, including extreme temperatures, intense solar radiation, water scarcity, fluctuations in relative humidity, weed infestation, nutrient imbalances, high wind velocity, and increased incidence of pests and diseases (Rasheed et al., 2020; Gerson & Weintraub, 2007). In this context, protected cultivation has emerged as a viable solution for mitigating such challenges and improving production stability. Among the various protected structures, walk-in polytunnels have recently gained prominence as economically viable technologies in the northern plains of India. These structures have demonstrated considerable effectiveness for the off-season cultivation of crops such as tomato, capsicum, cucurbits, and for nursery raising (Singh & Sabir, 2022). Greenhouses, which are typically covered with transparent materials such as glass or polyethylene sheets, are designed to selectively transmit solar radiation. These structures allow the entry of short-wave solar radiation while trapping long-wave thermal radiation, thereby maintaining a favourable internal temperature for crop growth (Van Veenhuizen & Danso, 2007; Sabir & Singh, 2013). The regulation of environmental conditions within protected structures has a direct influence on key physiological processes in plants, including photosynthesis, stomatal conductance, transpiration, and leaf temperature (Gorjian et al., 2021; Sindhu & Namita, 2018). Consequently, crop management practices under protected cultivation differ substantially from those followed in conventional open-field agriculture. Overall, protected cultivation systems have become indispensable components of modern horticultural production, particularly in peri-urban regions where the demand for high-quality fresh produce continues to rise. Their capacity to support intensive and efficient crop production under diverse climatic conditions underscores their importance in achieving sustainable horticultural development and enhancing food and nutritional security.

1.1 The Importance of the Protected Cultivation and its Compass

- Long- term advanced manufacturing quality and volume
- Water operation is maximised and consumption is dropped by 40 – 50
- Use of inputs efficiently
- The frequency of illness and pests is decreased or eliminated
- Throughout the period, crops will be completely grown.
- Fashionable technology for the synthetic goods made from precious crops, similar to flowers, apothecaries, etc.
- fresh job openings for educated, youthful people on subsidies.
- The hothouse's microclimate and bug substantiation point were manipulated for plant lineage, which led to the development of new seed kinds and products.

1.2 Need for Protected Cultivation

Rapid population growth, rising unemployment, climate change, fragmentation of agricultural landholdings, increasing pressure on natural resources such as land and water, and the growing demand for fresh vegetables have collectively intensified the need for advanced agricultural technologies such as protected cultivation. In this context, protected cultivation has emerged as a highly effective and sustainable production system capable of enhancing crop productivity, improving resource-use efficiency, and ensuring the year-round availability of high-quality horticultural produce. The adoption of protected cultivation is particularly advantageous in semi-urban and urban regions, including major metropolitan areas, where the demand for fresh vegetables continues to increase rapidly due to changing dietary preferences and expanding consumer markets. Furthermore, protected cultivation offers considerable potential for income generation and entrepreneurship development by creating substantial self-employment opportunities for educated unemployed youth. The technology supports intensive, high-value crop production within limited land areas, thereby contributing to livelihood enhancement, economic sustainability, and the strengthening of urban and peri-urban agricultural systems.

The need and importance of protected cultivation are explained below:

1. Product of vegetable crops under a protected structure not only provides nutrient effectiveness and high water, but it can also increase the product & productivity by 3- 5 crops over outside/ open field conditions for the crops under variedagro-climatic civilization of the country (Singh, 2014).
2. Adding population, dwindling natural resources (land, water, etc), and adding industrialisation & urbanisation will bear high product, which isn't possible from available coffers. Greenhouse cultivation is playing an important part in furnishing high- value crops, increasing productivity, better quality, economic return, and continuous force (Parmar, 2020).
3. Protected Cultivation provides the most suitable growing terrain, so farmers are able to produce advanced and off-season tomatoes, which brought decoration prices in demand (Santosh et al., 2017).
4. There is an urgent need to adopt the protected structures for water-saving, organic and integrated pest management, improving technology, maintaining high temperature, etc. (Owen & Behe, 2020).
5. A floriculture unit can only succeed if it produces ornaments with an export- focused approach and does it efficiently. It is excellent, and the quality is outstanding. For using the newest technologies in hothouse product is necessary to maintain affordable prices while guaranteeing thickness in product volume and quality. For instance, studies on the standardisation of agricultural technologies. Useful Applications of Low-Cost Greenhouses: The cultivation of roses, gerberas, carnations, and tuberoses, Invariably superior to the flowers and more fruitful" (Rahman et al., 2010, Trivedi & Awasthi, 2021, Trivedi & Awasthi, 2020)
6. Another area where the traditional nursery caregiving system needs to be completely diversified is in the high-quality nursery growing of vegetables. Because they don't have much money, low-cost or medium-sized farmers use modest structures (Verma, 2023).

