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Recent Advances in Protected Farming of Vegetables: A Comprehensive Review

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Protected vegetable cultivation is an established approach for producing crops under structures in which the growing environment can be controlled or modified. Open-field vegetable production is frequently constrained by adverse weather, seasonal limitations, biotic stresses, abiotic stresses and inefficient resource use, which can reduce yield, quality and economic returns. This review summarises recent advances in protected farming of vegetables, with emphasis on structural improvements, greenhouse microclimate management, soilless culture and precision technologies. Modern protected structures, ranging from low-cost polyhouses to automated high-cost greenhouses, provide varying levels of protection against rainfall, wind, insects, temperature fluctuations and other production constraints. Microclimate management focuses on regulating temperature, relative humidity, light and CO_2 to support plant physiological processes and crop productivity. Cooling, heating, ventilation, shading, humidification and dehumidification systems are discussed as major tools for maintaining favourable greenhouse conditions. The review also covers hydroponics and aeroponics as soilless cultivation approaches that support nutrient delivery, water management and year-round production where soil-based cultivation is limited. In addition, precision farming

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technologies, including sensors, Internet of Things platforms, geographic information systems, global positioning systems, variable rate technology, robotics and artificial intelligence, are considered in relation to monitoring, decision-making and targeted input application. Although protected cultivation requires substantial initial investment, technical knowledge and maintenance, it offers scope for improving resource-use efficiency, crop quality and resilience to climate variability. The review highlights the need for integrated, context-specific adoption of protected cultivation technologies for sustainable vegetable production. It also recognises the importance of practical technology integration, policy support and grower capacity building for improving the feasibility of protected vegetable farming.

Keywords: Protected cultivation; greenhouse; vegetable production; microclimate management; soilless culture; hydroponics; aeroponics; precision farming; Internet of Things; variable rate technology; climate resilience.

1. Introduction

Protected cultivation involves the production of horticultural crops, including vegetables, under structures such as forced-ventilated greenhouses, shade-net houses, polyhouses, net houses and high or low plastic tunnels, where the external growing environment can be controlled or modified to suit crop growth requirements. In regions where environmental conditions, including weather, soil and water, are not suitable for growing specific vegetables, or in urban areas with limited arable land, this farming system is important for ensuring stable productivity and good-quality vegetables. It enables a stable year-round market supply and can provide high economic returns to growers (Jalwania et al., 2025). World vegetable production reached 2.1 billion tons in 2023 (FAO, 2024). China is the leading vegetable-producing country, followed by India (FAO, 2024; Dixit et al., 2023). According to the 2003 joint guidelines issued by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), the recommended daily intake of fruits and vegetables is a minimum of 400g (WHO & FAO, 2003; Kalmpourtzidou et al., 2020). Although global vegetable production is steadily increasing, rapid population growth continues to create pressure on supply. With the world population now reaching 8.3 billion and India emerging as the most populous nation, current production levels remain insufficient to satisfy the fundamental nutritional requirements of the expanding population. Vegetable production is constantly affected by both biotic and abiotic factors. Protected cultivation technology enables farmers to grow vegetables year-round in controlled environments. However, high initial investment, technical skill requirements, high maintenance costs and environmental impacts are among its limitations. The economic implications of adopting protected cultivation methods are multifaceted. Initial setup costs, ongoing operational expenses and maintenance investments are important considerations. Assessing return on investment, comparing protected cultivation with traditional farming practices and exploring market opportunities for produce grown under protected cultivation are essential for understanding the economic viability of these methods (Hariraj et al., 2025). The growing consumer demand for high-quality vegetables has driven the development of agricultural strategies that prioritise yield optimisation, nutritional enhancement and ecological responsibility (Shah et al., 2024). Reportedly, the average surface temperature of the planet has increased by about 0.18 to 0.19 degrees Celsius per decade, which indicates a rise of roughly 0.9 to 1 degree Celsius over 50 years (Samset et al., 2023). Global warming affects vegetable production by increasing heat stress, abrupt drought conditions, and pest and disease pressure, which together reduce yield and quality (Kumari et al., 2018; Osabo et al., 2014). Protected cultivation is a promising climate-resilient technique for mitigating the negative effects of global warming on crop production. It creates a microclimate that can be regulated according to the preference of the producer (Gautam et al., 2024; Jain et al., 2023). Initially, protected cultivation referred mainly to protecting crops from adverse climatic conditions and pests and diseases. With technological advancement, its role has expanded beyond basic crop protection to include diverse structures suited to climatic conditions, smart sensors, automation, renewable energy, LED lighting, hydroponics, aeroponics and drip irrigation (Maragkaki et al., 2026). Thus, protected cultivation equipped with innovative features offers an efficient approach for year-round vegetable production, and growers may also secure better financial returns (Rehman et al., 2025; Nguyen & Singh, 2024; Sánchez-Guerrero et al., 2005).

