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Protected cultivation of cucurbit vegetables: Technologies, production strategies, and future prospects

VikrantDOI: <https://www.doi.org/10.33545/26631067.2026.v8.i7b.821>**Abstract**

Cucurbits (family Cucurbitaceae) constitute one of the most economically important groups of vegetable crops worldwide, including cucumber (*Cucumis sativus* L.), muskmelon (*Cucumis melo* L.), watermelon (*Citrullus lanatus* L.), bitter gourd (*Momordica charantia* L.), bottle gourd (*Lagenaria siceraria*), ridge gourd (*Luffa acutangula*), sponge gourd (*Luffa cylindrica*), pumpkin (*Cucurbita* spp.), and squash. These crops are valued for their high nutritional content, medicinal properties, and significant contribution to global food and nutritional security. However, conventional open-field cultivation of cucurbits is increasingly constrained by climate change, erratic weather patterns, water scarcity, emerging pests and diseases, and declining resource-use efficiency. Protected cultivation has emerged as a promising production system that provides a controlled growing environment for year-round cultivation, higher productivity, superior fruit quality, and efficient utilization of water, nutrients, and other agricultural inputs. Technologies such as naturally ventilated polyhouses, climate-controlled greenhouses, net houses, low tunnels, hydroponics, fertigation, and precision agriculture have significantly improved cucurbit production under protected environments. In addition, recent advances in sensor-based irrigation, Internet of Things (IoT), artificial intelligence (AI), automation, and climate-smart greenhouse management are revolutionizing protected vegetable cultivation by optimizing environmental parameters and minimizing production risks. Despite these advantages, challenges including high initial investment, skilled labor requirements, pollination management, disease outbreaks, and energy consumption continue to limit widespread adoption. This review summarizes the current status of protected cultivation technologies for cucurbits, discusses recent technological advancements, highlights major production constraints, and outlines future research priorities for sustainable and climate-resilient cucurbit production.

Keywords: Cucurbits, protected cultivation, greenhouse, polyhouse, precision agriculture, climate-smart agriculture, hydroponics, fertigation

Introduction

The family Cucurbitaceae comprises approximately 118 genera and over 960 species, making it one of the largest families of vegetable crops cultivated worldwide (Schaefer and Renner, 2011) ^[9]. Economically important cucurbits include cucumber, muskmelon, watermelon, bitter gourd, bottle gourd, pumpkin, squash, ridge gourd, sponge gourd, snake gourd, ash gourd, and pointed gourd, which are extensively grown in tropical, subtropical, and temperate regions. These crops contribute substantially to global vegetable production due to their high nutritional value, short crop duration, adaptability to diverse agro-climatic conditions, and significant commercial demand (Paris, 2016) ^[6].

Cucurbit vegetables are excellent sources of vitamins (A, C, and E), minerals, dietary fiber, antioxidants, carotenoids, flavonoids, and other bioactive compounds that contribute to human health. Several cucurbits, particularly bitter gourd, pumpkin, and cucumber, have also gained attention because of their medicinal properties, including antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and anticancer activities (Rolnik and Olas, 2020) ^[8]. Consequently, increasing consumer awareness regarding healthy diets and functional foods has substantially increased the demand for high-quality cucurbit vegetables throughout the year.

Despite their economic importance, cucurbit production under open-field conditions is becoming increasingly difficult due to the adverse impacts of climate change. Rising

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temperatures, erratic rainfall, prolonged droughts, flooding, salinity, and extreme weather events frequently reduce crop productivity and fruit quality. Moreover, cucurbits are highly susceptible to numerous insect pests and diseases, including whiteflies (*Bemisia tabaci*), aphids, thrips, fruit flies, powdery mildew, downy mildew, Fusarium wilt, cucumber mosaic virus (CMV), zucchini yellow mosaic virus (ZYMV), and Tomato Leaf Curl New Delhi Virus (ToLCNDV), all of which can cause severe economic losses (McCreight *et al.*, 2020) ^[5]. These production constraints necessitate the adoption of innovative cultivation technologies capable of ensuring stable and sustainable production.

Protected cultivation has emerged as one of the most effective strategies for overcoming these challenges. Protected structures such as naturally ventilated polyhouses, climate-controlled greenhouses, net houses, shade houses, and low tunnels create favorable microclimatic conditions by regulating temperature, humidity, solar radiation, ventilation, and irrigation. Such environmental control enables year-round production, higher yields, improved fruit quality, efficient water and nutrient utilization, and reduced dependence on chemical pesticides (Singh *et al.*, 2017) ^[12]. Protected cultivation also facilitates the production of premium-quality vegetables during off-season periods when market prices are significantly higher, thereby increasing farmers' profitability.

Rapid technological advancements have further transformed protected cultivation systems. Precision irrigation, fertigation, hydroponics, substrate culture, automation, Internet of Things (IoT), artificial intelligence (AI), remote sensing, and climate-control technologies are increasingly integrated into modern greenhouse production systems to optimize resource-use efficiency and improve crop performance. These innovations have significantly enhanced productivity while minimizing environmental impacts, making protected cultivation an essential component of sustainable horticulture and climate-smart agriculture.

This review provides a comprehensive overview of protected cultivation technologies in cucurbits, including production systems, environmental requirements, crop management practices, technological innovations, pest and disease management, economic considerations, challenges, and future prospects for sustainable vegetable production under changing climatic conditions.