1.3 New Trends of Protected Cultivation for Vegetable Crops

Vegetables constitute an essential component of the human diet and serve as an important source of vitamins, minerals, dietary fibre, and other bioactive compounds necessary for maintaining nutritional security. With the increasing demand for high-quality fresh produce, protected cultivation technologies have gained considerable importance as effective means of enhancing horticultural productivity and improving crop quality. Farmers residing in peri-urban regions are increasingly adopting various forms of protected cultivation to diversify traditional farming systems and to meet the rising market demand for both seasonal and off-season horticultural crops. Protected cultivation enables the year-round production of high-value vegetables such as slicing tomatoes, coloured capsicum, and parthenocarpic cucumbers, which command premium market prices owing to their superior quality and consistent availability. In addition, protected structures provide favourable conditions for the production of high-quality vegetable seedlings, thereby facilitating a substantial transformation in conventional nursery management practices. The adoption of scientifically managed nursery systems under protected environments contributes to improved seedling vigour, uniformity, and survival rates. Small and medium-scale farmers often prefer low-cost or moderately priced protected structures due to financial limitations and restricted access to investment capital. Nevertheless, even simple protected cultivation systems have demonstrated considerable potential in enhancing productivity and reducing crop losses. Among the various forms of protected cultivation, polyhouse technology has emerged as a specialised and efficient production system capable of mitigating both biotic and abiotic stresses while overcoming seasonal constraints associated with open-field cultivation. By providing a controlled growing environment, polyhouses facilitate extended cropping periods, improved crop growth, and enhanced production efficiency compared with conventional cultivation systems. Several studies have reported that vegetable crops cultivated under polyhouse conditions exhibit superior growth performance, higher fruit weight, and increased overall yield relative to those grown under open-field conditions. These advantages are primarily attributed to the optimisation of environmental parameters, reduced exposure to adverse weather conditions, and improved management of irrigation, nutrient supply, and pest control within protected cultivation systems.

2. New Trends of Protected Cultivation for Seed Production

The cultivation of seeds is presently an important element for effective growth, and seeds produced in polyhouse structures are free from the pests and diseases that are common in open husbandry. The primary structures include climate-controlled greenhouses, semi-controlled greenhouses, naturally ventilated greenhouses, insect-proof net homes, walk-in tunnels, inexpensive poly-houses, and plastic low tunnels, among others.

2.1 Climate and Semi-climate-controlled glasshouses

Glasshouses with temperature regulation or semi-climate control; poly houses are utilised for raising high-value exotic crops for hard growing seasons and increased yields. Otherwise, in an open field, the growth season is shorter. The high-value vegetables, such as sliced tomato products, cherries, sweet peppers, parthenocarpic cucumbers, etc., are suitable for growing within these structures. The main obstacle to using this type of structure is the initial or starting point of fabrication and the ongoing cost of similar glasshouses, which substantially increases the cost of seed when compared to seeds produced under other structures or in open fields. Yet, both the yield and the quality of seeds under similar structures are always significantly greater.