Although protected cultivation is increasingly discussed in relation to vegetable production, the available information often treats structural design, microclimate management, soilless systems and precision technologies as separate themes. A consolidated synthesis that links these advances with practical constraints such as investment cost, technical requirements, resource-use efficiency and climate-related production stress remains limited. This review addresses this gap by bringing together recent developments in protected vegetable farming and examining their relevance to improved production under controlled environments. Accordingly, the objective of this review is to provide an overview of modern technologies used in vegetable cultivation under protected conditions and to discuss the problems associated with traditional agriculture.

2. Methodology

A structured and systematic methodology was used to undertake this review. Comprehensive searches of electronic databases, including Google Scholar, PubMed, Academia, ResearchGate and Scopus, were carried out using a combination of keywords relevant to the study topic in order to identify relevant and applicable literature. Peer-reviewed books, journal articles and credible book chapters published within a specified time period were selected according to predefined inclusion criteria, with primary focus on recent advances in protected farming of vegetables. The screening procedure comprised an initial assessment of titles and abstracts, followed by full-text evaluation to determine the relevance and quality of the studies. Data from the selected sources were then extracted, systematically organised and thematically analysed to identify important trends, recurring patterns and existing inquiry gaps. This thorough and systematic approach improved the dependability, transparency and reproducibility of the review results.

3. Protected Cultivation of Vegetables: The Need of the Hour

Cultivation of vegetable crops under open-field conditions faces various biotic and abiotic stresses. Biotic stresses, namely insects, fungi, bacteria, nematodes and rodents, and abiotic stresses, namely drought, excessive heat, chilling stress, heavy metals and temperature, adversely affect the yield and quality of vegetables. In addition, other factors limiting production under open-field conditions are:

Dependent on Weather: Adverse weather conditions, such as drought and high rainfall, delay the planting of crops in the field, ultimately disturbing their normal growth pattern.

Seasonal Production: Crops require specific temperature, day length, moisture and photoperiod conditions for optimum growth. Therefore, crops cannot be grown outside their normal growing season.

Poor Resource Use Efficiency: Various agricultural inputs, such as composts, fertilisers and pesticides, are applied in large amounts in the field, since most of them are lost through processes such as leaching with flood water and volatilisation.

To overcome these major problems of open-field cultivation, protected cultivation is considered an effective solution. The benefits of this technique are briefly described below:

Environmental Control: It enables precise control of temperature, humidity, and light according to the needs of the crop.

Resource Optimisation: Growers can achieve considerably greater water- and fertiliser-use efficiency by managing inputs within a contained system.

Disease and Pest Management: The physical structure acts as a barrier against insects. It enables easier implementation of integrated pest management (IPM) and reduces reliance on chemical pesticides.

Enhanced Yield and Quality: By creating ideal growing conditions, the technique promotes rapid and uniform vegetable growth and supports the production of high-quality, market-ready crops.

Year-round Production: It allows farmers to grow vegetables year-round, which ultimately serves as a stable source of income generation.