2. Importance of protected cultivation in cucurbits

Protected cultivation refers to the cultivation of crops under structures that provide partial or complete control over the crop-growing environment. Unlike conventional open-field agriculture, protected cultivation allows growers to regulate key environmental parameters such as temperature, relative humidity, light intensity, carbon dioxide concentration, irrigation, and nutrient supply according to crop requirements (Jensen and Malter, 1995) ^[4]. This technology has become increasingly important in cucurbit production because these crops are highly sensitive to environmental fluctuations, particularly during flowering and fruit development.

Climate change has intensified abiotic stresses such as heat waves, cold injury, drought, heavy rainfall, hailstorms, and strong winds, all of which adversely affect cucurbit growth, pollination, fruit set, and yield. Protected structures mitigate

these stresses by maintaining a stable microclimate, thereby reducing crop losses and improving productivity. Temperature regulation within protected structures is particularly beneficial because most cucurbit crops perform optimally between 22 and 30°C. Controlled environments also improve pollination efficiency, reduce flower abortion, and promote uniform fruit development.

Protected cultivation significantly enhances water-use efficiency through drip irrigation and fertigation. Compared with flood irrigation, drip systems reduce water consumption by 30-60% while improving fertilizer-use efficiency and minimizing nutrient leaching. Furthermore, protected cultivation reduces weed infestation, lowers pesticide usage through insect-proof netting, and minimizes the incidence of soil-borne diseases by adopting soilless culture and substrate-based production systems.

One of the greatest advantages of protected cultivation is off-season production, enabling farmers to supply fresh cucurbits when open-field production is limited. Such production windows often command premium market prices, substantially increasing farm profitability. Moreover, greenhouse-grown cucurbits generally exhibit superior fruit appearance, uniform size, better shelf life, and higher nutritional quality compared with open-field crops.

Protected cultivation is therefore increasingly recognized as a climate-resilient production strategy capable of improving food security, resource-use efficiency, and economic sustainability while reducing the environmental footprint of vegetable production.

3. Types of Protected Structures

Protected cultivation employs various structures designed to modify the crop microenvironment according to local climatic conditions, available resources, and production objectives. The selection of an appropriate structure depends upon crop species, investment capacity, climatic conditions, and technological requirements.

The naturally ventilated polyhouse is the most widely adopted protected structure for cucurbit cultivation in tropical and subtropical countries because it provides effective environmental modification at relatively low construction and operating costs. Ventilation occurs naturally through roof and side openings covered with insect-proof nets, reducing temperature buildup while maintaining adequate air circulation. These structures are highly suitable for cucumber, muskmelon, parthenocarpic cucumber hybrids, and colored capsicum.

In regions with extreme climatic conditions, climate-controlled greenhouses equipped with cooling pads, exhaust fans, heating systems, foggers, and automated environmental controls provide precise regulation of temperature, humidity, and carbon dioxide concentration. Although construction and maintenance costs are considerably higher, these systems produce maximum yields and premium-quality fruits throughout the year.

Net houses: are relatively inexpensive structures covered with insect-proof nets that primarily protect crops from insect pests, birds, and excessive solar radiation. They are widely used for nursery production and cultivation of bitter melon, bottle melon, cucumber, and ridge melon in warm climates.

Shade houses: utilize shade nets of varying densities (30-75%) to reduce solar radiation and temperature during summer months. These structures protect young seedlings from heat stress and improve transplant establishment.

Low tunnels and walk-in tunnels are temporary plastic-covered structures that create favorable conditions during early crop establishment or winter cultivation. These systems enable earlier planting, enhance seed germination, protect young plants from frost and wind, and facilitate early harvesting, thereby increasing economic returns.

Modern protected cultivation increasingly incorporates smart greenhouse technologies, including automated climate control, wireless sensors, IoT-based monitoring, artificial intelligence, and robotic systems for irrigation, fertigation, and environmental management. These technologies represent the future of protected agriculture by enabling precise crop management, reducing labor requirements, and improving resource-use efficiency.

4. Suitable cucurbit crops for protected cultivation

Protected cultivation has revolutionized cucurbit production by enabling year-round cultivation of high-value crops with improved yield, fruit quality, and resource-use efficiency. Although almost all commercially important cucurbits can be cultivated under protected structures, their performance depends on crop physiology, growth habit, pollination requirements, environmental conditions, and the type of protected structure used. Crops with indeterminate growth habits, high market demand, and good response to trellising and fertigation are particularly suitable for greenhouse and polyhouse cultivation (Singh *et al.*, 2017) ^[12].

Among cucurbits, parthenocarpic cucumber (*Cucumis sativus* L.) is the most commercially important crop grown under protected cultivation worldwide. These hybrids develop fruits without pollination, ensuring uniform fruit set even under enclosed environments where insect pollinators

are scarce. Greenhouse cucumbers generally produce two to three times higher yields than open-field crops due to continuous harvesting, efficient nutrient management, and reduced pest pressure (Hochmuth *et al.*, 2018) ^[3].

Muskmelon (*Cucumis melo* L.) is another economically important greenhouse crop. Protected cultivation allows early planting, improved fruit sweetness, uniform fruit shape, and higher market prices during the off-season. Controlled irrigation and fertigation also improve total soluble solids (TSS) and fruit firmness, making greenhouse-grown muskmelons highly preferred in premium markets.

Watermelon (*Citrullus lanatus*) is increasingly cultivated under low tunnels, high tunnels, and polyhouses to facilitate early harvest and improve fruit quality. Protected cultivation protects the crop from excessive rainfall and fruit cracking while extending the harvesting season.

Other cucurbits such as bitter melon (*Momordica charantia*), bottle gourd (*Lagenaria siceraria*), ridge gourd (*Luffa acutangula*), sponge gourd (*Luffa cylindrica*), and snake melon (*Trichosanthes cucumerina*) are widely cultivated in naturally ventilated polyhouses and net houses. These climbing vegetables respond well to vertical trellising systems that improve light interception, reduce disease incidence, and facilitate harvesting.

