**A comprehensive review on protected cultivation of horticultural crops: Advances and Sustainability**

**Abstract**

Horticultural crop growing under protection has become a vital method in contemporary agriculture, providing several advantages like improved quality, higher yield, and defence against pests and unfavourable weather. The purpose of this thorough research is to outline the present state of protected cultivation methods and investigate their potential in horticulture going forward. The examination starts out by going over the many kinds of protected cultivation structures as well as their benefits and drawbacks, such as shade houses, high tunnels, and greenhouses. It then emphasizes how important protected farming is in tackling the issues of global food security by guaranteeing crop output all year round and lowering reliance on seasonal fluctuations. The review goes on to examine how protected cultivation methods, such as enhanced crop morphogenesis, better precipitation control, and the optimization of environmental parameters like temperature, humidity, and carbon dioxide levels, affect the growth and development of horticultural crops. Additionally, the use of cutting-edge technologies such as vertical farming, hydroponics, and aeroponics in protected growing systems is investigated, with a focus on how they might maximize crop output while consuming the fewest resources possible. The study also explores the difficulties and limitations associated with putting protected cultivation into practice, such as financial concerns, energy needs, and the need for artificial inputs. It talks about eco-friendly and sustainable ways to lessen these problems and support ecological balance, like using renewable energy sources and switching to organic farming methods. The paper concludes by outlining some potential future developments and trends in protected cultivation, such as the application of artificial intelligence, precision agriculture methods, and smart farming technology. In the end, these developments could result in higher yield and quality improvements in the production of horticulture crops by further optimizing resource use, enhancing automation, and improving crop monitoring and management.

**Keywords:** Food security, Eco-friendly, Hydroponics, Greenhouses, Protected Cultivation

**Introduction**

“The term protected cultivation refers to the practice of growing crops in an enclosed or partially enclosed environment, such as greenhouses, shade houses, or high tunnels” [1,20,21]. “The main goal of protected cultivation is to optimize environmental factors while creating a controlled microclimate that protects the crops from pests, diseases, and unfavourable weather conditions” [2]. “It involves the use of structures, materials, and technologies that provide a protective barrier and allow for the manipulation of temperature, humidity, light, and other environmental variables” [3, 22]. This technique allows for year-round or out-of-season cultivation, prolongs the growing season, improves crop quality and yield, and lessens reliance on external factors. Protected cultivation is widely used in the production of a variety of horticultural crops, including fruits, vegetables, flowers, and herbs [4, 23]. “Crop yield and quality are greatly impacted by biotic and abiotic stressors in the current shifting environment” [5]. “Extreme temperatures, sunlight, water availability, relative humidity, weeds, nutrient deficits, wind speed, carbon dioxide concentration, and the prevalence of illnesses and insect pests are some of the issues that North Indian horticulture crop production encounters” [6, 24]. “Protected growing methods have shown themselves to be an effective way to overcome these limitations, particularly in harsh climates” [7, 25]. “Using facilities like greenhouses, protected farming entails producing higher-quality crops outside of their typical growing seasons” [8, 26, 27]. This method guarantees the delivery of fresh product, especially in peri urban areas, while also increasing farmer income and cutting down on transportation time [9, 28, 29].

“Greenhouses are structures that are coated with transparent materials that filter radiation selectively, such glass or polythene. They trap long-wavelength solar light within while permitting short-wavelength radiation to flow through” [10, 32]. As a result, solar energy is trapped, increasing the structure's interior temperature and producing a greenhouse effect [11, 30, 31]. “The high temperature has an impact on the photosynthetic rate, stomatal aperture, transpiration, and leaf temperature of plants” [12, 33]. The physiological state of the plants can be manipulated by regulating the greenhouse environment [13]. “As an example, when the greenhouse is closed at night, plant respiration causes the CO2 levels to rise. The following day's early morning hours saw the use of this increased CO2 for photosynthesis. Fast growth and higher yield are encouraged by the greenhouse's higher temperature, relative humidity, CO2, and better nutrition” [14, 34, 35]. “Cooling devices like ventilation, fogging, or fan pad systems can be used to control the temperature inside a greenhouse” [15, 36]. These methods optimize the output potential of chosen vegetable crops and allow for year-round production. In protected farming, yields are further increased by closer planting and higher plant density [16, 37, 38].

