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Impacts of climate change on vegetable production: A review

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Abstract

Vegetables are the source of nutrients, vitamins, and minerals, and are an essential part of the human diet. Due to their short phenological cycles, limited physiological tolerance, and susceptibility to thermal and hydrological stress, they are extremely vulnerable to climate change. Vegetable cultivation becomes unprofitable due to crop failures, output shortages, declining quality, and increasing pest and disease issues under changing climatic conditions. Numerous physiological systems and enzymatic activities that depend on temperature will be significantly affected. Increased photosynthesis and biomass accumulation in C₃ vegetables and tuber crops, as well as CO₂ fertilization, may boost crop yields. However, heat stress and water shortages frequently outweigh these advantages. Furthermore, CO₂-induced yield increases are often linked to nutrient dilution, lowering concentrations of essential micronutrients and proteins, and endangering food and nutritional security. Anthropogenic air pollutants such as CO₂, CH₄, and CFCs are contributing to global warming. Nitrogen and Sulphur dioxides are causing depletion of the ozone layer and permitting the entry of harmful UV rays. These influence the pest and disease occurrences, host-pathogen interactions, ecology of insects and their distribution, time of appearance, migration to new places, and their overwintering capacity, thereby becoming a major setback to vegetable cultivation. In India, climate variability, particularly heatwaves, monsoon irregularities, and unseasonal rainfall, has emerged as a major driver of production instability in key vegetables such as tomato, onion, and potato. These climate shocks spread quickly via supply chains, causing price inflation, market volatility, and increased susceptibility to smallholder farmers' livelihoods. This review synthesizes the impacts of elevated atmospheric CO₂, rising temperatures, altered precipitation, and extreme weather events on vegetable productivity, physiology, and nutritional quality and evaluates adaptation strategies, including climate-resilient breeding, protected cultivation, precision agriculture, and climate-smart agronomic practices supported by national policies, and management strategies that enable overcoming the ill effects and sustain the production of vegetable crops.

Keywords: Vegetable, climate change, pollutants, adaptation

Introduction

Climate change is defined as the average change over time in a geographical area in a number of climatic factors, including temperature, rainfall, relative humidity, and gaseous composition (Raza *et al.*, 2019) ^[45]. With numerous effects on both human life and the environment, climate change is a critical concern of the twenty-first century. One of the sectors most impacted by climate change is agriculture and horticulture, which are essential to the world economy and food security. Among all the horticultural crops, vegetables are highly prone to climate change (Giordano *et al.*, 2021; Porter *et al.*, 2019) ^[23, 44]. Any type of plant life or plant product that is eaten raw or cooked is referred to as a vegetable. Fruit vegetables like tomato, cucumber, watermelon, and peas; root and tuber/root vegetables like carrot, potato, sweet potato, radish, and elephant foot yam; green leafy vegetables like amaranthus, celery, cabbage, curry leaf, and bulb vegetables like onion and garlic are all considered vegetable crops. In addition to being a source of nutritional security, growing vegetables gives farmers a steady stream of revenue. With an output of 197.23 million tons from an area of 10.97 million hectares, India is the second-largest producer of vegetables after China. Vegetables account for 59.58% of the overall horticultural production (Laxman *et al.*, 2024) ^[34]. Grown over more than four million hectares of land, tomatoes are the most significant vegetable crop in the world. A clear strategy to promote dietary diversity

and quality is to increase the production and consumption of vegetables, particularly in diets that are dominated by high-energy, low-micronutrient meals (Bhardwaj, 2012) ^[8]. Compared to staple crops, they provide smallholder farmers significantly higher incomes and jobs per hectare, making them the ideal resources for overcoming nutritional deficiencies. There are 200 vegetables worldwide, but only 30 to 40 crops are frequently grown.

The increased frequency of events like drought and flood, high and low temperatures, salinity, and changes in atmospheric CO₂ or ozone levels impacted the yield and quality of vegetable crops. According to reports, the production of vegetable crops decreased by 41% between 1965 and 2016 as a result of global warming (Scheelbeek *et al.*, 2018) ^[49]. Smallholder or subsistence farmers in developing nations are among those most impacted by climate change (Dumitru *et al.*, 2023) ^[19]. Increasing the growth of weeds and pests, rising temperatures are likely to reduce the number of desirable crops (Jasper *et al.*, 2020) ^[28].

The demand for vegetables has increased significantly in recent years as a result of rising population, price affordability, and increased knowledge of their nutritional advantages. Thus, persistent efforts have been made in this direction to meet the increasing demand for vegetables. However, sudden changes in the climate have become a major danger to global food production (Machado and Serralheiro, 2017; Chaudhary *et al.*, 2022) ^[14, 36]. Understanding the effects of climate change on vegetable production and management techniques is the main aim of this review. Thus, this paper discusses how climate change affects vegetable production as well as different management strategies that have been proposed to mitigate these negative consequences.

