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## Climate-Smart Vegetable Production Systems: A Sustainable Pathway for Resilient Horticulture

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Vegetable crops play a vital role in ensuring nutritional security, income generation and livelihood sustainability, particularly in countries like India. However, vegetable production is highly sensitive to climatic fluctuations due to shallow root systems, short crop duration and high water and nutrient requirements. Rising temperatures, erratic rainfall, prolonged droughts and increased pest incidence are posing serious challenges to sustainable vegetable cultivation. In this context, Climate-Smart Vegetable Production Systems (CSVPS) emerge as an integrated approach that enhances productivity, strengthens resilience to climate change and reduces greenhouse gas emissions. Rather than relying on a single intervention, climate-smart vegetable production combines improved varieties efficient resource management, protected cultivation, conservation practices and digital technologies into a holistic framework.

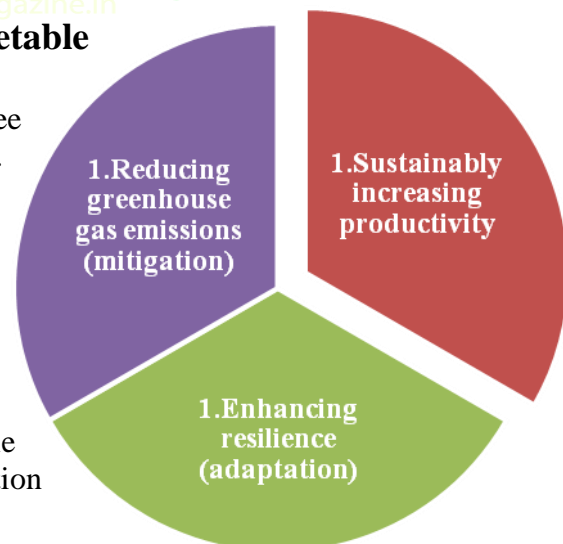


### The Concept of Climate-Smart Vegetable Production

Climate-smart agriculture is built upon three fundamental pillars as mentioned in the figure. When applied specifically to vegetable crops these pillars translate into practices that ensure yield stability, resource-use efficiency and environmental sustainability.

### Sustainable Intensification for Higher Productivity

To meet the growing demand for vegetables while conserving resources, sustainable intensification becomes essential. Key approaches include:



## 1. Improved Varieties and Hybrids

Development and adoption of stress-tolerant varieties capable of withstanding heat, drought, salinity, and emerging diseases are crucial. Hybrid cultivars often provide higher yields and uniform produce, though economic feasibility must be considered.

## 2. High-Density Planting

Optimizing plant population per unit area increases productivity without expanding cultivated land.

## 3. Intercropping and Crop Rotation

Intercropping vegetables with legumes enhances nitrogen fixation and soil cover, reducing soil erosion and improving soil fertility. Crop rotation minimizes pest and disease buildup while maintaining soil health.

For example:

- Tomato intercropped with marigold as a trap crop.
- Okra combined with cowpea to improve nitrogen balance.

## 4. Enhancing Resilience to Climatic Stresses

### Heat Stress Management

High temperatures especially above 35°C, significantly reduce fruit set in crops like tomato due to pollen sterility. Climate-smart interventions include:

- Adoption of heat-tolerant cultivars
- Use of shade nets
- Evening irrigation schedules
- Foliar sprays of potassium nitrate (KNO<sub>3</sub>) or calcium chloride (CaCl<sub>2</sub>)

These practices help maintain reproductive efficiency and fruit quality under heat stress conditions.

### Drought Management

Water scarcity is a major constraint in vegetable cultivation. Climate-smart strategies include:

- Drip irrigation, which saves 30–50% water compared to flood irrigation
- Plastic mulching to reduce evaporation losses
- Raised bed planting to improve water-use efficiency
- Use of antitranspirants to minimize moisture loss

These interventions not only conserve water but also improve nutrient uptake and crop growth.

### Flood and Heavy Rainfall Management

In regions experiencing erratic and intense rainfall, vegetable crops suffer from root rot and nutrient leaching. Adaptive measures include:

#### ✓ Raised Beds

Raised beds elevate the root zone above ground level, improving soil aeration and preventing water stagnation during heavy rainfall. They enhance root growth, reduce root rot incidences and improve nutrient-use efficiency in vegetable crops.

#### ✓ Ridge and Furrow Planting

In this system, crops are planted on ridges while water flows through furrows, preventing direct water contact with the root collar. It is particularly effective in managing excess moisture and ensuring better drainage in high rainfall areas.

#### ✓ Efficient Drainage Systems

Well-designed surface and subsurface drainage channels quickly remove excess rainwater, preventing waterlogging and nutrient leaching. Proper drainage reduces disease incidence and improves crop survival during extreme weather events.