Pumpkin (*Cucurbita moschata*), zucchini (*Cucurbita pepo*), and summer squash have also shown considerable potential under protected cultivation, particularly in temperate regions where low temperatures limit open-field production. These crops benefit from enhanced temperature regulation and protection against frost during early growth stages.

Protected cultivation is particularly advantageous for producing off-season vegetables, enabling growers to supply fresh cucurbits during periods of limited field production. This significantly increases profitability because off-season vegetables command premium market prices.

Table 1: Major cucurbit crops suitable for protected cultivation

Crop	Preferred Protected Structure	Optimum Temperature (°C)	Yield Advantage over Open Field (%)
Parthenocarpic cucumber	Polyhouse/Greenhouse	22-28	150-250
Muskmelon	Polyhouse	24-30	60-120
Watermelon	Low tunnel/Polyhouse	24-32	40-80
Bitter melon	Net house/Polyhouse	24-30	50-100
Bottle gourd	Polyhouse	22-30	40-90
Ridge gourd	Polyhouse	24-32	50-100
Sponge gourd	Polyhouse	24-30	50-90
Summer squash	Greenhouse	18-25	80-150
Zucchini	Greenhouse	18-24	70-140

5. Environmental requirements for protected cultivation of cucurbits:

Successful production of cucurbits under protected cultivation depends on maintaining optimal environmental conditions throughout the crop growth cycle. Unlike open-field cultivation, protected structures allow regulation of temperature, relative humidity, solar radiation, carbon dioxide concentration, irrigation, and ventilation according to crop requirements (Jensen & Malter, 1995) ^[4].

Temperature is the most critical environmental factor affecting seed germination, vegetative growth, flowering, pollination, fruit development, and yield. Most cucurbit crops perform optimally between 22 and 30°C during the day and 18-22°C at night. Temperatures above 35°C reduce pollen viability, increase flower abortion, and impair fruit development, whereas temperatures below 15°C retard plant

growth and delay flowering (Gruda, 2005) ^[2].

Relative humidity (RH) also plays an important role in greenhouse crop performance. A relative humidity of 60-80% is generally considered optimum for cucurbit production. Excessive humidity favors fungal diseases such as powdery mildew, downy mildew, and Botrytis gray mold, while very low humidity increases transpiration and causes water stress.

Light intensity directly influences photosynthesis and fruit quality. Most cucurbits require approximately 20-30 mol m⁻² day⁻¹ of photosynthetically active radiation (PAR) for maximum productivity. During winter months or cloudy conditions, supplemental lighting may be required in climate-controlled greenhouses.

Carbon dioxide enrichment has become an important practice in commercial greenhouse production. Increasing CO₂ concentration from the ambient level (~420 ppm) to 800-1,000 ppm enhances photosynthetic efficiency, biomass accumulation, and fruit yield by 20-30%, particularly in cucumber and muskmelon.

Proper ventilation is essential for regulating temperature, humidity, and carbon dioxide concentration. Naturally ventilated polyhouses utilize roof and side vents, whereas modern greenhouses employ exhaust fans, evaporative cooling pads, fogging systems, and automated climate-

control equipment to maintain optimum environmental conditions.

Efficient irrigation and nutrient management are equally important. Drip irrigation combined with fertigation ensures precise delivery of water and nutrients directly to the root zone, thereby reducing water losses and improving fertilizer-use efficiency. Soilless media such as cocopeat, perlite, vermiculite, and rockwool are increasingly adopted because they provide excellent aeration, water-holding capacity, and reduced incidence of soil-borne diseases.

Table 2: Optimum environmental conditions for greenhouse cucurbit production

Parameter	Recommended Range
Day temperature	22-30°C
Night temperature	18-22°C
Relative humidity	60-80%
CO ₂ concentration	800-1,000 ppm
Soil/Media pH	5.8-6.5
EC of nutrient solution	2.0-2.8 dS m ⁻¹
Light intensity (PAR)	20-30 mol m ⁻² day ⁻¹
Irrigation method	Drip irrigation
Growing medium	Cocopeat, Perlite, Rockwool

6. Crop establishment and cultural practices

Proper crop establishment and adoption of scientific cultural practices are essential for maximizing productivity and maintaining fruit quality under protected cultivation. Since greenhouse production involves intensive crop management, every stage from nursery raising to harvesting requires careful attention.

Healthy seedlings form the foundation of successful greenhouse cultivation. Seedlings are generally raised in protrays filled with sterilized cocopeat or other inert growing media to ensure uniform germination and disease-free planting material. Seedlings are transplanted at the two- to three-true-leaf stage, usually 20-25 days after sowing.

Plant spacing varies depending on crop species and training system. Parthenocarpic cucumber is commonly planted at a spacing of 90 × 45 cm, while muskmelon and watermelon require wider spacing because of their vigorous vine growth. Adequate spacing promotes better air circulation, reduces disease incidence, and improves light penetration.

Vertical training and trellising are indispensable components of protected cultivation. Plants are trained using nylon strings attached to overhead support wires, allowing vertical growth that maximizes light interception and facilitates intercultural operations. Lower leaves and lateral shoots are periodically pruned to improve ventilation and reduce disease pressure.

Pruning is particularly important in indeterminate cucumber hybrids. Removal of old leaves, excessive side shoots, and unproductive branches directs assimilates toward fruit development and improves overall productivity. Fruit thinning is practiced in muskmelon and watermelon to retain only one or two fruits per vine, thereby enhancing fruit size and quality.

