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Advancements and innovations in protected cultivation for horticultural and floricultural crops: A Comprehensive Review

Deepika Bansal[1]*, Hitesh[2], Arvind Malik[2], AbhishekOjha[3]

[1]Department of Horticulture (FLS), CCS Haryana Agricultural University, Hisar, Haryana, India. 125004
[2]Department of Genetics and Plant Breeding, CCS Haryana Agricultural University, Hisar, Haryana, India. 125004

ABSTRACT

The practice of protected cultivation of horticultural crops has become increasingly important in contemporary agriculture, providing advantages that include higher yields, improved quality and defense against pests and unfavorable weather. This review aims to evaluate current protected cultivation practices and investigate their potential in horticulture and floriculture. The examination begins by reviewing the various protected production structures, such as greenhouses, high tunnels and shade houses, detailing their structural benefits and environmental limitations. The importance of protected farming in addressing global food security issues is emphasized, particularly its role in maintaining crop output year-round. Furthermore, this review examines the impact of climate control and the optimization of environmental parameters—including temperature, humidity and carbon dioxide levels—on crop morphogenesis. The application of cutting-edge technologies, such as aeroponics, hydroponics and vertical farming, is critically analyzed, highlighting their potential to maximize output while consuming minimal resources. However, implementing these systems presents profound systemic challenges, primarily the substantial initial capital required, the high energy consumption of climate regulation in regions with irregular electricity, and the risk of rapid disease spread in enclosed spaces. Adapting this advanced infrastructure to be economically scalable for smallholder farmers across diverse agro-climatic zones remains a critical bottleneck. The study also identifies major difficulties and limitations associated with adopting protected cultivation, such as high energy requirements and financial constraints and outlines critical research gaps in sustainable infrastructure. Finally, the investigation explores future perspectives, including the application of artificial intelligence and precision agriculture methods, which could lead to increased yields by further optimizing resource utilization.

Keywords: *Protected cultivation, Floriculture, Greenhouse technology, Precision agriculture, Sustainable horticulture, Aeroponics, Hydroponics, Agrivoltaics, Climate control.*

1. Introduction

India's integration into global markets and its economic liberalization have created immense opportunities for the export of premium horticultural crops, alongside a rapidly expanding domestic market [31, 63]. To satisfy the expectations of quality-conscious consumers, agricultural systems must simultaneously enhance crop yield and quality [53]. While basic elements such as planting material and routine cultural practices can be managed in open fields, the precise environmental regulation required for optimal growth is only possible in enclosed settings [7, 28, 35].

Consequently, there is a pressing need for innovative production technologies that align high yields with strict market quality parameters [24]. Protected cultivation, widely known as greenhouse technology, fulfills this requirement by artificially tailoring the microclimate surrounding the plant to its specific developmental needs.

*Corresponding Author: **Deepika Bansal***
*Email Address: **deepikabansal1710@gmail.com***

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This approach holds exceptional promise for the floriculture sector, which exhibits an annual growth rate of 25–30% and has the potential to generate significantly higher foreign revenue than traditional cereal crops [63]. As illustrated in Figure 1, consistent high growth in the floriculture sector underscores the economic necessity of protected structures.

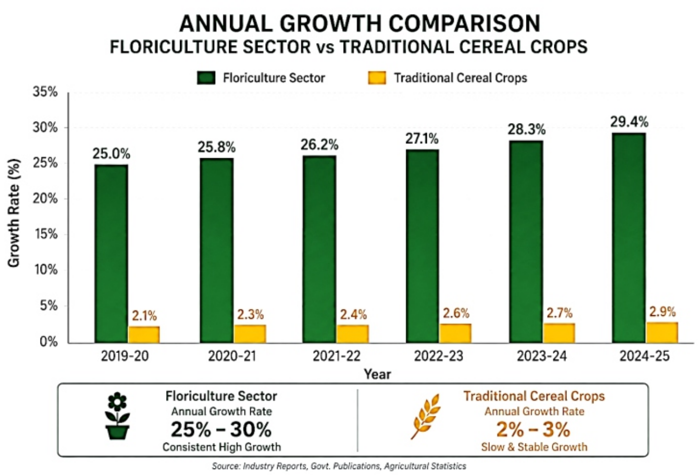

***Figure 1:** Annual growth rate comparison between the floriculture sector and traditional cereal crops*

By safeguarding plants against unpredictable weather hazards and pest infestations, regulated environments guarantee a reliable, consistent and high-quality harvest [21, 53 and 59]. The transition to protected environments provides substantial physiological and financial advantages, promoting faster maturity and improving crucial floral characteristics. Because this method can amplify yields four to five times compared to conventional farming [53], commercial floriculture heavily relies on these structures for export markets [31, 34]. The primary objective of this review is to synthesize recent literature on protected cultivation, critically analyze current technological advancements and identify knowledge gaps to guide future horticultural research.

2. Literature Review

The existing literature extensively covers the structural designs and environmental manipulations required for protected cultivation. This section categorizes the fundamental components and major commercial applications identified in recent studies.

2.1 Types of Protected Cultivation Structures

Depending on agro-climatic conditions and resource availability, growers utilize a variety of protective structures (Figure 2 and Figure 3) [21, 26, 54].