1. **Naturally ventilated greenhouses**: Greenhouses have natural aeration; these may be utilised to grow tomatoes, sweet peppers, and cucumbers, including parthenocarpic cucumbers, summer squash, muskmelon, etc., as seeds. However, compared to climate-controlled or semiclimate-controlled greenhouses, the duration of cultivation and seed production is shorter.
2. Net houses that are insect-proof can be used commercially to produce sweet pepper, tomato, brinjal, and other vegetable seeds, such as cucurbits. These constructions can protect crops from viruses and other insects, such as fruit borers, during the rainy and post-rainy seasons. In comparison to all types of greenhouses, the seed yield is always lower, but the cost of production is also considerably lower.
3. Walk-in coverts can be utilised for cucurbit seed products, similar to muskmelon, watermelon, summer squash, bottle gourd, bitter gourd, etc (Nair & Barche, 2014). High coverts are used in temperate regions of the world to extend the growing season by warming the soil for crop development (Lamont, 2009).

3. Intercultural Activities Protected Agriculture

3.1 Pruning and Training

In solanaceous and cucurbit vegetables, the source- Gomorrah relationship affects the growth pattern, fruit-bearing pattern, and seed yield. Tomatoes can have determinate, semi-determinate, or indeterminate growth habits (Yadav et al., 2023; Nandeha & Trivedi, 2024).

The first to fourth clusters at each branch are frequently named for masculinity in the case of cold-blooded seed products. In single stems, terminal pinching is carried out six weeks later. Regular lateral shoot removal is done. Only when the fourth cluster forms do the leaves start to defoliate (Gouthami et al., 2023; Mani, 2022).

Deciduous or semi-deciduous types are less common and not favoured for greenhouse seed production. In the event of hybrid seed production, the first to fourth clusters at each branch are usually picked for emasculation. Terminal pinching is done after 6 weeks in single stems. Lateral shoots are removed regularly. Defoliation of the leaves begins only when the fourth cluster is formed. Training and pruning are routine processes in greenhouse tomato crops, so paying close attention is always beneficial for high seed yield. Pruning in sweet pepper is typically restricted to the shoots that grow on the stem below the first branching or to some of the weak side shoots. Because pepper leaves have low photosynthetic efficiency, a large area of active leaves is required to produce sufficient dry matter. Pruning is done only in a few cases where the growth is lush. The pepper stem structure is frequently too weak to withstand protected cultivation.

3.2 Improvements to Irrigation Infrastructure and Micro Irrigation

The growth pattern, fruit- bearing pattern, and seed affair are impacted by the source- Gomorrah connection in both solanaceous and cucurbit vegetables. In the case of tomatoes, the growth habit may be indeterminate, semi-determinate, or determinate. In greenhouse hybrid seed production, indeterminate varieties/hybrids are favoured. Such plants can generate numerous fruit trusses and be grown for an extended period. Staked and upright-trained indeterminate tomato cultivars. To retain a single stem or a double stem at the most, side branches must be pruned. Deciduous or semi-deciduous types are less common and not favoured for greenhouse seed production. In the event of hybrid seed production, the first to fourth clusters at each branch are usually picked for emasculation. Terminal pinching is done after 6 weeks in single stems. Lateral shoots are removed regularly. Defoliation of the leaves begins only when the fourth cluster is formed. Training and pruning are routine processes in greenhouse tomato crops, so paying close attention is always beneficial for high seed yield. Pruning in sweet pepper is typically restricted to the shoots that grow on the stem below the first branching or to some of the weak side shoots. Because pepper leaves have low photosynthetic efficiency, a large area of active leaves is required to produce sufficient dry matter. Pruning is done only in a few cases where the growth is lush. The pepper stem structure is constantly too weak to withstand protected cultivation.

3.3 Interface between Fertiliser and Water

Fertigation: In order to meet the wholesome conditions at different stages of crop development, fertilisation is the slow and regulated use of necessary composts or factory supplements (water detergent) with the water system water. The full quantum of ordure that a particular tree requires is generally spread in several sections. Depending on the wholesome needs at different stages of the crop, the necessary number of composts can be administered in ten, fifteen, or further corridors under fertilisation.