Pollination management differs among cucurbit species. Parthenocarpic cucumber hybrids do not require pollination and are therefore highly suitable for greenhouse cultivation. In contrast, muskmelon, watermelon, bitter melon, and gourds require insect pollination or manual pollination when natural pollinators are absent. Commercial greenhouses frequently introduce bumblebees (*Bombus* spp.) or honeybees to ensure efficient pollination.

Nutrient management is generally achieved through fertigation, where water-soluble fertilizers are supplied through drip irrigation according to crop growth stages. Fertigation improves nutrient uptake efficiency, minimizes fertilizer wastage, and enhances fruit yield and quality.

Integrated crop management practices including mulching, sanitation, biological pest control, crop rotation, and regular environmental monitoring are essential for sustainable greenhouse production. Adoption of these practices significantly reduces pesticide use while maintaining high productivity and environmental sustainability.

Table 3: Recommended cultural practices for greenhouse cucurbits

Cultural Practice	Recommendation
Nursery medium	Sterilized cocopeat
Seedling age	20-25 days
Training system	Single-stem vertical trellis
Pruning	Weekly removal of lateral shoots and old leaves
Irrigation	Drip irrigation
Fertigation	Daily or alternate-day application of water-soluble fertilizers
Pollination	Bumblebees/Hand pollination (except parthenocarpic cucumber)
Mulching	Black or silver-black polyethylene mulch
Harvesting	Regular harvesting every 2-3 days for cucumber

7. Precision irrigation and fertigation

Protected cultivation enables precise management of water and nutrients, making precision irrigation and fertigation indispensable components of modern cucurbit production. Compared with conventional surface irrigation, drip irrigation combined with fertigation substantially improves water-use efficiency (WUE), nutrient-use efficiency (NUE), fruit quality, and crop productivity while reducing fertilizer losses through leaching and runoff (Sonneveld & Voogt, 2009) ^[13]. Since greenhouse-grown cucurbits have a high nutrient demand due to rapid vegetative growth and continuous fruit production, maintaining an optimum root-zone environment is critical for achieving maximum yield. Drip irrigation is the most widely adopted irrigation method in protected cultivation because it delivers water directly to the root zone with minimal evaporation losses. Studies have shown that drip irrigation can reduce water consumption by 30-60% while increasing yields by 20-50% compared with conventional irrigation methods (INC, 2023). Automated irrigation systems equipped with soil moisture sensors, tensiometers, and weather-based controllers further enhance

irrigation efficiency by applying water according to crop demand.

Fertigation involves the application of water-soluble fertilizers through drip irrigation. Nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients are supplied according to different crop growth stages. Nitrogen and potassium requirements are highest during flowering and fruit development, whereas phosphorus is particularly important during early root establishment. Fertigation not only ensures uniform nutrient distribution but also allows growers to adjust nutrient concentrations according to crop growth and environmental conditions.

The integration of sensor-based irrigation, Internet of Things (IoT), wireless monitoring systems, and artificial intelligence (AI)-based decision support systems has further transformed greenhouse irrigation management. These technologies continuously monitor substrate moisture, electrical conductivity (EC), pH, temperature, and nutrient concentrations, enabling precise real-time adjustments that maximize productivity while conserving resources.

Table 4: General fertigation schedule for greenhouse cucumber

Crop stage	N:P ₂ O ₅ :K ₂ O ratio	Frequency
Seedling establishment	1:1:1	Daily
Vegetative growth	2:1:2	Daily
Flower initiation	2:1:3	Daily
Fruit development	2:1:4	Daily
Harvesting stage	2:1:4 + Ca & Mg	Daily

8. Advanced protected cultivation technologies

Recent technological innovations have significantly improved the efficiency, sustainability, and profitability of protected cultivation. Modern greenhouse systems increasingly integrate hydroponics, soilless cultivation, vertical farming, automation, Internet of Things (IoT), artificial intelligence (AI), robotics, and precision agriculture, enabling optimized resource utilization and higher crop productivity (Shamshiri *et al.*, 2018) ^[10, 11].

Hydroponics has emerged as one of the most promising production systems for greenhouse cucurbits. Plants are grown in nutrient solutions without soil, using substrates such as cocopeat, perlite, rockwool, or vermiculite. Hydroponic systems provide excellent control over nutrient availability, eliminate soil-borne diseases, and improve water-use efficiency by up to 90% compared with conventional agriculture.

Vertical farming and high-wire cultivation have become increasingly popular for cucumber production. Plants are trained vertically using overhead support systems, allowing greater plant density, improved light interception, and easier

crop management. Vertical systems also facilitate harvesting and reduce disease incidence by improving air circulation.

Automation technologies have greatly reduced labor requirements in commercial greenhouses. Automated climate control systems regulate temperature, humidity, ventilation, irrigation, fertigation, and CO₂ enrichment using programmable controllers. Smart sensors continuously monitor environmental variables and communicate with cloud-based management platforms through IoT networks.

Artificial intelligence and machine learning algorithms are increasingly being used to predict irrigation requirements, nutrient deficiencies, pest outbreaks, and disease development. Image-based crop monitoring systems employing computer vision enable early detection of nutritional disorders and diseases before visible symptoms appear, allowing timely intervention.

The future of protected cultivation lies in smart greenhouses, where integrated digital technologies optimize production while minimizing resource consumption and environmental impacts.