Impacts of climate change on the cultivation of vegetables

Like other agricultural crops, vegetable crops are susceptible to changes in the climate. Vegetables are typically vulnerable to environmental extremes, and high temperatures are the main reason for low yields, which will be exacerbated by climate change. The major obstacles to maintaining and raising vegetable yield would be rising temperatures, decreased irrigation water supply, flooding, and salinity. The output of different vegetable crops will be impacted by persistently deteriorating weather conditions and climate changes brought on by rising temperatures, unpredictable rainfall, increased water demand, and an increase in disease incidence. Rainfall is one of the key elements influencing crop productivity (Abewoy, 2018) ^[1]. Below is a summary of some of the major environmental pressures that have an impact on the development of vegetable crops.

Impact of Temperature

Global air temperatures have been steadily rising over the past century. From 1850 to 1900, the temperature increased by 1.1 °C. Global temperatures are predicted to rise by more than 1.5 °C on average during the next 20 years (IPCC, 2022). Crop growth and yield are impacted by morphological, physiological, and biochemical changes brought on by the elevated air temperature (Laxman *et al.*, 2024) ^[34]. All the stages of plant development, such as seed germination, vegetative stage, and reproductive stages, are impacted by heat stress, but the reproductive stage suffers the greatest.

In vegetable crops, critical physiological and developmental processes are frequently precisely regulated by temperature thresholds and seasonal signals, which are directly impacted by temperature stress. Vernalization and winter chilling, which are essential for healthy vegetative growth, floral initiation, and coordinated development in many horticultural species,

particularly sensitive ones, are disrupted by warming trends (Dumitru *et al.*, 2023) ^[19]. If these temperature-dependent processes are messed up, plants may not grow as quickly or as completely as they should, and their growth patterns may not be regular. Sensitive leafy vegetables, such as arugula, show this susceptibility; exposure to elevated growth temperatures nearing 40 °C has been demonstrated to severely hinder seed germination, biomass accumulation, regenerative capacity, and overall plant survival. Physiological disruptions during early vegetative stages hinder stand establishment and constrain yield potential long before crops reach reproductive maturity.

Extreme heat is especially harmful during the reproductive stage of horticultural crops, where even short-term exposure can cause permanent yield losses and a decline in quality traits (Graci and Barone, 2024) ^[25]. Tomatoes and other plants in the Solanaceae family are some of the most heat-sensitive vegetables, and they are often used as model systems to study how plants respond to heat stress. Higher temperatures have a bad effect on many reproductive factors, such as pollen viability, pollen germination rates, flower production, fruit set, and marketable yield. In conditions of heat stress, these reproductive failures are often the biggest problem that crops face when it comes to productivity.

The temperatures above 37 and 40 °C adversely affect pollen viability, and flower and fruit development in tomato and chili, respectively (Dahal *et al.*, 2006; Mazzeo *et al.*, 2018) ^[15, 37]. Moreover, the temperature above 33 °C in pepper causes pollen abnormalities, which include shrunken and empty pollen (Erickson & Markhart, 2002) ^[20]. In the case of peas, the temperature above 28 °C causes a reduction in yield, and particularly short-duration cultivars are more vulnerable. The temperatures above 25 °C affect the onion seed germination rate and percentage. In carrots, temperatures beyond 35 °C led to decreased cell membrane stability and increased relative cell injury (Nijabat *et al.*, 2020) ^[42]. The tomato requires an optimum temperature in the range of 25 to 30 °C, and temperatures beyond this threshold affect the plant growth and development.

Cold stress leads to disruption of the integrity of intracellular organelles, leading to the loss of compartmentalization. It also causes reduction and impairment of photosynthesis, protein assembly, and general metabolic processes (Atayee *et al.*, 2020) ^[4]. Some studies reported that low temperatures of 8 to 12 °C reduce seed germination, crop growth, pollen tube growth, and the percent fruit set by reducing enzymatic antioxidant activities, increasing ROS, lipid peroxidation, hampering membrane stability, reducing chlorophyll biosynthesis and damaging the photosynthetic system in tomato (Bai *et al.*, 2021) ^[6], muskmelon (Risser *et al.*, 1978) ^[46], watermelon (Bradow, 1990) ^[12], Pakchoi (*Brassica chinensis* L.), cucumbers (Han *et al.*, 2019) ^[26], zucchini (Zhang *et al.*, 2019) ^[58]. The safe low temperatures with chilling injuries observed in vegetable crops are shown in Table 1.