4. Structural Advances in Protected Cultivation

Structural developments in protected cultivation of vegetables have played an important role in enhancing crop growth, yield and quality (Tiwari et al., 2025). Modern structures are now built with robust and durable materials, such as galvanised iron pipes and steel frames, which provide greater stability and longer service life. Covering materials, such as UV-stabilised polyethylene sheets, polycarbonate panels and insect-proof nets, are used to protect crops from harsh weather conditions, pests and diseases. Based on the cost of establishment, these structures can be classified into three major categories:

Low-cost Polyhouse: Low-cost structures are made from inexpensive and locally available materials, such as bamboo, wood, thatch and polyethylene sheets. They provide basic protection against rainfall, wind, insects and minor temperature variations. Examples include low tunnels, bamboo greenhouses and basic shade-net houses.

Medium-cost Polyhouse: These structures are made with relatively strong materials, such as galvanised iron pipes, aluminium frames and UV-stabilised plastic films. These structures provide partial control over temperature and humidity. Examples include naturally ventilated polyhouses and medium-quality net houses.

High-cost Structures: Steel frames, glass and polycarbonate sheets are among the strong and long-lasting materials used to build high-cost structures. These structures often include advanced features, such as heating, cooling, fogging, fertigation and automated climate-control systems. They are mostly used for research purposes, high-value crop production and export production. Examples of high-cost protected structures include glasshouses, climate-controlled greenhouses and fully automated polyhouses.

5. Microclimate Management Inside Greenhouse

Using smart microclimate management systems in greenhouses has been reported to increase productivity by reducing human error and maintaining suitable growing conditions (Goswami & Pariyar, 2022). It involves the planned modification of environmental factors, such as temperature, relative humidity (RH), light and CO_2 concentration, to improve plant physiological processes and maximise productivity (Yadav et al., 2024; Shukla et al., 2024). The major factors controlled inside greenhouses are discussed below:

Temperature: Temperature affects the major physiological processes in terrestrial plants, including germination, respiration, transpiration, photosynthesis and flowering. The temperature required inside a greenhouse largely depends on the type of crop being grown (Yadav et al., 2024).

6. Methods of Controlling Temperature Inside the Greenhouse

All greenhouse growing systems have basic climate-control components. These systems can have different levels of environmental control depending on their design and level of advancement (Santosh et al., 2017). Various cooling and heating systems inside the greenhouse are briefly discussed below:

Cooling Systems: Minimising the heat load inside the greenhouse is a major concern in tropical and subtropical areas. This is achieved mainly by three methods, namely ventilation (natural and forced), evaporative cooling and shading. Shade nets have different shading percentages, such as 30%,50% and 75%. In recent times, coloured shade nets have been widely used in vegetable production. They can modify the spectrum of light and create ideal conditions for plant growth and development (Shahak et al., 2008). In a study on the effect of different coloured shade nets on plant growth, it was found that cast iron plant (*Aspidistra elatior* L.) exhibited better growth under black shade, while Japanese pittosporum (*Pittosporum tobira* T.) showed optimum growth under red shade net (Stamps & Chandler, 2008). The nets are available in different colours, such as green, red, blue, black, white and beige. They can be installed according to the requirements of the specific crop.

Heating Systems: Heating inside greenhouses is generally required in cold climates, such as the Himalayan regions of the country (Santosh et al., 2017). Several methods are available for heating greenhouses. Among them, the unit heater system is the most common. Others include central heating systems, hot water heating systems, steam heating systems, radiant heating systems and solar heating systems.

CO_2: When plants inside the greenhouse are grown densely, the amount of carbon dioxide can decrease to a level below the outdoor concentration, even when ventilation is adequate. In the morning, the concentration is at its highest; it then gradually decreases during the day and reaches its lowest point around noon (Yadav et al., 2024; Akilli et al., 2000). Optimum CO2 levels for most greenhouse crops lie in the range of 800-1000µmol mol-1 (Wang et al., 2022).

