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# Protected cultivation of horticultural crops: A sustainable approach to climate-resilient agriculture in India

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**Abstract**
Protected cultivation is a climate-smart agricultural technique that provides a controlled environment for horticultural crops, shielding them from adverse weather, pests, and diseases. With increasing climate variability in regions like South and Southeast Asia, including India, traditional open-field farming is becoming more vulnerable. Protected structures such as polyhouses, shade nets, and greenhouses help maintain optimal temperature, humidity, and light levels, promoting higher yields and better-quality produce. These systems also allow off-season production and efficient resource use, including water and fertilizers, making them economically and environmentally sustainable. In India, protected cultivation has gained momentum, especially in high-value crops like capsicum, tomato, cucumber, gerbera, and rose. However, adoption remains limited due to high initial costs, lack of technical know-how, and inadequate market linkages. Government schemes like MIDH and state-level subsidies aim to address these challenges, promoting wider adoption. Overall, protected cultivation has immense potential to transform Indian horticulture by ensuring higher productivity, improving income stability, and enhancing resilience to climate change. With increased awareness, financial support, and access to low-cost technologies, protected cultivation can play a crucial role in achieving sustainable and profitable farming systems in India.

**Keywords:** Protected cultivation, climate-resilient agriculture, controlled environment horticulture, sustainable farming systems in India

## Introduction

Climate change has resulted in increased average temperatures, extended periods of drought or heavy rainfall, and the appearance of new pests and diseases, all of which negatively affect agricultural productivity in Southeast and South Asia. (Rosenzweig, *et al*. 2001) [9]. Protected cultivation is a high-technology approach to crop production that involves growing plants in controlled environments protected from unfavorable weather conditions. This is achieved through the use of advanced structures such as polyhouses, net houses, screen houses, and tunnels, as well as protective measures like windbreaks, irrigation, and mulching. This method is more sustainable than traditional open-field farming because it minimizes the impact of climate variability by regulating the environment and allows for more efficient use of inputs like fertilizers, pesticides, and water. Protected cultivation has the potential to reduce greenhouse gas emissions and lessen the environmental footprint of food production. However, activities such as heating, artificial lighting, post-harvest transportation, packaging, and fertilizer use in high-tech greenhouses remain significant environmental challenges. Here is a paraphrased version of the given paragraph: Protected cultivation has demonstrated yield levels that are three to five times higher than those obtained through conventional open-field farming, depending on the crop type (Jethi *et al*., 2012) [4]. It has also been recognized as a highly profitable approach, especially for cultivating vegetables and flowers (Sabir and Singh, 2013) [13]. However, the findings indicate that to encourage broader adoption among farmers, there is a need for supportive measures such as subsidy schemes, improved access to quality inputs, and comprehensive financial and market support systems (Kumar *et al*., 2021) [6]. Despite its benefits, the adoption rate of protected cultivation in India remains minimal, accounting for only 0.2

percent far behind countries like the Netherlands, Turkey, and Israel. Over the past two decades, there has been a growing awareness of modern agricultural techniques and their potential to drive economic growth. Still, the progress in implementing such innovations often involves a balance between success and missed opportunities, reflecting both advancements and limitations in agricultural development efforts (Nimbrayan *et al*., 2018) [8]. India needs new and developed production technologies to remain a self-sufficient country or provide the ultimate surety of feeding all the individual natives. Besides this, to become an exporter of good quality vegetables and fruits, farmers should adopt the greenhouse technology required to continuously improve productivity, profitability and respectability of the Indian agricultural sector. Economic return from high-quality agricultural produce under protected conditions can be maximized substantially through protected cultivation by reducing the residues of chemical insecticides and pesticides on the crop grown in a greenhouse environment.

**Overview of Protected Horticultural Practices in India and the World**

The global area under protected cultivation of horticultural crops was estimated to be around 623,302 hectares in 2023 with China accounting for the largest share (45%), according to the latest data from the Food and Agriculture Organization of the United Nations (FAO, 2023) [14]. In India, the area under protected cultivation of horticultural crops is around 11 thousand hectares. The major crops produced under protected cultivation include vegetables (tomatoes, cucumbers, peppers, lettuce, etc.), fruits (strawberries, raspberries, blueberries, etc.) and flowers (roses, gerberas, carnations, etc.) In India, the major horticultural crops produced under protected cultivation include tomatoes, cucumbers, capsicums, roses, and gerberas (Pachiyappan, *et al.* 2022) [15]. According to the Food and Agriculture Organization of the United Nations (FAO), the global area under protected cultivation was estimated to be 2.76 million hectares in 2020. China is the world leader in protected cultivation, with over 4 million hectares under production.