“Open-field agriculture and sheltered cultivation use different management techniques. Multi-story greenhouse crop growing has become essential in peri-urban locations to satisfy the need for fruit tree nurseries, fresh vegetables, strawberries, and flowers” [17, 39, 40]. Protected cultivation systems use a variety of methods, including fertigation, drip irrigation, mulching, and naturally ventilated polyhouses [18, 43]. “Furthermore, walk-in polytunnels have lately become a lucrative technology in India's northern plains, demonstrating their potential for off-season nurseries and the cultivation of crops including tomatoes, capsicum, and cucurbits” [19, 42].

**The importance of the protected cultivation and its compass**

* Long-term advanced manufacturing quality and quantity
* Water usage is maximized and consumption is decreased by 40–50%.
* Use of inputs efficiently
* The frequency of illness and pests is decreased or eliminated
* Throughout the period, crops will be fully grown.
* Fashionable technology for the synthetic goods made from valuable crops, such as flowers, pharmacies, etc.
* Additional tone: job opportunities for educated young people on grants
* The hothouse's microclimate and bug-evidence point were manipulated for factory parentage, which led to the development of new seed varieties and products.

**Need of protected cultivation**

Shops are protected from biotic variables like pests and the frequency of complaints, as well as abiotic stressors like temperature, water shortages or excesses, and hot and cold waves [41, 53]. “Reduced use of water and controlled growth of weeds Increasing output per unit area. Reducing the amount of fungicides used in agricultural products. Encouragement of high-quality, high-value horticulture production. Propagation, a valuable adaptation, and the addition of crops that are proven to thrive in particular areas Off-season and year-round products of fruit, vegetable, or flower crops. The result of genetically superior and complaint-free transplants. New developments in protected ornamental crop cultivation adaptation of agricultural techniques for flower production in indoor greenhouses. Recently, growing vegetables in greenhouses has become more popular in India as a way to produce high-quality products for export in the off-season” [52]. “A floriculture unit can only succeed if it produces ornaments with an export-focused approach and does it efficiently. is excellent, and the quality is outstanding. Using the newest technologies in greenhouse production is necessary to maintain affordable prices while guaranteeing consistency in production quantity and quality. For instance, studies on the standardization 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” [11, 50, 51]. Emerging patterns of protected vegetable crop production People have been eating vegetables for decades because they are a good source of nourishment.

“Many growers in peri-urban areas of the country will be able to successfully diversify their traditional husbandry by embracing or utilizing colourful situations of defended civilization technologies for the production of horticultural crops looking to their coffers, the vacuity of arising requests of usual and unusual off-season horticultural yield, the year-round demand of high-value vegetables like slicing tomatoes, coloured peppers, parthenocarpy cucumbers, etc” [54, 55]. 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 [56]. In contrast to open field conditions, polyhouse civilization of vegetables is emerging as a technical product technique to break the seasonal barrier and overcome biotic and abiotic constraints, resulting in an extended crop duration. When compared to open field settings, the highest number of fruit weights and yield were obtained in poly homes. While it was the smallest in open field conditions, several protected technologies showed lower net return and BC in the poly house.

**Emerging patterns in seed production using protected cultivation**

“Nowadays, efficient growth depends on the growing of seeds, and seeds grown in polyhouse structures are immune to the diseases and pests that are prevalent in open agriculture. Several structures are used in order to produce seeds: Insect-proof net dwellings, walk-in tunnels, low-cost poly-houses, climate-controlled greenhouses, semi-controlled greenhouses, naturally ventilated greenhouses, and plastic low tunnels are some of the main constructions” [57, 58].

**1. Climate and semi-climate-controlled glasshouses:** “Poly houses are used to produce high-value exotic crops for challenging growing seasons and higher yields. Glasshouses with temperature regulation or semi-climate control are also used. Otherwise, the growth season is shorter on an open field. High-value foods can be grown in these structures, including parthenocarpy cucumbers, sweet peppers, cherries, and sliced tomato products” [59, 60]. In comparison to seeds grown under other structures or in open fields, the primary barrier to the usage of this type of structure is the initial or starting point of construction and ongoing cost of similar glasshouses, which significantly raises the cost of seed. However, seeds with comparable structures consistently produce and are of higher quality.