Fertigation is a fashion that allows shops to get small quantities of compost before the crop's vegetative season. The dimension increases as the burden of natural products and supplement conditions increases, and also decreases as shops near the end of the crop's cycle (Trivedi et al., 2024).

Rather than only many massive pieces, this establishes the necessary order measures throughout the development cycle. When compared to conventional styles, fertilisation produces yields that are on par with or advanced, while leaving substantial reserve finances in the compost. The secret to excellent yield and produce quality is the proper ratio of water to supplements (Nandeha & Kewat, 2018).

The right blend of water and supplements is the key to high returns and the nature of the produce. Safeguarded Development of Green Yields Composts (fluid or water-solvent) can be infused into the dribble framework, utilising all three of the following strategies:

1. **Manure tank:** some portion of the water streaming into the framework is passed through a tank containing manure, and coming about arrangement again joins the primary stream.
2. **Venturi:** A venturi is introduced in a shunt pipe lined up with the primary line and making sufficient pull to ensure that the compost is arranged into the framework.
3. **Fertigation syphon:** Compost arrangement is introduced into the mainline using a positive dislodging syphon.

Knowledge of the nutritional requirements for different yields is crucial for successful fertigation. It is important to understand that the water system approach may not affect the organic product trees' absolute nutrient requirements. This has led to a far more realistic demand for robotisation and sophisticated mechanics, given the continued demands on mortal labour. Robotisation has recently surfaced and rooted the environment of numerous processes, similar to harvesting (Singh et al., 2009; Nandeha et al., 2017).

3.4 Challenges in Protected Vegetable Farming in India

While being very old, protected vegetable husbandry is fairly new in India. Exploiting the enormous potential of protected vegetable agriculture has received very little attention. The entourages are some limitations and issues that limit the cultivation of protected vegetables in India.

Despite the importance of vegetables like the tomato, cherry tomato, sweet pepper, and cucumber, no specific breeding work has been done to generate varieties or hybrids that are appropriate for production in greenhouses or other protected environments. Because exotic seeds are so expensive, Indian farmers cannot afford them.

Even though some of these vegetable kinds are sold domestically, they do not match the requirements for export or higher-end markets.

Their high initial cost and ongoing operating expenses make climate-controlled greenhouses are not suitable for Indian growers.

The heating and cooling systems of the glasshouses bear a further harmonious power source in numerous corridors of the nation.

Sunlight exposure during very important periods may lower the yields of certain plants in some areas, such as sweet pepper in winter circumstances in Delhi (Sahu et al., 2018).

Despite the country's several agro-climatic regions, not much has been done to standardise greenhouse-protected structure designs.

Various types of covered structures have not been used to test potential vegetable crop production technologies for the nation's diverse agroclimatic zones.

Materials for cladding the necessary qualifications are not easily accessible. Moreover, greenhouses lack the proper instruments for controlling the atmosphere.

There aren't any special research initiatives on cultivating protected vegetables.

For the provision of high-quality products to markets, there is a paucity of packaging and on-farm value addition materials (Sabir & Singh, 2013).

4. Indian Status of Protected Cultivation

Rapid Growth in India: the event of protected cultivation strategies has been constantly expanding as of late, determined by the need to satisfy the developing need for new and offseason yield (Kumar & Singh, 2020).

Favourable Environment: India's diverse climate, with its extreme temperatures and monsoon patterns, is ideal for protected cultivation to extend growing seasons and shield crops from bad weather (Kumar et al., 2019).

Horticultural Diversity: A wide assortment of plant crops, including vegetables, flowers, and extraordinary organic products, are developed involving protected cultivation procedures in India (Asati & Yadav, 2004).

Government Drives: The Indian government has introduced different plans and motivating forces with advanced safeguarded development, empowering farmers to take on nursery and polyhouse innovations **(**Pachiyappan et al. 2022).

Challenges: Regardless of development, there are still difficulties, including the high introductory venture cost, specialised information holes among small-scale drovers, and manageability enterprises (Abegunde et al., 2019).