**Current Status and Potential of Protected Horticultural Crop Production**

**Global Progress in Protected Cultivation Systems**

Global progress in protected cultivation systems has been remarkable, driven by the growing demand for high-quality horticultural produce and the need to mitigate the adverse effects of climate change. Countries like the Netherlands, Spain, China, and India have significantly advanced greenhouse and controlled-environment agriculture technologies, integrating innovations such as climate-controlled polyhouses, hydroponics, and automated fertigation systems. These developments have not only enhanced productivity and resource-use efficiency but also enabled year-round production of vegetables, fruits, and flowers. The adoption of protected cultivation is expanding globally due to its potential to improve crop quality, reduce pesticide use, and ensure food security. However, its success largely depends on factors such as regional agro-climatic conditions, infrastructure availability, and skilled workforce, highlighting the need for localized strategies and policy support to fully harness its potential. Protected cultivation techniques, such as greenhouses and high tunnels, have gained widespread adoption across the globe, particularly in regions with extreme climates or limited arable land (Fernandez, *et al* 2018) [3]. There's a growing emphasis on eco-friendly and organic methods within Protected horticulture aimed at minimizing agriculture's environmental footprint.

**Indian Perspective on Protected Cultivation Systems**

India has witnessed significant strides in protected cultivation systems, driven by a combination of government initiatives, climatic necessity, and market demand. The government has implemented several schemes and subsidies to promote greenhouse and polyhouse technologies, encouraging farmers to adopt modern horticultural practices. India's diverse agro-climatic zones and erratic weather patterns make protected cultivation an ideal solution for extending growing seasons and shielding crops from environmental stresses (Kumar *et al*., 2019) [7]. This has facilitated the production of a wide range of horticultural crops, including vegetables, flowers, and exotic fruits, contributing to increased horticultural diversity. The sector has experienced rapid growth due to rising consumer demand for fresh and off-season produce (Kumar and Singh, 2020) [16]. However, challenges such as high initial investment, limited technical expertise among smallholder farmers, and concerns about long-term sustainability persist. Despite these hurdles, protected cultivation is opening new avenues for export, positioning India as a competitive player in the global horticultural market.

**Classification of Protected Structures**

Protected cultivation refers to the practice of growing crops in controlled environments, protecting them from unfavourable climatic conditions, pests, and diseases. It has become increasingly vital in India to ensure sustainable, climate-resilient horticulture (Singh, *et al*., 2024) [2]. These structures offer higher productivity, improved quality, and off-season availability of fruits, vegetables, and flowers.

Protected cultivation structures in India can be broadly classified into low-cost, medium-tech, and high-tech based on materials, environmental control, and investment level.

**1. High-Tech Structures**

**High-Tech Structures** in protected cultivation refer to advanced, engineered facilities designed to optimize plant growth by precisely controlling environmental parameters such as temperature, humidity, light, and $CO_2$ levels. These structures include climate-controlled greenhouses, naturally ventilated polyhouses, net houses, and fully automated glasshouses equipped with sensors, actuators, and remote monitoring systems. The theoretical foundation of high-tech structures lies in the principles of plant physiology, microclimate regulation, and resource-use efficiency. By creating a controlled environment, these systems minimize external stressors, enhance photosynthetic activity, and ensure consistent crop quality and yield throughout the year. Additionally, high-tech structures support the integration of technologies like hydroponics, fertigation, and climate modeling, enabling data-driven precision horticulture. Although the initial capital investment is high, the long-term benefits—such as improved productivity, reduced pesticide use, and higher returns—justify their adoption, particularly in regions facing climate extremes or aiming for year-round cultivation and export-quality production. While the initial investment is high, they support year-round cultivation, making them suitable for commercial farming and export-oriented production (Atheequlla, *et al*., 2022) [1].

