



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(1): 855-859
Received: 14-10-2025
Accepted: 20-11-2025

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Climate change and its impacts on vegetable crop production: A review

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i11.4810>

Abstract

Climate change presents one of the most significant challenges to global agriculture in the 21st century, affecting the productivity, quality, and sustainability of vegetable crop cultivation. Rising temperatures, altered precipitation patterns, increased frequency of extreme weather events, elevated atmospheric CO₂ levels, and changing pest and disease dynamics collectively influence vegetable growth and yield outcomes. Vegetables are particularly vulnerable due to their physiological sensitivity to temperature and water stress, as well as their importance in human nutrition and food security. While elevated CO₂ may temporarily enhance photosynthesis and growth under certain conditions, the net impacts of climate change including heat stress, drought, salinity, and erratic rainfall often result in reduced yields and compromised quality. Additionally, these abiotic stresses interact with biotic factors like pest and pathogen pressure, further threatening vegetable production systems. This review synthesizes findings from a broad range of studies to characterize the direct and indirect effects of climate change on vegetable crops, highlights adaptation and mitigation strategies such as breeding climate-resilient varieties, improved irrigation and crop management practices, and protected cultivation, and identifies significant research gaps. A nuanced understanding of these impacts and responses is essential to ensure sustainable vegetable production and food security under future climatic conditions.

Keywords: Nanourea, conventional urea, growth, LAI, yield and wheat

Introduction

Climate change driven by anthropogenic greenhouse gas (GHG) emissions is increasingly affecting global agriculture. Vegetable crops, being sensitive components of horticultural systems, are particularly vulnerable due to their dependence on specific climatic conditions for growth, development, quality, and yield (Kumari *et al.* 2018) ^[14]. Climate change is a pressing issue of the 21st century with several implications for both human life and the environment. Agriculture is one of the areas most affected by climate change, and it is a crucial sector for the global economy and food security. Vegetable crops, which play a crucial role in the global food system, can be deeply affected by climate fluctuations (Porter *et al.* 2019) ^[22].

Vegetables are particularly sensitive to variations in temperature, water availability, extreme weather events, CO₂ levels, pest and disease dynamics, and soil conditions. The responses of vegetable crops to climate change involve complex interactions among physiological, biochemical, and ecological processes (Kumari *et al.* 2018) ^[14]. Vegetable crops such as tomatoes, potatoes, onions and cabbage play a vital role in providing food and supporting local economies. Thus, understanding their sensitivity to climatic variations is crucial in devising strategies to safeguard and adapt them against future environmental challenges (Scheelbeek *et al.* 2020) ^[24]. High temperatures and drought can cause heat stress in plants, which has a direct impact on their health and growth (Zhang *et al.* 2018) ^[29].

Impacts of Climate Change on Vegetable Crops

1. Temperature Rise and Heat Stress

Elevated temperatures influence plant physiology, including photosynthesis, respiration, flowering, and fruit set. Many vegetables perform poorly outside optimal temperature ranges (Kumari *et al.* 2018) ^[14].

Heat stress shortens crop development periods and can reduce yield, especially in crops like tomatoes and cucurbits (Mehdi *et al.* 2018) ^[19]. Some crops requiring vernalization (cold periods before flowering), such as cauliflower, may suffer poor development under warming trends (Mehdi *et al.* 2018) ^[19]. In pepper, high temperature exposure at the pre-anthesis stage did not affect pistil or stamen viability but high post-pollination temperatures inhibited fruit setting suggesting that fertilization is sensitive to high temperature stress (Erickson and Markhart 2002) ^[8]. High temperature affects red colour development in ripen chilli fruits and also causes flower drop ovule abortion poor fruit set and fruit drop in chilli (Arora *et al.* 1987) ^[1]. Sprouting of potato is best at 22-34°C. The normal temperature for tuberization is at temperatures between 17°C-21°C but it is adversely affected at temperatures above 21°C and there is no tuberization at 29°C and above temperature (Swarup 2012) ^[28]. In onion, bulbing is induced by photo period, once induced it occurs rapidly at higher temperature (Brewster 1997) ^[5]. The optimum temperature before bulbing is between 13°C and 24°C. The ideal temperature for bulb development is 15 to 25°C. In the rabi season a sudden rise in temperature may result in early bulb maturity and smaller-sized bulbs. Temperature influences the development of seed stalk (Swarup 2012) ^[28].