Table 5: Emerging technologies in protected cultivation

Technology	Application	Benefits
Hydroponics	Soilless crop production	Higher water-use efficiency
Cocopeat culture	Root substrate	Disease-free cultivation
IoT sensors	Environmental monitoring	Real-time crop management
Artificial Intelligence	Decision support	Optimized irrigation and fertigation
Automation	Climate control	Reduced labor requirement
Robotics	Harvesting and spraying	Improved operational efficiency
Vertical farming	Space utilization	Higher plant density
Remote sensing	Crop health monitoring	Early stress detection

9. Pest and disease management under protected cultivation

Although protected cultivation reduces exposure to adverse environmental conditions, enclosed environments may favor rapid multiplication of insect pests and pathogens if appropriate management practices are not adopted. Consequently, Integrated Pest Management (IPM) forms the cornerstone of sustainable greenhouse cucurbit production (McCreight *et al.*, 2020) ^[5].

Among insect pests, whiteflies (*Bemisia tabaci*) are the most destructive because they directly damage plants by sucking sap and transmit devastating viral diseases such as Tomato Leaf Curl New Delhi Virus (ToLCNDV) and Cucurbit Leaf Curl Virus. Aphids (*Aphis gossypii*) transmit cucumber mosaic virus (CMV), while thrips (*Thrips tabaci*) damage flowers and young fruits and vector tospoviruses. Spider mites thrive under hot, dry greenhouse conditions, causing leaf bronzing and reduced photosynthesis. Fruit flies remain major pests of bitter melon and gourds.

Fungal diseases such as powdery mildew, downy mildew, Fusarium wilt, Pythium root rot, and Botrytis gray mold frequently occur in greenhouses due to high humidity and dense plant canopies. Viral diseases including ToLCNDV, CMV, ZYMV, and Papaya Ring Spot Virus (PRSV-W) cause severe yield losses in cucurbits.

Integrated management strategies combine cultural, biological, physical, and chemical control methods. Insect-proof nets prevent entry of vectors, while yellow and blue sticky traps assist in monitoring and mass trapping of whiteflies, aphids, and thrips. Biological control agents such as *Encarsia formosa*, *Trichoderma harzianum*, *Beauveria bassiana*, and *Verticillium lecanii* provide effective eco-friendly management. Sanitation, crop rotation, removal of infected plants, resistant cultivars, and environmental management further reduce disease incidence.

Chemical pesticides should be used only when pest populations exceed economic threshold levels to minimize pesticide resistance and residue accumulation.

Table 6: Major pests and diseases of greenhouse cucurbits

Pest/Disease	Symptoms	Management
Whitefly	Leaf curling, virus transmission	Insect-proof net, sticky traps, <i>Encarsia formosa</i>
Aphids	Curling leaves, CMV transmission	Neem products, predators, selective insecticides
Thrips	Silvering of leaves	Blue sticky traps, biological control
Powdery mildew	White powdery growth	Sulfur, resistant cultivars, fungicides
Downy mildew	Yellow angular lesions	Ventilation, fungicides
Fusarium wilt	Plant wilting	Resistant rootstocks, soil sterilization
ToLCNDV	Leaf curling, stunting	Vector management, resistant hybrids

10. Pollination management

Successful pollination is essential for fruit set and yield in most cucurbit crops. Unlike open-field cultivation, pollination under protected structures is often limited because insect pollinators cannot freely enter enclosed environments (Delaplane & Mayer, 2000) ^[1].

Most cucurbits are monoecious, producing separate male and female flowers on the same plant, and rely primarily on insects for pollen transfer. Honeybees (*Apis mellifera*), bumblebees (*Bombus terrestris*), and native bees are the principal pollinators. Their activity directly influences fruit set, fruit size, shape, and seed development.

Commercial greenhouses increasingly introduce bumblebee colonies because bumblebees remain active under low light intensity, cool temperatures, and enclosed environments where honeybees are less efficient. Bumblebee pollination improves fruit quality and reduces labor costs associated

with manual pollination.

Hand pollination remains common in muskmelon, watermelon, bitter melon, pumpkin, and bottle gourd production, particularly in small-scale protected cultivation. Manual transfer of pollen from freshly opened male flowers to receptive female flowers during early morning hours significantly improves fruit set.

Parthenocarpic cucumber hybrids have revolutionized greenhouse cucumber production because they develop fruits without pollination or fertilization. These hybrids produce seedless fruits with excellent uniformity, eliminating dependence on pollinating insects and reducing production risks.

Future greenhouse systems are expected to employ robotic pollination technologies, artificial pollinators, and AI-assisted pollinator management to overcome pollination constraints under controlled environments.

Table 7: Pollination requirements of major cucurbits

Crop	Pollination type	Recommended method
Parthenocarpic cucumber	No pollination required	Natural fruit development
Muskmelon	Cross-pollination	Bumblebees/Hand pollination
Watermelon	Cross-pollination	Honeybees/Bumblebees
Bitter melon	Cross-pollination	Honeybees
Bottle gourd	Cross-pollination	Hand pollination
Pumpkin	Cross-pollination	Honeybees
Summer squash	Cross-pollination	Bumblebees

11. Yield, quality, and economic performance of cucurbits under protected cultivation

Protected cultivation has emerged as an efficient technology

for increasing productivity, improving fruit quality, and enhancing economic returns in cucurbit production. The controlled microenvironment provided by greenhouses and polyhouses allows optimization of temperature, humidity,

irrigation, nutrition, and pest management, resulting in improved plant growth and yield compared with conventional open-field cultivation. The yield advantage is particularly significant in crops such as cucumber, muskmelon, watermelon, and bitter melon, where continuous harvesting and vertical training systems maximize production per unit area (Jensen & Malter, 1995) [4].