**2. Naturally ventilated greenhouses:** These can be used to grow tomatoes, sweet peppers, cucumbers (including parthenocarpy cucumbers), summer squash, muskmelon, and other vegetables as seeds since they naturally aerate the air [50]. However, the time required for cultivation and seed production is shorter than in greenhouses with climate control or semi-climate control.

**3.** Sweet pepper, tomato, brinjal, and other vegetable seeds, including cucurbits, can be economically produced in insect-proof net buildings. These structures can shield crops from fruit bores and other insects, including viruses, during and after rainy seasons. The seed output is consistently lower than in all other types of greenhouses, but the production costs are also significantly lower.

**4.** Cucurbit seeds, such as those for muskmelon, watermelon, summer squash, bottle gourd, bitter gourd, etc., can be produced in walk-in tunnels [25, 49]. By warming the soil for crop development, high tunnels are utilized in temperate regions of the world to prolong the growing season [24, 48].

**Intercultural activities in protected agriculture**

* **Pruning and training**

In solanaceous and cucurbit vegetables, the source-sink relationship affects the growth pattern, fruit-bearing pattern, and seed yield. Tomatoes can have determinate, semi-determinate, or indeterminate growth habits [61, 62]. Indeterminate varieties/hybrids are preferred in greenhouse hybrid seed production. These plants can be grown for a long time and produce several fruit trusses. Indeterminate tomato cultivars that have been streaked and upright-trained. Side branches need to be clipped to leave only one stem or, at most, two stems. Less frequent and not preferred for greenhouse seed production are deciduous or semi-deciduous varieties [63, 64]. The first to fourth clusters at each branch are often selected for emasculation in the case of hybrid seed production. 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 [65, 77, 78]. In greenhouse tomato crops, training and pruning are regular procedures, thus it is always advantageous to pay special attention for a high seed output. Only the shoots that develop on the stem beneath the first branching or a few of the weaker side shoots are usually pruned in sweet peppers. To produce enough dry matter, a vast area of active leaves is needed because pepper leaves have a low photosynthetic efficiency [66, 67]. Only a small percentage of situations where the growth is abundant are pruned. Under protected culture, pepper stem structure is often too weak.

* **Improvements to irrigation infrastructure and microirrigation**

A major contributor to green yields in arid and semi-arid regions is the water system. To ensure optimal growth, desired output, and acceptable organic product quality, plants must have a reliable source of water and nutrients. One of the best methods for applying water and fertilizer to agricultural harvests is the drip water system, which is being promoted to increase water efficiency and supplement use productivity in the face of concerns about natural corruption and water accessibility. It is a water system technique in which water is applied as beads at specific locations (the root spread region) and assisted through a line framework to the mark of utilization, leaving some of the area between the yields dry [44, 45, 46, 47]. It has been proposed to use a Dribble water system to receive widely distributed harvests, such as vegetables, cotton, sugarcane, and plantations. Water shortages are occurring in many areas due to limited availability. It is anticipated that growing food demand will continue to contribute to the increasing demand on water resources. Enhancing the efficiency of current water resources, such as collecting more food from limited water resources, is the greatest long-term strategy for managing water scarcity, according to water executives' experts. As a result, adopting water-saving technologies is essential for efficient agricultural water use. When compared to surface and sprinkler water system strategies, water conservation in the trickling water system strategy is mostly related to the controlled use of water in limited areas of the entire field [68]. Only a portion of the all-out field's soil surface and root zone gets wetted as a result of the way water is applied by a trickle water system framework. Furthermore, limited soil wetting indicates a smaller area that may be utilized by plants that were created with dribbling water systems, necessitating frequent water and supplement treatments. There are basically two ways to implement a water shortage system for a yield:

* By applying less water to the system,
* By extending the time between water system cycles.

With a trickling water system, completing the two steps is not difficult.