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2. Water Stress: Drought and Flooding

Rising temperatures increase evapotranspiration and drought risk, limiting soil moisture and reducing vegetable yields (Das *et al.* 2023) ^[6]. Waterlogging is a serious problem which affects crop growth and yield in low lying rainfed areas. The main cause of damage under waterlogging is oxygen deprivation which affect nutrient and water uptake so the plants show wilting even when surrounded by excess of water. Lack of oxygen shifts the energy metabolism from aerobic mode to anaerobic mode (Sairam *et al.* 2008) ^[23].

3. Elevated CO₂ and Ozone (O₃)

Increasing CO₂ caused an increase in mean global temperature (Houghton 2001) ^[12] leading to climate change with perturbations such as more frequent and more severe drought events across the globe (Mpelasoka *et al.* 2008) ^[20]. Plant growth and metabolism, and consequently, global crop production will be profoundly affected by such changes. A constantly high temperature causes an array of morpho-anatomical changes in plant which affect the seed germination, plant growth, flower shedding, pollen viability, gametic fertilization, fruit setting, fruit size, fruit weight, fruit quality etc. Fluctuations in daily mean maximum and minimum temperature is the primary effect of climate change that adversely affects vegetable production as many plant physiological, bio-chemical and metabolic activities are temperature dependent (Ayyogari *et al.* 2014) ^[2]. For most vegetables, optimum growth is obtained within temperature range up to 25°C. High temperature causes injuries resulting in reduction of the productivity.

Higher atmospheric CO₂ can stimulate photosynthesis and biomass production, a phenomenon known as CO₂ fertilization. However, this benefit is often offset by heat stress and water shortage in field conditions (Kumari *et al.* 2018) ^[14]. Increased ozone levels can impair leaf function and reduce crop quality and yields.

4. Pest and Disease Dynamics

Climate change alters pest and pathogen dynamics expanding ranges, increasing reproductive rates, and intensifying infection pressure (Kumari *et al.* 2018) ^[14]. Warmer and wetter conditions can enhance pathogen survival and contamination risks, affecting both yield and food safety.

5. Product Quality and Nutritional Traits

Climate stress can alter biochemical pathways in crops, affecting nutrient content, flavor profiles, texture, and storage quality. For example, heat stress may reduce glucosinolates in leafy vegetables like arugula (Eduard *et al.* 2023) ^[7]. Some vegetables may show short-term CO₂ fertilization benefits, increasing biomass, but these gains are often offset by heat stress and water limitations. (Kumari *et al.* 2018) ^[14]. Quality traits like nutrient density and flavor compounds are also affected by stressful growth conditions.

Underlying Physiological and Biochemical Mechanisms

Vegetable crops often have narrow optimal temperature and moisture ranges. Climate-induced stresses affect: Photosynthesis and respiration, often constrained by heat and water scarcity (Mehdi *et al.* 2018) ^[19]. Membrane integrity and oxidative balance, leading to cellular damage (Laxman *et al.* 2024) ^[15]. Pollination behavior and seed set, as high temperatures disrupt pollinators and flowering timing (Khalid *et al.* 2021) ^[13].

Geographic and Socio-Economic Dimensions

Research indicates a bias toward industrialized countries, but developing regions especially in South Asia, Sub-Saharan Africa, and parts of Latin America are projected to experience disproportionately large impacts due to limited access to adaptive resources (Eduard *et al.* 2023) ^[7]. Vegetable farming in smallholder systems also faces increased vulnerability due to scarce irrigation, limited storage infrastructure, and marginal land (Babu *et al.* 2024) ^[3].

Adaptation and Mitigation Strategies

The impacts of climate change on vegetable production will depend not only on climate, but also on the internal dynamics of agricultural systems, including their ability to adapt to the changes (FAO 2001) ^[9]. Adoption of effective and efficient measures is required to mitigate the adverse effects of climate change on vegetable production, and particularly on their productivity, quality and yield. New technologies being developed through plant stress physiology research can potentially contribute to mitigate threats from the climate change on vegetable production. As most of the farmers in developing countries are smallholders, have fewer options and must rely heavily on resources available in their farms or within their communities. Thus, technologies that are simple, affordable, and accessible must be disseminated to increase the resilience of farms in less-developed countries. Many institutes have been working on addressing the effect of environmental stress on vegetable production. Germplasm of major vegetable crops, which are tolerant to high temperatures, flooding and drought have been identified and advanced breeding lines are being

developed in many institutions. Efforts are also underway to identify nitrogen-use efficient germplasm. In addition, development of production systems geared towards improved water-use efficiency and expected to mitigate the effects of hot and dry conditions in vegetable production systems are the top research and development priorities.