#### ✓ Grafting onto Tolerant Rootstocks

Grafting combines a high-yielding scion with a stress-tolerant rootstock that resists diseases, salinity or flooding. This technique enhances plant vigor, resilience and yield stability under adverse climatic conditions.

### 5. Protected Cultivation: A Key Climate-Smart Strategy

Protected structures such as polyhouses, shade net houses and low tunnels play a significant role in climate-smart vegetable production. These systems:

- Protect crops from extreme temperatures and rainfall
- Enable off-season cultivation
- Increase yield by 2–5 times
- Improve produce quality

Though initial investment is high, long-term benefits in terms of yield stability and market returns make protected cultivation an important climate adaptation strategy.



### 6. Precision Water and Nutrient Management

Excessive fertilizer use contributes to greenhouse gas emissions, particularly nitrous oxide (N<sub>2</sub>O), a potent greenhouse gas. Climate-smart systems promote:

- Drip fertigation
- Soil testing and leaf nutrient diagnostics
- Use of biofertilizers
- Integrated nutrient management (INM)

Precision application improves nutrient-use efficiency, reduces leaching losses and lowers production costs.

### 7. Conservation Agriculture in Vegetables

Conservation practices are increasingly relevant in vegetable production systems:

- Minimum or reduced tillage
- Crop residue retention
- Diversified crop rotations

A rotation such as Tomato → Onion → Cowpea helps maintain soil organic carbon, suppress pests and improve soil structure. Conservation agriculture enhances long-term sustainability and climate resilience.

### 8. Crop-Specific Climate-Smart Interventions

#### Tomato

- Heat-tolerant hybrids
- Grafting on disease-resistant rootstocks
- Mulching and drip irrigation
- Protective structures during peak summer

#### Onion

- Raised beds in high rainfall areas
- Proper curing for improved storage
- Balanced sulphur nutrition for better bulb quality

#### Cucurbits

- Low tunnel cultivation for early sowing
- Staggered planting to escape heat waves
- Pollinator-friendly farming practices

### 9. Digital and Smart Technologies

Modern climate-smart vegetable systems increasingly integrate digital tools such as:

#### ✓ Weather Forecasting Applications

Weather forecasting apps provide real-time data on temperature, rainfall, humidity and wind patterns, enabling farmers to plan sowing, irrigation and harvesting more efficiently. Early warnings about extreme weather events help reduce crop losses and improve decision-making.

### ✓ **Pest and Disease Prediction Models**

These models use climatic data, crop stage and historical patterns to predict the likelihood of pest and disease outbreaks. Timely alerts allow farmers to adopt preventive measures, reducing pesticide use and minimizing economic damage.

### ✓ **Soil Moisture Sensors**

Soil moisture sensors monitor real-time soil water status in the root zone, helping farmers irrigate only when necessary. This improves water-use efficiency, prevents over-irrigation and enhances crop growth and nutrient uptake.

### ✓ **Smart Irrigation Controllers**

Smart controllers automatically regulate irrigation schedules based on weather data and soil moisture levels. They optimize water application, reduce wastage and ensure consistent crop performance under varying climatic conditions.

These technologies enhance decision-making, reduce risk and improve resource efficiency.

## 10. **Socio-Economic Implications**

Climate-smart vegetable production improves:

### ✓ **Yield Stability**

Climate-smart practices reduce the impact of extreme weather, pests and nutrient stress ensuring more consistent production across seasons. This minimizes crop failure risk and maintains steady output even under climatic variability.

### ✓ **Income Security**

By stabilizing yields and improving produce quality, farmers achieve better market returns and reduced financial risk. Diversification, protected cultivation and efficient resource use further strengthen long-term economic resilience.

### ✓ **Water Productivity**

Efficient irrigation methods like drip and mulching increase crop output per unit of water used. This is especially crucial in water-scarce regions, where maximizing water-use efficiency ensures sustainable production.

### ✓ **Soil Health**

Practices such as crop rotation, residue retention, and integrated nutrient management improve soil organic carbon and microbial activity. Healthy soils enhance nutrient availability, root growth and long-term sustainability of vegetable systems.

However, challenges such as high initial investment, limited awareness and fragmented landholdings must be addressed through policy support, subsidies and capacity building programs.

## **Conclusion**

Climate-smart vegetable production systems represent a sustainable and resilient pathway for modern horticulture. By integrating improved genetics, precision resource management, protected cultivation, conservation practices and digital innovations, vegetable farming can withstand climatic uncertainties while ensuring productivity and profitability. In regions facing increasing climatic variability, such as hill and subtropical ecosystems, adopting climate-smart vegetable systems is no longer optional it is essential for future food and nutritional security.