**2. Low-Cost Structures**

Shade Net Houses use polyethylene shade nets of varying densities (35% to 75%) to protect plants from harsh sunlight, wind, and pests. Low-Cost Structures in protected cultivation are designed to offer affordable and practical solutions for small and marginal farmers, enabling them to protect crops from environmental stresses with minimal investment. The theoretical foundation of these structures is based on the principles of microclimate modification and passive environmental control. Typically made from locally available materials like bamboo, wood, or low-cost galvanized iron pipes and covered with polyethylene sheets or insect-proof nets, these structures include low tunnels, walk-in tunnels, shade nets, and simple polyhouses. They help in extending the growing season, reducing pest and disease incidence, and improving crop quality without relying on advanced automation. The design focuses on cost-efficiency, ease of construction, and adaptability to local agro-climatic conditions. Though they offer limited environmental control compared to high-tech systems, low-cost structures are crucial in promoting protected cultivation among resource-poor farmers and play a vital role in enhancing food security, income generation, and sustainable horticultural development at the grassroots level. These are suitable for crops like leafy vegetables, herbs, and ornamentals such as orchids and ferns. Their affordability makes them ideal for small-scale farmers (Krishna, *et al*., 2023) [5]. Insect-Proof Net Houses are constructed with fine mesh nets (usually 40–50 mesh) to physically block insects. These are suitable for crops like capsicum, tomato, and cucumber, especially in regions prone to viral diseases.

**3. Medium-Cost Structures**

Naturally Ventilated Polyhouses (NVPs) are semi-permanent structures with polyethylene cladding and roof ventilation. Medium-Cost Structures in protected cultivation represent a balanced approach between low-cost and high-tech systems, offering moderate environmental control with reasonable investment. The theoretical basis for these structures lies in achieving optimal microclimatic conditions using semi-automated or manually operated systems that are both efficient and economically viable. These offer basic environmental control without high energy input and are suitable for growing vegetables, cut flowers, and exotic crops. The reduced cost and moderate efficiency make them a popular choice among Indian farmers (Balraj Singh, 2024) [2]. Typically constructed using galvanized iron frames and UV-stabilized polyethylene films, medium-cost structures include naturally ventilated polyhouses, fan-and-pad systems with basic automation, and improved net houses. These setups allow for better regulation of temperature, humidity, and ventilation than low-cost options, while being more affordable and manageable than fully automated high-tech structures. Medium-cost structures support the cultivation of a wider range of crops—including high-value vegetables, flowers, and nursery plants—and are particularly suitable for peri-urban and semi-urban areas. They enable increased productivity, better quality produce, and extended cropping seasons, making them ideal for farmers looking to transition from traditional methods to more modern, sustainable horticultural practices without incurring prohibitive costs.

**Performance Across India's Agro-Climatic Zones**

Protected cultivation systems in India perform variably across different agro-climatic zones due to the country's vast environmental diversity, which affects temperature, humidity, radiation, and rainfall—key factors in controlled-environment agriculture. The theoretical basis of this performance variation lies in ecological zoning and microclimate engineering, where structures are tailored to optimize crop growth by modifying local environmental conditions (Kumar *et al*., 2019) [7]. In arid and semi-arid zones such as Rajasthan and parts of Maharashtra, naturally ventilated polyhouses and drip irrigation technologies are effective in conserving water and reducing heat stress. In humid and tropical zones like Kerala and the North-Eastern states, shade nets and insect-proof net houses help manage excess moisture and disease incidence (Kumar & Singh, 2020) [16]. Temperate zones, including Himachal Pradesh and Jammu & Kashmir, benefit from polyhouses and low tunnels to extend the growing season for vegetables and floriculture (NHB, 2021). The performance of protected cultivation is thus directly linked to its agro-climatic adaptability, where region-specific design and management strategies enhance crop productivity, quality, and profitability.

Arid and Semi-Arid Zones (e.g., Rajasthan, Gujarat): Shade net houses and insect-proof net houses are preferred due to their ability to reduce evapotranspiration and minimize pest incidence. NVPs are useful in conserving moisture while enhancing productivity.