1. Agronomic Practices

Adjusted planting dates, conservation tillage, use of mulches, and crop residues to improve water retention and reduce stress (Das *et al.* 2023) ^[6]. Precision irrigation systems (e.g., drip irrigation, soil moisture sensors) to enhance water efficiency (Bhatia *et al.* 2025) ^[4].

Adjusted planting dates

Shifting planting dates is a key climate-smart agronomic strategy to synchronize sensitive crop growth stages (flowering and grain filling) with periods of optimal soil moisture and temperature. Early planting can help crops escape terminal drought and heat stress, while delayed planting may be beneficial in regions experiencing erratic early-season rainfall. Das *et al.* (2023) ^[6] reported that optimizing sowing windows significantly improves crop establishment, reduces evapotranspiration losses, and enhances yield stability under variable climatic conditions.

Conservation tillage

Conservation tillage practices, including minimum and zero tillage, reduce soil disturbance and maintain soil structure, thereby improving water infiltration and retention. By leaving crop residues on the soil surface, conservation tillage lowers soil temperature, reduces evaporation losses, and minimizes erosion. These practices also enhance soil organic carbon, microbial activity, and aggregate stability, leading to improved drought resilience and long-term soil fertility (Das *et al.* 2023) ^[6].

Use of mulches and crop residues

Organic mulches (crop residues, straw, compost) and synthetic mulches act as protective soil covers that reduce direct evaporation, suppress weed growth, and moderate soil temperature fluctuations. Residue retention increases soil moisture availability during dry spells and reduces surface runoff during intense rainfall events. Mulching has been shown to improve root development and nutrient uptake while reducing plant water stress, particularly in rainfed and semi-arid agroecosystems (Das *et al.*, 2023) ^[6].

Precision irrigation systems

Precision irrigation technologies such as drip and micro-irrigation systems deliver water directly to the root zone, significantly reducing conveyance losses and non-productive evaporation. These systems improve water use efficiency by ensuring uniform water distribution and minimizing over-irrigation demonstrated that drip irrigation can reduce water use by 30-50% while maintaining or increasing crop yields compared to conventional surface irrigation methods (Bhatia *et al.* 2025) ^[4].

Soil moisture-based irrigation scheduling

The integration of soil moisture sensors, remote sensing tools, and automated irrigation controllers enables real-time monitoring of soil water status. Sensor-based irrigation scheduling ensures that water is applied only when crops reach critical moisture thresholds, preventing both drought stress and

waterlogging. Such data-driven irrigation management enhances water productivity, reduces energy consumption, and supports sustainable water resource use under increasing climate variability (Bhatia *et al.*, 2025) ^[4].

2. Genetic and Biotechnological Approaches

Breeding and biotechnological development of heat, drought and salinity-tolerant cultivars (Das *et al.* 2023) ^[6].

A. Traditional and Molecular Breeding Approaches

i. Conventional Breeding

Traditional breeding involves crossing plants with desirable traits (e.g., drought tolerance) and selecting offspring with better performance under stress.

- **Hybridization and selection:** Cross high-yielding but stress-sensitive lines with stress-tolerant germplasm, then select progeny with improved traits.
- **Mutation breeding:** Chemical or radiation-induced mutations create genetic diversity, and mutants with improved stress responses are selected (Erkilic *et al.* 2024) ^[11].
- **Backcross breeding:** Repeatedly cross offspring with an elite parent to introgress stress tolerance without losing yield traits.

Limitations: Conventional breeding is *time-consuming*, constrained by natural genetic variation, and less effective for *complex*, polygenic traits like drought and heat tolerance.

ii. Marker-Assisted Selection (MAS) and QTL Mapping

Modern breeding uses molecular markers (DNA sequences linked to traits) to accelerate selection.

- **QTL mapping:** Identifies chromosome regions that control tolerance traits.
- **Marker-assisted selection (MAS):** Uses these markers to select plants carrying beneficial alleles without waiting for full stress exposure in the field.

This way breeders can reliably introgress multiple tolerance traits (e.g., drought + salinity) into elite cultivars more rapidly than by visual selection alone. (Maity *et al.* 2025) ^[18].

B. Biotechnological and Genetic Engineering Approaches

i. Transgenic Breeding and Genetic Engineering

Genetic engineering introduces specific genes into crops that help them cope with stress:

- **Stress-responsive regulatory genes:** Transcription factors such as HD-Zip, NAC, MYB, WRKY, and DREB families regulate pathways controlling water balance, antioxidant defense, and stress signaling. Introducing these can enhance tolerance.
- **Heterologous gene transfer:** Genes from stress-tolerant species (extremophiles) can be moved into crops. For example, the HAHB4 gene from sunflower was introduced into wheat to delay stress-induced senescence and improve drought performance in *HB4 wheat*.
- **Osmoprotectant and antioxidant genes:** Genes that boost production of osmoprotectants (like proline, glycine betaine) and enzymes like superoxide dismutase (SOD) or catalase (CAT) help protect cellular structures under drought and salinity (Mahamed *et al.* 2024) ^[17].