New Research Ideas: Indian agrarian foundations and examination associations are effectively engaged with creating location-specific advancements for protected cultivation and further developing crop efficiency (Raina et al., 2009).

Export Opportunities: Protected cultivation has likewise opened up open doors for India's agricultural products, with specific yields being tr traded to worldwide business sectors (Sengar & Rani, 2020).

5. Future Possibilities

The eventual fate of protected cultivation looks encouraging. As the crowd supplements and accessible pastoralist land diminish, protected cultivation offers a provident answer for fulfilling the developing need for green yields (Slathia et al., 2018).

Many advances in protected cultivation incorporate the application of robots for crop checking, mechanical technology for gathering, and precision husbandry styles (Baylis, 2017).

Protected cultivation’s growing significance in meeting global food demands assumes a critical part in fulfilling worldwide food requirements (Alansari et al., 2018).

It considers the creation of top-notch crops in locales with ominous climatic conditions. Moreover, it decreases post-harvest misfortunes, upgrades crop efficiency, and guarantees a predictable stock of new produce consistently. While protected cultivation offers colourful open doors, it likewise faces many difficulties. These incorporate introductory arrangement costs, energy utilisation, appropriate upkeep, and guaranteeing ideal natural circumstances for crop development (Subin et al., 2021).

6. Robotics in Protected Cultivation

Automation is a good technology in which a part of the robotic work is maintained. There are different types of machinery that involve the strategy of safeguarding technology. Shielded development is an escalated creative strategy with high enterprise and functional expenses, consequently allowing only the creation of high-esteem foods crops like tomatoes, sweet pepper and cucumber, flowers like roses, chrysanthemums and gerbera and many kinds of pruned plants. In Western social orders, this sort of creation has been challenged with the size of creation offices, rising work costs, expanding issues with the accessibility of adequately talented work, medical conditions of the representatives because of weighty and dreary undertakings and developing rivalry in the public and worldwide business sectors. Furthermore, accuracy cultivation approaches in which plants are treated on a singular premise are becoming normal since they enable improving the amount and nature of yield creation while involving resources as effectively as possible. Given the ongoing imperatives on human work, this has prompted a significantly more grounded call for computerisation and advanced mechanics. In the view of different operations like harvesting, one of the criteria where mechanisation has recently come up and been established is (Van Henten et al., 2013).

7. Conclusion

Protected cultivation refers to the practice of growing crops under controlled or partially controlled environmental conditions, whereby critical factors such as temperature, humidity, light intensity, and ventilation are regulated according to the specific physiological requirements of the crop. This approach facilitates the creation of an optimal microclimate that promotes healthy plant growth, improves crop productivity, and enhances produce quality. By minimising exposure to adverse environmental conditions, protected cultivation also contributes to greater production stability and resource-use efficiency.

A wide range of protected cultivation systems and technologies are currently employed in horticultural production. These include naturally ventilated polyhouses, forced-ventilated greenhouses, insect-proof net houses, shade-net houses, low tunnels, and plastic tunnels. In addition, several complementary agronomic practices such as mulching, raised-bed cultivation, trellising, drip irrigation, and micro-irrigation systems are commonly integrated into protected cultivation systems to optimise crop performance. These techniques may be adopted individually or in combination to establish favourable growing conditions that protect crops from harsh climatic factors and support extended or off-season cultivation.

Protected agricultural systems also incorporate advanced production approaches, including the use of improved crop varieties, precision farming technologies, and efficient water and nutrient management practices. Structures such as high tunnels and net houses are particularly valuable for reducing the detrimental effects of excessive rainfall, extreme temperatures, wind, and pest infestation, thereby enabling the cultivation of crops beyond their normal growing seasons.

The adoption of protected cultivation technologies offers several agronomic and economic advantages, including improved soil moisture conservation, enhanced weed suppression, efficient utilisation of water resources, and reduced dependence on chemical inputs. Furthermore, these systems contribute to higher crop yields, improved produce uniformity, and increased profitability for growers. Consequently, protected cultivation has become an increasingly important component of sustainable and intensive horticultural production systems in many parts of the world.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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