Greenhouse-grown cucumbers are among the most productive vegetable crops under protected environments. High-wire cultivation systems, combined with fertigation and optimized environmental control, allow prolonged harvesting periods and increased yield. Studies have reported that protected cucumber cultivation can achieve yields of 150-300 tonnes ha⁻¹, compared with approximately 30-50 tonnes ha⁻¹ under open-field conditions (Hochmuth *et al.*, 2018) [3]. Similar improvements have been observed in muskmelon and watermelon, where protected structures facilitate early harvesting, improved fruit uniformity, and higher market value.

Protected environments also improve fruit quality characteristics, including fruit size, shape, color, firmness, total soluble solids (TSS), vitamin content, and shelf life. Controlled nutrient supply enhances carbohydrate accumulation and improves sweetness in melon crops. Reduced mechanical damage and lower pest incidence result in visually attractive fruits with higher consumer acceptance. In addition, protected cultivation reduces pesticide residues, making produce more suitable for premium domestic and export markets.

Economic analysis indicates that although protected cultivation requires higher initial investment for construction of greenhouse structures, irrigation systems, and environmental control equipment, the increased productivity, off-season production, and premium market prices often compensate for these costs. Profitability depends on crop selection, greenhouse technology, management skills, market access, and production scale.

Table 8: Comparison of open-field and protected cultivation of cucurbits

Parameter	Open-field cultivation	Protected cultivation
Yield	Low to moderate	2-5 times higher
Production season	Limited by climate	Year-round production
Fruit quality	Variable	Uniform and superior
Water requirement	Higher	30-60% lower
Pest incidence	High	Reduced through exclusion
Fertilizer efficiency	Moderate	High through fertigation
Initial investment	Low	High
Market value	Normal	Premium/off-season price

12. Climate change adaptation through protected cultivation

Climate change has become one of the greatest challenges affecting global vegetable production. Rising temperatures, irregular rainfall, prolonged droughts, extreme weather events, and emerging pest and disease pressures negatively influence cucurbit productivity. Since cucurbits are sensitive to environmental fluctuations, protected cultivation provides an effective approach for climate adaptation by buffering crops against adverse conditions and maintaining favorable growth environments (Gruda, 2005) [2].

Temperature extremes significantly affect cucurbit physiology. High temperatures reduce pollen viability, increase flower abortion, decrease fruit set, and negatively influence fruit quality. Protected structures equipped with ventilation systems, evaporative cooling, shade nets, and automated climate control help maintain optimum temperature ranges and minimize heat stress. Similarly, during cold periods, greenhouse structures provide thermal insulation, enabling off-season production.

Water scarcity is another major concern under changing climatic conditions. Protected cultivation systems integrated with drip irrigation, fertigation, rainwater harvesting, and

recycling technologies significantly improve water-use efficiency. Closed hydroponic systems can recycle nutrient solutions, reducing water consumption and preventing nutrient losses.

Protected cultivation also contributes to sustainable intensification by producing higher yields from smaller land areas while reducing pesticide and fertilizer inputs. The controlled environment enables biological pest management, precision nutrient application, and reduced chemical dependency, thereby decreasing environmental contamination.

Furthermore, protected cultivation can reduce the vulnerability of farmers to climate-related production failures. Stable yields, extended production seasons, and improved market availability enhance income security and resilience among vegetable growers.

However, greenhouse systems themselves require careful management because excessive energy use for cooling, heating, and ventilation can increase production costs and carbon emissions. Future research should focus on low-energy greenhouse designs, renewable energy integration, passive cooling technologies, and climate-smart protected cultivation systems.

Table 9: Role of protected cultivation in climate change adaptation

Climate challenge	Impact on cucurbits	Protected cultivation solution
High temperature	Flower abortion, poor fruit set	Cooling systems, shade nets
Drought	Reduced growth and yield	Drip irrigation, hydroponics
Heavy rainfall	Root diseases, nutrient loss	Controlled irrigation and drainage
Frost/cold stress	Growth retardation	Greenhouse protection
Pest outbreaks	Virus transmission	Insect-proof nets and IPM
Climate variability	Unstable production	Controlled environment production

13. Recent advances in protected cultivation technologies

The future of protected cultivation is strongly influenced by advancements in digital agriculture, automation, and precision crop management. Modern greenhouses are evolving from simple protective structures into intelligent production systems capable of monitoring and regulating crop environments automatically.

13.1 Internet of things (IOT)-based greenhouse management

IoT technology enables real-time monitoring of environmental parameters including temperature, humidity, soil moisture, electrical conductivity, pH, and carbon dioxide concentration through interconnected sensors. Data collected by sensors are transmitted to cloud platforms, allowing growers to make rapid management decisions. Automated irrigation and fertigation systems based on sensor feedback improve resource-use efficiency and reduce human errors (Shamshiri *et al.*, 2018) ^[10, 11].

13.2 Artificial intelligence and machine learning

Artificial intelligence has emerged as a powerful tool for predicting crop performance and optimizing greenhouse management. Machine learning models can analyze environmental data to forecast irrigation requirements, nutrient deficiencies, disease outbreaks, and yield potential. Computer vision-based systems can detect plant stress

symptoms, leaf diseases, and fruit maturity using image analysis.

13.3 Robotics and automation

Labor availability is a major constraint in protected cultivation. Robotic technologies are being developed for automated harvesting, pruning, pollination, and spraying. Robotic harvesting systems equipped with cameras and sensors can identify mature fruits and reduce labor dependence.

13.4 Vertical and soilless cultivation

Vertical farming and hydroponic systems maximize production efficiency by increasing plant density and reducing land requirements. Soilless cultivation eliminates soil-borne diseases and enables precise nutrient management. These systems are particularly promising for urban and peri-urban vegetable production.