**Comparison-Based Analysis: Low-Cost vs. High-Tech Structures**

The theoretical distinction between low-cost and high-tech structures in protected cultivation is grounded in principles of microclimate management, technology adoption, and agricultural sustainability. Low-cost structures rely on passive environmental control, utilizing basic materials like polyethylene sheets, shade nets, and bamboo or simple metal frames. These systems align with the theory of appropriate technology, emphasizing affordability, ease of adoption, and adaptability for small-scale farmers. Their design focuses on reducing external stress from wind, rain, and pests, providing minimal yet effective protection to support seasonal cultivation with low investment and simple management practices. In contrast, high-tech structures are based on the theory of controlled-environment agriculture, which integrates automation, precision farming, and real-time monitoring to regulate temperature, humidity, light, and $CO_2$ levels. These structures are equipped with advanced technologies such as climate sensors, automated irrigation and fertigation systems, and computerized control panels. They enable year-round cultivation of high-value crops, enhance resource-use efficiency, and ensure uniform crop quality. However, they require higher capital, technical skills, and energy inputs, making them more suitable for commercial enterprises or export-oriented farming. The theoretical comparison highlights a clear trade-off: low-cost structures offer inclusivity and accessibility, whereas high-tech structures provide precision and productivity. The optimal choice depends on the farmer's resources, skill level, crop type, and market goals, reinforcing the importance of context-specific strategies in protected cultivation. Low-cost structures are effective for marginal and smallholder farmers, promoting inclusivity and reducing entry barriers in horticulture. High-tech structures, though capital-intensive, offer maximum efficiency and profitability when managed well.

## Horticultural Species Suited to Protected Cultivation

Theoretical principles of protected cultivation emphasize creating optimal microclimatic conditions tailored to the physiological needs of specific horticultural crops, enhancing their growth, yield, and quality. Cucumbers, for instance, respond well to controlled environments such as greenhouses and high tunnels, where regulated temperature and humidity reduce pest and disease pressure, leading to improved fruit quality and higher yields. Tomatoes are among the most widely cultivated protected crops due to their sensitivity to climatic fluctuations; greenhouses provide a stable environment that supports uniform flowering, fruit set, and maturation, resulting in superior yield and fruit quality compared to open-field cultivation. Similarly, lettuce and other leafy greens like spinach, kale, and arugula benefit from year-round cultivation in protected environments where temperature extremes are mitigated and moisture levels precisely controlled, reducing stress and extending harvest periods. These examples illustrate how protected cultivation aligns with crop-specific ecological requirements to maximize productivity and resource efficiency.

## Key Horticultural Crops Cultivated in Protected Environments

Protected cultivation systems provide an optimized environment that supports the growth of a broad spectrum of horticultural crops by regulating factors such as temperature, humidity, light, and pest exposure. The theoretical basis for selecting crops in protected environments hinges on their physiological requirements and sensitivity to external stresses. Among flowers, species like rose, carnation, gerbera, anthurium, lilium, orchids, and chrysanthemum flourish due to their demand for stable climatic conditions that enhance flowering intensity and longevity. For vegetables, crops such as tomato, capsicum, cucumber, eggplant, lettuce, leafy greens, zucchini, and melon benefit from the controlled environment that reduces disease incidence and allows for off-season production, increasing yield and quality. Similarly, fruit crops including grapes, apple, pear, peach, plum, cherry, strawberry, and various other berries respond favourable to protected environments that facilitate improved fruit set, extended harvesting periods, and protection from adverse weather events. The integration of these crop types in protected cultivation reflects the underlying theory of matching crop biology with microclimate modification to maximize productivity and resource-use efficiency.

## Benefits of Protected Cultivation

Protected cultivation systems are grounded in the theory of controlled-environment agriculture, which emphasizes the manipulation of climatic factors to create optimal growing conditions for plants. This approach maintains a beneficial microclimate by regulating temperature, humidity, and light, ensuring plants experience ideal conditions for growth and development. Such systems enable continuous, year-round crop production, independent of external environmental extremes, thereby stabilizing food supply and market availability. The controlled environment significantly enhances yield and crop quality per unit area by improving traits such as size, colour, flavour, and nutritional value. Additionally, protected cultivation extends the production cycle by safeguarding crops from adverse weather, allowing longer harvest periods and increased overall output.