To maintain the optimum level mentioned above, CO_2 is added to the greenhouse. This can be accomplished by pumping pure CO_2 from containers into a greenhouse or by installing a pipeline network similar to fertigation systems. Special gauges are installed on the distribution pipes to measure CO_2 concentration (Santosh et al., 2017). Pure liquefied CO_2 from storage tanks is injected through control valves into the greenhouse. This method facilitates spatially uniform ppm-level control of CO_2. Other emerging technologies include carbon capture, utilisation and storage. This method employs adsorption processes to capture CO_2 from the atmosphere and provide a continuous supply for the greenhouse (Qasem, 2017; Qasem & Ben-Mansour, 2022).

Relative Humidity: Humidity also affects plant growth and development because the rate of transpiration depends on the moisture level of the air. Excessive humidity reduces transpiration efficiency, which can inhibit plant growth and promote fungal growth. Low humidity, on the other hand, can cause plants to lose water, leading to wilting (Jain et al., 2017).

Humidity can be increased by installing high-pressure nozzles, which create fine droplets and increase humidity through evaporation. Wetted pads can also increase humidity.
As ventilation cannot be used in a closed greenhouse, dehumidification is the major issue in controlling the microclimate in such structures (Soussi et al., 2022; Vadiee & Martin, 2012). In a partly closed greenhouse, ventilation can also be used to remove moisture. There are two main types of dehumidification systems: those that use refrigeration and those that use desiccants. In refrigeration systems, moist air is cooled until it reaches its saturation point. This causes water vapour to condense and be removed. The air is then heated again (Santosh et al., 2017). Desiccant systems, on the other hand, remove moisture from the air in vapour form without cooling it. This process releases heat from adsorption, which makes the air warmer and less humid than usual (Yadav et al., 2024).

Light Intensity: The three important mechanisms controlled by light in plant growth are photosynthesis, photoperiodism and photomorphogenesis. Any change in light duration or intensity affects these processes and ultimately results in impaired plant growth (Santosh et al., 2017). Supplementary lighting is helpful for growing plants in commercial greenhouses in places that receive less than 4.5 hours of direct sunlight each day. To provide crops with sufficient light for normal growth during winter and on cloudy days, special lamps are used. LED bulbs, fluorescent lights, tube lamps, metal halide lamps and heat lamps are among the most common lighting types.

7. Advances in Soilless Culture

Soilless culture is the practice of growing plants without soil. Also known as the "container system", this method involves growing plants in containers of different shapes and sizes with drainage holes (Garg et al., 2021; Savvas & Gruda, 2018). Common containers include pots, buckets, crates, plastic bags and long troughs. To ensure that excess water drains quickly, these containers should have holes at the bottom (Atzori et al., 2021). A drip irrigation system delivers water and nutrients to rows of containers through polyethylene pipes. Emitters then provide water to each plant individually.

The amount of substrate used in each pot depends on the crop type, substrate type and water-holding capacity of the substrate (Di Lorenzo et al., 2013). Different types of substrates include cocopeat, peat moss, compost, perlite, vermiculite, sawdust, rock wool, rice hulls, pine bark, peanut hulls or similar materials.

Hydroponics: This is the method of growing crops in a nutrient-rich water solution. Roots remain in the solution or in an inert medium, such as gravel or perlite.

In hydroponics, a nutrient solution is a liquid containing essential soluble plant nutrients. It is mainly composed of macronutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium and sulphur. It also contains micronutrients, such as iron, manganese, zinc, boron, copper, molybdenum and chlorine.

To keep plants healthy, the nutrient solution should remain clean and free from harmful biological activity that could spread diseases or cause nutrient problems (Ahmed et al., 2024). pH and electrical conductivity (EC) are checked regularly. The optimum pH range is 5.5 to 6.5, which helps crops grow and ensures nutrient availability. Studies were conducted to standardise the flow rate of the nutrient solution in hydroponics using brackish water, and the results suggested that 1.5L/min and 100% ionic strength were most effective (Kaur &