13.5 Digital phenotyping and genotype × environment studies

High-throughput phenotyping platforms allow continuous monitoring of plant growth, canopy development, and stress responses. Integration of phenomics with genomics can accelerate development of cucurbit varieties specifically adapted to protected environments.

Table 10: Advanced technologies in protected cultivation

Technology	Application	Major advantage
IoT sensors	Climate monitoring	Real-time decision making
AI-based models	Yield and disease prediction	Precision management
Robotics	Harvesting and spraying	Reduced labor
Hydroponics	Soilless production	High resource efficiency
Automated fertigation	Nutrient management	Improved NUE
Digital phenotyping	Crop monitoring	Faster breeding decisions

14. Challenges and constraints in protected cultivation of cucurbits

Despite numerous advantages, adoption of protected cultivation remains limited due to several technical, economic, and biological constraints. The high initial investment required for greenhouse construction is one of the major barriers, particularly for small and marginal farmers. Costs associated with structures, irrigation systems, climate control equipment, and maintenance can be substantial.

Protected cultivation requires specialized knowledge regarding environmental management, fertigation, pest control, and crop training. Lack of skilled labor and technical expertise often reduces productivity and profitability.

Disease and pest management also present unique challenges. Although protected structures reduce pest entry, enclosed environments can promote rapid multiplication of pests and pathogens once introduced. Viral diseases

transmitted by whiteflies, particularly ToLCNDV and other begomoviruses, remain serious threats in cucurbit production.

Pollination management is another important constraint. Many cucurbit crops require insect pollination, and insufficient pollinator activity inside protected structures can result in poor fruit set. Although bumblebees and artificial pollination techniques provide solutions, their availability and cost remain limiting factors.

Energy consumption for cooling, heating, ventilation, and automation contributes significantly to production costs. Sustainable greenhouse designs using renewable energy, passive ventilation, and energy-efficient technologies are needed to reduce operational expenses.

Plastic waste management is an emerging environmental concern because greenhouse structures and mulching materials generate significant plastic residues. Development of biodegradable materials and recycling systems is necessary for sustainable protected cultivation.

Table 11: Major constraints and possible solutions

Constraint	Impact	Possible solution
High initial cost	Limited adoption	Low-cost greenhouse designs
Skilled labor requirement	Poor management	Farmer training programs
Pest and disease outbreaks	Yield losses	IPM and resistant varieties
Pollination problems	Reduced fruit set	Bumblebees/parthenocarpic hybrids
Energy consumption	Increased cost	Renewable energy systems
Plastic waste	Environmental pollution	Biodegradable materials
Market instability	Reduced profitability	Contract farming and value addition

15. Future Perspectives of Protected Cultivation in Cucurbits

Protected cultivation of cucurbits is rapidly transitioning from conventional greenhouse production systems toward highly automated, resource-efficient, and climate-resilient agricultural systems. Future developments will focus on integrating advanced technologies, improving sustainability, reducing production costs, and developing crop varieties specifically adapted to protected environments. With increasing pressure on agricultural land, water scarcity, climate uncertainty, and rising consumer demand for safe and high-quality vegetables, protected cultivation is expected to play a crucial role in future horticultural production systems.

One of the major future directions is the development of smart greenhouses equipped with automated climate control systems. Conventional greenhouses often depend on manual monitoring, which limits precision and increases labor costs. Future greenhouse systems will integrate artificial intelligence (AI), Internet of Things (IoT), robotics, and sensor-based technologies to automatically regulate temperature, humidity, ventilation, irrigation, nutrient supply, and pest management. These systems will enable real-time decision-making and optimize resource utilization while maintaining ideal crop growth conditions (Shamshiri *et al.*, 2018) ^[10, 11]. Another important area is the development of low-cost protected structures suitable for small and marginal farmers. Although high-tech greenhouses provide excellent productivity, their high installation and operational costs limit adoption in developing countries. Research efforts are therefore focused on passive solar greenhouses, naturally ventilated polyhouses, locally available materials, and affordable

automation technologies that can provide climate protection at reduced costs.

Future protected cultivation will increasingly incorporate climate-smart production approaches. Climate change is expected to intensify heat stress, drought, and unpredictable weather conditions, affecting cucurbit production. Greenhouse systems integrated with renewable energy sources such as solar power, rainwater harvesting, water recycling, and energy-efficient cooling systems will contribute to sustainable production. Closed-loop hydroponic systems and precision fertigation will further improve water and nutrient-use efficiency.

The development of protected cultivation-specific cucurbit varieties is another emerging priority. Most existing cultivars were developed for open-field environments and may not perform optimally under greenhouse conditions. Future breeding programs should focus on traits such as compact plant architecture, parthenocarp, disease resistance, high fruit quality, tolerance to high humidity, and suitability for vertical production systems. Molecular breeding approaches, including genome-wide association studies (GWAS), genomic selection, and CRISPR/Cas genome editing, will accelerate the development of improved cultivars.

Urbanization is also expected to increase demand for protected cultivation systems. Vertical farming, rooftop greenhouses, and controlled environment agriculture (CEA) can enable vegetable production closer to consumers, reducing transportation costs and improving freshness. Cucurbits such as cucumber, zucchini, and miniature melons are particularly suitable for urban protected production due to their high market value and rapid growth cycle.

Table 12: Future research priorities for protected cucurbit cultivation

Research area	Future direction	Expected benefit
Smart greenhouse	AI and IoT-based automation	Precision crop management
Climate adaptation	Energy-efficient structures	Reduced climate risk
Crop improvement	Greenhouse-specific hybrids	Higher productivity
Water management	Closed-loop irrigation systems	Improved water efficiency
Automation	Robotics and sensors	Reduced labor dependence
Urban agriculture	Vertical farming	Local vegetable production
Sustainability	Renewable energy integration	Lower carbon footprint

16. Role of protected cultivation in sustainable vegetable production

Sustainable agriculture aims to increase productivity while conserving natural resources and minimizing environmental impacts. Protected cultivation contributes significantly to sustainable vegetable production by improving resource-use efficiency, reducing chemical inputs, and enabling intensive production on limited land resources.