Genetic engineering can also modify physiological mechanisms

- e.g., enhancing stomatal regulation for better water use and maintaining ionic balance under salinity. (Srivastava *et al.* 2025) [27].

ii. Genome Editing (CRISPR/Cas Systems)

CRISPR/Cas and related tools enable *precise, targeted changes* to endogenous stress-related genes:

- **Knock-outs and knock-ins:** Negative regulators of stress pathways can be disabled, while positive regulators can be enhanced.
- **Multiplex editing:** Multiple genes can be edited simultaneously to stack traits like deeper roots, improved water uptake, and enhanced ROS scavenging. (Shelake *et al.* 2022) [26].

This approach overcomes limitations of traditional transgenic methods because it can leverage existing plant pathways without inserting foreign DNA (depending on regulatory frameworks) (Shelake *et al.* 2022) [26].

3. Protected and Climate-Smart Agriculture

Greenhouse and controlled environment agriculture to buffer crops against extreme weather and facilitate stable production (Babu *et al.* 2024) [3]. Climate-smart agricultural practices (CSA) aimed at reducing greenhouse gas emissions while improving resilience (Babu *et al.* 2024) [3].

4. Pest and Disease Management

Use of biological controls, crop rotation, resistant varieties and integrated pest management to combat climate-induced pest pressure (Eduard *et al.* 2023) [7].

Biological Control

- **Natural predation and parasitism:** Beneficial species can reduce pest numbers without chemicals, stabilizing pest populations even when climate fluctuations favour pests (Nguyen *et al.* 2025) [21].
- **Microbial antagonism:** Certain bacteria and fungi directly attack or outcompete harmful pathogens and insect pests.
- **Reduced chemical reliance:** Because heavy pesticide use can harm natural enemies and drive resistant pest strains, biological control helps *sustain* ecological balance.
- **Ecosystem resilience:** A diverse community of natural enemies adapts better to environmental changes than single chemical tactics.

Crop Rotation

- **Breaks pest life cycles:** Pests that specialize on one crop find no suitable host when that crop is replaced, reducing their numbers over time (Liang *et al.* 2025) [16].
- **Reduces disease inoculum:** Soil-borne pathogens often decline when their host is absent, lowering disease pressure (Liang *et al.* 2025) [16].
- **Enhances soil health:** Rotation improves soil structure and biodiversity, which in turn strengthens crop resistance to stress (Liang *et al.* 2025) [16].
- **Lowers pesticide use:** With fewer target pests, reliance on insecticides and fungicides decreases, helping preserve beneficial organisms.

Resistant Varieties

Resistant crop varieties are bred (either through traditional breeding or modern genetics) to withstand pests and diseases

better-by deterring pest feeding, slowing pest growth, or tolerating damage with minimal yield loss (Zhou *et al.* 2024) [30].

Integrated Pest Management (IPM)

- **Monitoring and thresholds:** Actions are taken only when pest levels exceed economic thresholds, reducing unnecessary interventions.
- **Decision-based control:** Uses weather forecasts, pest life-cycle data, and field observations to time interventions effectively.
- **Multiple tactics:** Encourages combining cultural, biological, mechanical, and chemical tactics to reduce pest populations sustainably.

5. Policy, Education, and Institutional Support

Strengthened agricultural policies, extension services, and community participation to build adaptive capacities among growers (Babu *et al.* 2024) [3].

Future Research Needs

More crop-specific research, especially for lesser-studied vegetables (Gouthami *et al.* 2023) [10]. Integrative studies on nutritional quality, food safety, and post-harvest resilience. (Eduard *et al.* 2023) [7]. Regional adaptation models that incorporate smallholder perspectives and socioeconomic constraints (Babu *et al.* 2024) [3].

Conclusion

Climate change significantly influences vegetable crop productivity, physiology, pest-disease dynamics, and product quality. While rising CO₂ may offer some growth benefits, the net impacts of temperature extremes, water stress, and biotic pressures largely threaten sustainable vegetable production. A multi-pronged approach combining innovative cultivation techniques, technological tools, genetic improvement, and climate-smart practices is essential to buffer these impacts and ensure food and nutritional security.

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