Dewan, 2023). Green production methods such as hydroponics could improve the health-promoting and nutritional qualities of vegetables by increasing bioactive compounds and nutrients, such as beta-carotene and antioxidants. Research has indicated distinct quality characteristics between hydroponically and traditionally cultivated lettuce (Murphy et al., 2011). Hydroponic cultivation resulted in improved taste, acidity, carotenoid concentration and vitamin content in tomatoes (Gruda, 2008). Also, in a study, it was reported that tomatoes grown in a mix of 80% pumice, 10% perlite, and 10% peat had a 30% higher yield than those grown in soil (Mastouri et al., 2005). Researchers also found that tomatoes grown hydroponically were softer and tastier than those grown in soil (Kaur & Dewan, 2023).

Aeroponics: This is a method in which plants are grown in a trough or another container where the roots are suspended in air and nutrients are sprayed onto them in mist form. This method is relatively new and remains mainly at the research stage (Debnath & Deb, 2023). Few farms practise this method at the commercial level.

8. Precision Farming: The New Era of Modern Horticulture

Precision farming is a modern management strategy that uses data-driven technologies to optimise farming practices within a greenhouse (Ceccarelli et al., 2022). It monitors variations in plants and soil in detail with the help of various components, such as GPS, drones and sensors, and provides site-specific treatment. Sensors are used to gather information about soil moisture, nutrient levels, canopy characteristics and environmental conditions (Onyango et al., 2021). With the help of GIS, modelling tools and AI-based algorithms, these data are analysed and used to generate actionable recommendations. Precision interventions are then carried out using variable-rate technologies, automated irrigation systems and targeted input application. The components of precision farming are discussed briefly below:

Automation Inside Greenhouse: Automation in precision farming refers to the use of sensors, machines and software to perform multiple functions inside the greenhouse without human intervention (FAO, 2022). It basically works on the principle of diagnosing any deformity in the crop or microclimate with the help of sensors, making decisions on how to solve the problem with the help of controllers and finally acting on the decision with the help of AI-driven automated tools.

Role of AI in Precision Farming: Artificial intelligence facilitates automated, data-driven solutions for monitoring, decision-making and optimisation of agricultural operations for crop management. AI has the capacity to analyse extensive datasets, identify different patterns and generate forecasts with high accuracy (Hoque & Padhiary, 2024).

Robotic Tools: Robotic tools integrated with automated systems enhance the efficiency of agricultural production systems within protected cultivation (Matache et al., 2026). Some important robotic tools used in greenhouses are:

- Robotic harvesters
- Robotic pollinators (Sabir & Singh, 2013)
- Autonomous tractors and robotic sprayers
- Drones and UAVs
- Robotics in seeding, planting and thinning (Hoque & Padhiary, 2024)
- Spraying robots
- Pruning robots
- Robotic potting cells and arms

GPS and GIS: Global Positioning System (GPS) can be described as the foundation of precision agriculture. The Global Positioning System is primarily used to locate and map regions of fields that are highly infested by pests or diseases, or that have high weed populations. It is also used to locate and map soil-sampling locations, which allows growers to develop contour maps showing fertility variations throughout fields. The different datasets are added as map layers in geographic information systems (GIS) computer programs. GIS programs are used to examine and connect information between GIS layers. The development and implementation of precision agriculture or site-specific farming have been made possible by combining the Global Positioning System (GPS) and geographic information systems (GIS) (Kanakeri & Swamy, 2016).

Sensor and Internet of Things (IoT): Sensors are fundamental components in modern precision agriculture. They enable farmers to monitor various agroclimatic parameters, such as temperature, soil moisture, humidity, crop health and nutrients. Sensor networks incorporated into agricultural fields provide high-resolution spatiotemporal data, which are essential for optimisation of irrigation and fertilisation. Alharbi and Alam (2024) demonstrated that the implementation of AI-enabled IoT sensors facilitated real-time irrigation management, resulting in substantial water conservation and improved crop yields.