- **Greenhouses:** Transparent, framed, or inflatable structures used to grow crops in a controlled environment [14, 50]. They can be classified by shape (Lean-to, Even Span, Uneven Span, Ridge and Furrow, Saw Tooth, Quonset) or construction material (Wooden Frame, Pipe Frame, Truss Frame). Cost considerations divide them into low-cost (bamboo/wood with UV film), medium-cost (galvanized iron with semi-automatic controls) and high-cost (aluminum/iron frames with computerized controls) structures.

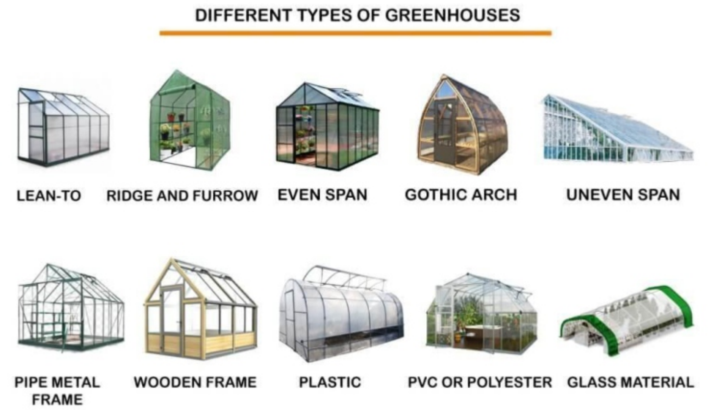

Figure 2: Classification of greenhouse structures based on shape and construction design.

- **Cladding Materials:** Polythene is an affordable cladding material, while UV-stabilized fiberglass and polycarbonate panels act as durable alternatives. Linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE) have a three to four-year lifespan when treated with UV stabilizers [40].
- **Alternative Structures:** Shade net houses provide filtered sunlight for shade-loving plants, utilizing materials like commercial plastic nets with specific cut-out percentages (e.g., 40%, 60%, 80%). Lath houses, cold frames and hot beds provide seasonal protection and early germination benefits [56].

Figure 3: Structural and functional comparison of high-tech glasshouses, standard polyhouses and shade net houses

2.2 Environmental Factors in Protected Cultivation

The optimization of environmental parameters (**Figure 4**) is essential for preventing disease and maximizing yield [50, 54, 56].

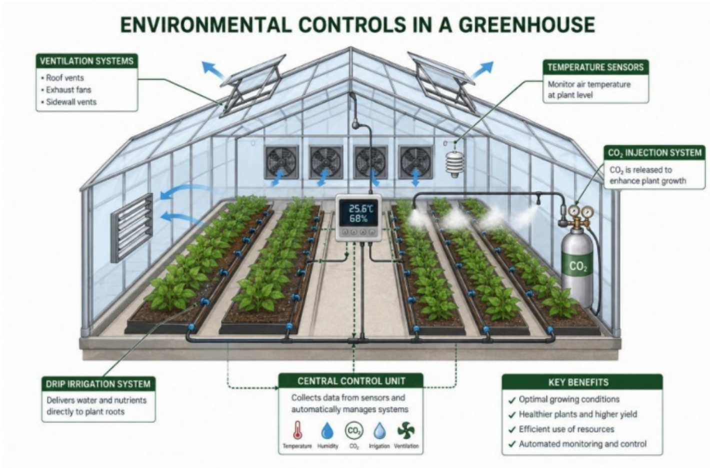

Figure 4: Schematic representation of automated environmental control systems within a modern greenhouse

- **Temperature and Humidity:** Optimal temperatures (15–30°C for ornamentals) and humidity (50–80%) are critical [50]. Insufficient humidity causes dehydration, while excess promotes fungal diseases [55].

- **Light Intensity and Photoperiod:** Enhancing light with LED systems encourages compact growth [58]. Photoperiod manipulation is crop-specific; for instance, petunias require long days, while chrysanthemums require short days [25, 66]. Red and blue light wavelengths are notably effective for improving photosynthesis [37, 42].

- **Carbon Dioxide Enrichment:** Raising carbon dioxide levels (700–1,500 ppm) increases plant productivity and water-use efficiency [7, 33, 45, 68].

- **Nutrient and Water Management:** Drip irrigation saves 30–70% on water while achieving high efficiency [9, 30]. Precise macronutrient and micronutrient delivery via fertigation ensures effective absorption when substrate pH is maintained between 5.5 and 6.5 [51, 57].

2.3 Major Commercial Flower Crops

Protected cultivation is predominantly utilized for high-value ornamentals (Figure 5) [61].

Figure 5: Major commercial high-value floricultural crops cultivated in protected environments

A critical summary of their propagation and environmental requirements is provided in Table 1.