**Interface between fertilizer and water**

**Fertigation:** In order to meet the wholesome requirements at different stages of harvest development, fertilization is the slow and regulated use of necessary composts or plant supplements (water solvent) with the water system water. The full amount of manure that a particular tree requires is typically spread in several sections. Depending on the wholesome need at different stages of harvest, the necessary number of composts can be administered in ten, fifteen, or more parts under fertilization. Fertigation is a technique that allows plants to get small amounts of compost before the crop's vegetative season. The measurement increases as the burden of natural products and supplement requirements increases, and then decreases as plants near the end of the crop's cycle [69]. Instead of only a few massive pieces, this establishes the necessary manure measures throughout the development cycle. When compared to conventional methods, fertilization produces yields that are on par with or higher while leaving substantial reserve funds in the compost. The secret to excellent yield and produce quality is the proper ratio of water to supplements [70]. Protected Growth of Green Yields Both of the following three methods can be utilized to incorporate composts (fluid or water-solvent) into the dribbling framework:

**1. Manure tank:** a portion of the water that flows into the structure passes through a manure tank before rejoining the main stream.

**2. Venturi:** A venturi is installed in a shunt pipe parallel to the main line, providing enough pull to allow the compost to be arranged within the framework.

**3. Fertigation syphon:** Compost arrangement is introduced into the mainline using a positive dislodging syphon.

The main guidelines for determining the amount, kind, and time of manure application are the following: the plants' request for supplements both at all stages of development and at different points in time; the soil's fruitfulness; the physical-synthetic characteristics of the soil; the compost's qualities, including its structure, dissolvability, accommodation, and cost of the available manure material; and the water system's water quality [71, 72]. 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 computerization and sophisticated mechanics given the continued demands on human labor. Mechanization has lately emerged and entrenched itself in the context of many processes, such as harvesting [34, 73].

**Challenges in Protected Vegetable Farming in India**

In India, protected vegetable growing is very new, although being very old. Very little attention has been paid to utilizing the vast potential of protected vegetable agriculture.   
Some restrictions and problems that restrict the production of protected vegetables in India are as follows:

1. No particular breeding work has been done to produce types or hybrids that are suitable for production in greenhouses or other protected environments, despite the significance of vegetables like the tomato, cherry tomato, sweet pepper, and cucumber. The high cost of exotic seeds prevents Indian farmers from purchasing them.

2. Despite being sold domestically, some of these vegetable varieties do not meet the standards for export or upscale markets.

3. Climate-controlled greenhouses are unsuitable for Indian producers because to their high initial cost and continuous operational expenses.

4. The heating and cooling systems of the greenhouses require a more consistent power source in many parts of the nation.

5. 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 [74].

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

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

8. It is difficult to obtain the materials for cladding that are required. Furthermore, greenhouses are not equipped with the right tools to regulate the atmosphere.

9. No specific research projects are in place to cultivate protected crops.

10. There is a lack of packaging and on-farm value-added materials to supply markets with high-quality products [30].

**Conclusion**

The practice of producing crops in a controlled setting, known as protected farming, enables the management of variables including temperature, light, humidity, and other factors according to the crop's particular needs. This regulated setting raises the total yield and encourages healthier plants. Protected farming methods come in many forms, such as plastic tunnels, insect-proof net houses, shade net houses, naturally ventilated polyhouses, forcibly ventilated greenhouses, and mulching, raised beds, trellising, and drip irrigation [75]. By prolonging the cultivation time or facilitating the production of crops during off-seasons, these techniques can be used singly or in combination to produce a favourable growth environment that protects plants from harsh climates. By decreasing evaporation losses, drip irrigation combined with raised beds and mulch films improves soil moisture retention and helps manage weeds. Protected horticulture allows crops to grow in a controlled environment where variables like light, rainfall, and temperature may be changed according to the needs of the crop. Healthy plants are encouraged in this setting, and overall productivity rises [76]. Various structures and methods, including as high tunnels, net houses, drip irrigation, micro irrigation, variety selection, and precise technology, are all part of safe agricultural practices. The ideal growth environment is created by shielding crops from unfavourable weather, prolonging the growing season, and permitting off-season crop production. Adopting this advancement provides advantages including higher soil moisture retention and weed control.

**Disclaimer (Artificial intelligence)**

Option 1:

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.

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