IoT is a network of interconnected devices embedded with different types of sensors, software and communication technologies that facilitate data exchange over the internet. The Internet of Things (IoT) is fundamentally altering agricultural practices by fostering intelligent resource oversight and improving overall efficiency (Mansoor et al., 2025). Using advanced sensors, IoT-integrated systems capture real-time field data and transmit it to cloud platforms, allowing highly accurate irrigation control (Rajak et al., 2023). Additionally, the intersection of IoT and mobile technology facilitates remote management of agricultural processes through dedicated mobile software. The integration of IoT with robotic systems marks a significant advancement in smart farming, as autonomous robots are increasingly used for precise tasks such as sowing, fertilising and crop protection (Botta et al., 2022). IoT frameworks support ecological oversight and proactive pest identification through technologies such as video monitoring and specialised lamps for remote tracking. Furthermore, meteorological data acquired through IoT-integrated sensors contribute significantly to the prediction of agricultural disasters (Mansoor et al., 2025).

9. Variable Rate Technology

Variable rate technology is a powerful tool in precision farming. Traditionally, the same amount of fertiliser or other inputs is applied in the field regardless of the variations present in the field. This raises many problems, such as under- or over-utilisation of resources, additional farming costs, variations in yield across the field and, most importantly, impacts on environmental sustainability (Lark & Stafford, 1997). Over the last twenty years, the evolution of Variable Rate Technology (VRT) has facilitated the targeted application of water, nutrients and crop-protection agents. Variable Rate Technology (VRT) empowers growers and agronomists to apply agricultural inputs, such as irrigation, nutrients and crop-protection chemicals, at specific rates that correspond to the spatial variability found within a field. This technology is versatile and integrates seamlessly into practices such as seeding, fertilisation and pest management. Implementation typically follows one of two approaches: (1) map-based VRT and (2) sensor-based VRT systems. When deployed effectively, VRT enables stakeholders to maximise crop productivity, decrease operational and labour expenses, improve net profitability and significantly reduce environmental impact (Grisso et al., 2011; Campos et al., 2020).

10. Conclusions

Protected cultivation has become an important approach for improving vegetable production under conditions where open-field farming is constrained by weather, seasonality, pests, diseases and inefficient input use. The review shows that protected structures, from low-cost polyhouses to automated greenhouses, can modify the growing environment and support year-round production of quality vegetables. Effective microclimate management remains central to this system, as temperature, relative humidity, light and CO_2 directly influence plant growth and productivity. Cooling, heating, ventilation, shading, humidification and dehumidification technologies therefore require careful selection according to crop needs, structure type and local climate. Soilless systems, particularly hydroponics and aeroponics, provide additional options for vegetable cultivation where soil limitations, nutrient management and water-use efficiency are major concerns. Precision farming tools, including sensors, IoT-based monitoring, GIS, GPS, robotics, AI and variable rate technology, can further improve decision-making and targeted input application. However, the successful adoption of these technologies depends on affordability, technical skills, maintenance capacity and appropriate policy or subsidy support. Overall, protected vegetable farming should be viewed as an integrated production strategy rather than a single technology. Its future value will depend on context-specific designs that balance productivity, resource efficiency, economic feasibility and environmental responsibility for growers and production systems alike.

11. Limitations

This review is limited by its reliance on published literature and secondary information rather than primary experimental data. Although the manuscript covers protected structures, microclimate management, soilless systems and precision farming technologies, the discussion does not quantitatively compare crop performance, production costs or economic returns across different regions and protected cultivation systems. Variations in climate, crop species, structure design, grower skill and input availability may influence the suitability and effectiveness of the technologies described. Some emerging tools, including AI-enabled automation, robotic systems and IoT-based platforms, are also developing rapidly, and their long-term performance under commercial vegetable production conditions remains context dependent. The review therefore provides a broad synthesis rather than a definitive evaluation of technology performance. Future work should include region-specific economic assessments, field-level validation and comparative studies that examine productivity, resource-use efficiency, environmental effects and adoption constraints under practical farming conditions for both small and large-scale vegetable growers alike.

Declaration of AI Use

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Competing Interests

Authors have declared that no competing interests exist.

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