One of the greatest advantages of protected cultivation is efficient water management. Cucurbits require substantial amounts of water, particularly during flowering and fruit development. Conventional irrigation systems often result in significant water losses through evaporation, runoff, and deep percolation. In contrast, drip irrigation and fertigation systems used in protected structures deliver water and nutrients directly to the root zone, reducing wastage and

improving water-use efficiency. Protected cultivation also reduces pesticide dependency through physical barriers and biological control methods. Insect-proof nets prevent entry of major insect vectors such as whiteflies and aphids, which are responsible for transmitting viral diseases in cucurbits. Integration of biological control agents such as *Encarsia formosa*, *Beauveria bassiana*, *Trichoderma spp.*, and predatory mites reduces reliance on synthetic pesticides and promotes environmentally friendly production.

Soilless cultivation systems such as hydroponics and substrate-based production contribute to sustainability by reducing soil degradation and eliminating soil-borne pathogens. These systems allow cultivation in regions with poor soil quality, salinity problems, or limited arable land.

Nutrient recycling technologies further enhance sustainability by reducing fertilizer losses and minimizing environmental contamination.

Protected cultivation also supports **food security** by enabling year-round production independent of seasonal climatic fluctuations. This is particularly important in regions experiencing climate instability, where open-field vegetable production is increasingly vulnerable.

However, sustainability of greenhouse systems depends on addressing challenges such as plastic waste generation, energy consumption, and greenhouse gas emissions. Future approaches should emphasize biodegradable covering materials, renewable energy sources, and circular production systems.

Table 13: Contribution of protected cultivation toward sustainability

Sustainability aspect	Contribution of protected cultivation
Water conservation	Drip irrigation and recycling systems
Nutrient efficiency	Precision fertigation
Chemical reduction	IPM and biological control
Land-use efficiency	Higher yield per unit area
Climate resilience	Controlled growing environment
Food security	Year-round production
Soil conservation	Soilless cultivation

17. Integration of genomics and biotechnology in protected cucurbit production

The future improvement of cucurbits under protected cultivation depends not only on environmental management but also on the development of genetically superior cultivars adapted to controlled environments. Advances in genomics and biotechnology provide powerful tools for accelerating breeding programs and improving productivity, quality, and stress tolerance.

Traditional breeding approaches have successfully developed improved cucurbit varieties; however, complex traits such as yield, fruit quality, disease resistance, and environmental adaptation are controlled by multiple genes. Modern genomic approaches including genome-wide association studies (GWAS), quantitative trait locus (QTL) mapping, genomic selection, and transcriptomics allow identification of genes and molecular markers associated with desirable traits.

For protected cucumber production, important breeding targets include parthenocarpy, gynoecy, compact growth

habit, resistance to powdery mildew, downy mildew, and viral diseases. Molecular studies have identified key genes controlling sex expression, fruit development, and disease resistance. Similarly, muskmelon and watermelon breeding programs focus on improving fruit sweetness, aroma, disease resistance, and stress tolerance.

Genome editing technologies such as CRISPR/Cas9 provide opportunities to precisely modify genes controlling important traits. For example, editing genes associated with susceptibility to pathogens can generate disease-resistant cultivars, while modification of flowering and plant architecture genes can improve suitability for high-density greenhouse production.

Integration of phenomics and artificial intelligence with genomics will further accelerate breeding by enabling rapid evaluation of large plant populations under controlled environments. Digital phenotyping platforms can measure growth rate, canopy structure, fruit development, and stress responses automatically, reducing the time and cost of cultivar development.

Table 14: Biotechnological approaches for protected cucurbit improvement

Technology	Application	Target traits
QTL mapping	Identification of genetic regions	Yield and quality
GWAS	Marker discovery	Disease resistance
Genomic selection	Breeding prediction	Complex traits
Transcriptomics	Gene expression analysis	Stress response
CRISPR/Cas9	Gene editing	Disease resistance, architecture
Phenomics	Automated screening	Growth and stress traits

18. Conclusion

Protected cultivation represents a transformative approach for sustainable and climate-resilient cucurbit production. The technology has evolved from simple protective structures to highly sophisticated controlled environment systems integrating precision irrigation, fertigation,

automation, artificial intelligence, and digital agriculture. By providing favorable growing conditions, protected cultivation enhances productivity, improves fruit quality, extends production seasons, and increases economic returns. The future success of protected cucurbit cultivation will depend on the integration of advanced technologies with

affordable production systems. Development of low-cost greenhouses, renewable energy-based systems, efficient water management strategies, and greenhouse-specific cultivars will be essential for expanding adoption among small and medium-scale growers.

Furthermore, combining genomics, biotechnology, and precision agriculture will accelerate the development of next-generation cucurbit varieties with improved yield, disease resistance, nutritional quality, and environmental adaptability. Sustainable management practices, including biological pest control, recycling systems, and reduced chemical inputs, will ensure that protected cultivation contributes positively to environmental conservation.

Despite challenges related to investment costs, technical expertise, energy consumption, and pest management, protected cultivation offers enormous opportunities for meeting future demands for safe, nutritious, and high-quality vegetables. With continued research, technological innovation, and policy support, protected cultivation will become a cornerstone of modern horticulture and play a critical role in ensuring food and nutritional security under changing climatic conditions.

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