Table 1: Summary of Requirements for Major Commercial Flower Crops under Protected Cultivation

Crop	Primary Propagation Method	Optimal Substrate / Soil pH	Key Environmental / Management Factors
Rose	Budding / Top-grafting	5.5 – 6.5 (Loamy / Soilless)	Humidity 50–60%; Drip fertigation (N, P, K, Mg)
Carnation	Stem cuttings (IBA/NAA)	5.5 – 6.5 (Well-drained)	EC 1.2–1.7 mS/cm; Strict ventilation
Gerbera	Tissue culture / Cuttings	5.5 – 6.5 (Slightly acidic)	Biological control of mites; Precise fertigation
Orchid	Tissue culture / Seed	Bark chips, coir, sphagnum	High humidity (70–80%); Symbiotic fungi reliance
Chrysanthemum	Terminal cuttings / Tissue	6.5 (Sandy loam / Perlite)	Strict photoperiod control; Cold storage post-harvest

(Data synthesized from: 8, 19, 23, 49)

3. Current Advances

Recent literature indicates a shift toward integrating high-technology systems with traditional protected cultivation to enhance sustainability and yield [59].

3.1 Automation and Smart Greenhouse Technology

Combining robotics, the Internet of Things (IoT) and Artificial Intelligence (AI) facilitates the real-time monitoring of temperature, humidity and soil moisture [3]. Predictive analytics modifies environmental conditions, while robotics automates planting, harvesting and irrigation [38, 41].

3.2 Hydroponics and Aeroponics

Soilless cultivation techniques offer exact control over growth conditions (**Figure 6**). Aeroponics suspends roots in misted air, while hydroponics grows plants in nutrient-rich water. Both are increasingly enhanced by fuzzy logic-based IoT systems, significantly reducing water usage compared to soil-based methods [69].

3.3 Greenhouse Agrivoltaics

Incorporating photovoltaic (PV) panels in greenhouse farming presents a viable method to modify microclimates, offset high energy consumption and increase overall farm sustainability [17]. Agrivoltaic systems allow for dual land use, balancing energy production with horticultural output [14].

3.4 Biostimulants and Organic Cultivation

The reliance on synthetic inputs is being mitigated by the use of phytohormones and biostimulants, such as *Pseudomonas entomophila* PE3, which increase stress tolerance and yield [18, 44].

4. Challenges and Research Gaps

While protected cultivation offers numerous benefits, critical analysis reveals several systemic challenges and significant gaps in current research.

Current Challenges:

- **Financial Constraints:** The high initial capital required for infrastructure, coupled with ongoing maintenance expenses and market volatility, poses a barrier to smallholder farmers [6, 21].
- **Energy Consumption:** Advanced climate regulation technology demands high, consistent energy input, which is particularly challenging in developing regions with irregular electricity supply [26].
- **Biotic Stresses in Enclosed Environments:** Diseases can spread rapidly in controlled spaces. Furthermore, the exclusion of natural pollinators necessitates artificial pollination, which increases labor costs [1, 12, 15].

Identified Research Gaps:

1. Region-Specific Cost Models: Most literature focuses on high-tech glasshouses suitable for temperate zones. There is a lack of comprehensive studies on optimizing low-to-medium cost polyhouses specifically for tropical and sub-tropical microclimates [28].

2. Scalability of AI and IoT: While smart greenhouses are proven in experimental settings, research addressing the economic scalability and user-friendly adoption of these technologies for rural farmers remains sparse [3].

3. Long-term Environmental Impact of Cladding: The degradation and disposal of polyethylene films present an ecological issue that requires further investigation into biodegradable or fully recyclable cladding alternatives [40].

5. Future Perspectives

The future of protected cultivation relies on harmonizing technological innovation with ecological sustainability [7, 34]. Developing polyhouse designs tailored to localized climatic requirements will be essential for boosting efficiency. Furthermore, making advanced UV-stabilized plastic sheets and shading nets more accessible to marginal farmers will improve the widespread robustness of these systems [21].

Future research must prioritize breeding plant varieties specifically genetically tailored specifically for enclosed environments (e.g., varieties that require less ventilation or have higher resistance to greenhouse-specific pathogens) [6]. The continued integration of AI-driven precision agriculture and renewable energy (agrivoltaics) will be the primary driver in overcoming current energy and labor constraints, maximizing resource efficiency and ensuring the economic viability of floriculture in the coming decades [34, 61].

6. Conclusion

Protected cultivation offers an essential, modern approach for the floriculture and horticulture industries by providing substantial advantages in crop yield, quality and environmental control. It successfully mitigates the unpredictability of open-field farming, ensuring year-round production of premium crops. Despite challenges such as high initial costs, high energy demands and the necessity for skilled labor, technological advancements like AI, IoT, hydroponics and the use of biostimulants are making protected agriculture increasingly resilient. By addressing existing research gaps and tailoring infrastructure to regional needs, the sector can sustainably meet both domestic and international market demands well into the future.

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Authors Contribution

Deepika Bansal conceptualized the review, conducted the primary literature search, drafted the initial manuscript and revised the final version for submission. Hitesh assisted in data synthesis, literature screening and writing the sections on environmental parameters and commercial crop applications. Arvind Malik contributed to the analysis of structural materials, cladding technologies, and agro textiles and helped draft the technological advancements section. Abhishek Ojha provided a critical review of the manuscript, assisted with formatting and contributed to the discussion on challenges and future research gaps. All authors read, reviewed and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

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