These systems are particularly suited for off-season and high-value crops, providing farmers with the opportunity to capitalize on market demands during periods when open-field production is limited. A further advantage is hygienic crop production, as the reduced pest and disease incidence minimizes the need for toxic pesticide applications, leading to safer produce. The physical barrier created by protected structures also facilitates better pest and disease control, limiting infestations and improving crop health. Protected cultivation supports early nursery raising, accelerating seedling establishment and enabling timely crop cycles. Moreover, these structures offer protection from environmental hazards like wind, rain, snow, hail, and birds, reducing crop damage and losses.

## Conditions governing the adoption of controlled environmental condition in horticulture

The adoption of controlled environmental cultivation in horticulture is guided by a range of interrelated conditions that align with the theories of technology diffusion, innovation adoption, and agricultural sustainability. From a theoretical standpoint, economic feasibility remains a primary condition—farmers are more likely to adopt protected cultivation systems when the perceived benefits, such as higher yields and better crop quality, outweigh the initial investment and operational costs. The availability of technical knowledge and access to training are also crucial, as outlined in the innovation-diffusion theory, which emphasizes that adoption increases with awareness and understanding of the technology.

Agro-climatic suitability plays a foundational role, where regions experiencing erratic weather, extreme temperatures, or rainfall variability are more inclined toward controlled cultivation to stabilize production. Additionally, the institutional support system, including government subsidies, policy incentives, and credit availability, significantly influences adoption, reinforcing the theory that enabling environments accelerate technological uptake. Social factors such as peer influence, market access, and perceived reliability of the system also affect decision-making, particularly in rural settings.

Thus, the theoretical framework indicates that adoption is not merely a function of the technology itself but a result of how economic, environmental, institutional, and social factors interact within a farmer's decision-making process. Controlled environmental horticulture spreads most effectively when these conditions converge to lower risks and increase perceived value.

## Future prospects

Protected cultivation holds great potential for the future. With the global population on the rise and arable land becoming increasingly scarce, this method offers an environmentally sustainable way to meet the growing need for horticultural produce (Slathia *et al*., 2018) [11]. It supports continuous production throughout the year, enhances crop quality, and reduces reliance on water and chemical pesticides.

Technological innovations are transforming protected cultivation. Developments such as drone-based crop surveillance, robotic harvesting systems, precision farming techniques, and the application of Internet of Things (IoT) for data-driven management are shaping the next generation of protected farming. Its role in ensuring global food security is becoming more critical. Protected cultivation enables the cultivation of high-quality produce even in regions with challenging climates. It also minimizes losses after harvest, improves yield levels, and ensures a stable year-round supply of fresh fruits and vegetables.

Nonetheless, there are both challenges and opportunities associated with this approach. Major obstacles include high initial investment costs, energy requirements, regular upkeep, and the need to maintain ideal growing environments. Still, progress in technology and a rising interest in sustainable agriculture practices provide promising pathways to address these issues and broaden the adoption of protected cultivation. Furthermore, it supports the export of select horticultural crops to international markets (Sengar and Rani, 2020) [10].

## Conclusion

Protected cultivation offers a viable solution to counter the adverse impacts of climate change on horticulture. By creating a favourable microclimate, it enhances crop growth, yield, and quality while reducing losses due to environmental stressors. It supports off-season production, efficient use of inputs, and better disease and pest management. Despite its proven benefits, large-scale adoption in India is hindered by factors such as high establishment costs, lack of skilled manpower, and limited awareness. However, ongoing research, government incentives, and public-private partnerships are working to overcome these barriers. Technological advancements, including automation, low-cost designs, and integrated nutrient management, are further increasing the feasibility of protected farming systems. Protected cultivation is particularly advantageous for growing high-value and export-oriented crops, contributing to increased farmer income and market competitiveness. With proper training, extension support, and access to credit, this technology can uplift small and marginal farmers. Protected cultivation is a forward-looking approach that aligns with India's goals for sustainable agriculture, climate resilience, and food security. Its integration into mainstream horticulture can significantly improve productivity, profitability, and environmental sustainability, positioning India as a leader in modern, climate-resilient farming practices.

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