Table 1: List of safe low temperatures with chilling injuries observed in vegetables

Vegetable	Symptoms of chilling injury	Safe low temperatures (°C)
Okra	Pitting, discoloration, and decay	7
Tomato (green to mature)	Alternaria rot	13
Tomato (ripen)	Softening, decay	7-10
Asparagus	Limp tips, dull green	0-2
Pumpkin	Alternaria rot	10
Sweet potato	Internal discoloration	10
Potato	Browning, sweetening	7
Cucumber	Water-soaked lesions, pitting	7

Source: Laxman *et al.* (2024) ^[34]

Drought

Climate change is predicted to have a significant impact on water availability, and extreme water stress will have an impact on agricultural yield, especially vegetable productivity. A significant issue in arid and semi-arid areas, drought is the main cause of crop loss globally, lowering average yields for the majority of crop plants by more than 50% (Sivakumar *et al.*, 2016) ^[51]. Water scarcity brought on by little rainfall or low soil moisture can trigger a variety of biochemical, physiological, and genetic reactions in plants, severely limiting crop development (Vadez *et al.*, 2012) ^[54]. Drought circumstances have a negative impact on the sprouting of potato tubers and the germination of seeds in vegetable crops like okra and onions. Tomato flower abscission is caused by drought. Water stress during the reproductive stage has been shown to reduce tomato yields by more than 50%. Water stress during the flowering stage has been proposed to decrease photosynthesis and the quantity of photosynthetic assimilates given to floral organs, potentially increasing the rate of abscission (Abewoy, 2018) ^[1].

Vegetables are highly succulent and contain 90% water; water stress has a significant impact on both productivity and quality. Drought stress is caused by low soil moisture conditions or prolonged below-normal precipitation. Drought stress has been shown to have more detrimental effects on photosynthesis, abscission of flowers and flower buds in susceptible tomato cultivars than in tolerant cultivars (Laxman *et al.*, 2024) ^[34]. An osmotic movement of water out of plant cells results from an increase in solute concentration in the soil brought on by drought stress. This lowers the productivity of most vegetables by increasing water loss in plant cells and inhibiting a number of physiological and biochemical activities, including respiration and photosynthesis. Drought stress causes metabolic impairment in addition to lowering stomatal conductance, which inhibits photosynthetic rate (Dias and Brüggemann, 2010) ^[17]. Limited water conditions result in a decrease in photosynthesis and photosynthetic capacity. Additionally, a reduction in the activities of invertase and Sucrose Phosphate Synthase (SPS), which influence the availability and use of sucrose, suggests that the water stress also had an impact on the biochemical capacity. The SPS is thought to be crucial for sucrose resynthesis and for maintaining the assimilatory carbon flux from the source to the growing sink. The ability to use sucrose may be impacted by the decreased invertase activity, which could lead to lower ovarian development and hexose concentration (Andersen *et al.*, 2002) ^[2].

Long-term drought circumstances have a negative impact on potato tuber sprouting and onion and okra seed germination (Arora *et al.*, 2010) ^[3]. Imposing moisture stress during the late flowering-early fruit set stage of bell peppers (*Capsicum annuum* L.) results in a 44% decrease in output, primarily from decreased fruit set and reduced fruit weight. Additionally, moisture stress at the 3 and 7-leaf stages reduces onion yield by 26%.

Flood

The majority of vegetables are quite susceptible to excessive soil moisture. Waterlogging is the term used to describe the presence of more soil moisture than is ideal. Water-logging causes the soil's pores to fill with water, resulting in hypoxia (low oxygen concentrations) or anoxia (total lack of oxygen) (Fukao *et al.*, 2019) ^[22]. Wilting, epinasty, or downward curving of leaves and stems are the results of waterlogging. Simply put, the root system is unable to provide water and nutrients quickly enough to keep leaves from wilting and turning yellow. Waterlogging

causes ethylene to build up in the roots, which causes leaves and stems to curl downward, resulting in epinasty (Yamauchi *et al.*, 2018) ^[57].

Under water-logging circumstances, vegetable crops like tomato and capsicum species exhibit decreased chlorophyll content, chlorophyll fluorescence, photosynthetic rate, leaf water potential, and increased proline content (Bhatt *et al.*, 2015) ^[9], which ultimately results in significant production losses. Additionally, due to its shallow root system, the onion crop is susceptible to waterlogging. It was documented that the onion cultivar, Arka Kalyan, experienced waterlogging for seven days, which reduced photosynthetic rate, leaf area, fresh weight, and dry matter by 86, 51, 46, and 47%, respectively. Among the different stages of onion development, the bulb initiation stage is the most susceptible to water stagnation and claims a 50% reduction in bulb yield after seven days of waterlogging due to a high incidence of purple blotch and twister diseases. In this way, excess moisture stress has a significant impact on vegetable crops (Srinivasa Rao, 2010; Samra *et al.*, 2006) ^[48, 52].

Atmospheric Carbon dioxide (CO₂) concentration

By 2050, the amount of CO₂ in the atmosphere will approach 550 parts per million (ppm). The crops react to rising atmospheric CO₂ concentrations, which are the main cause of climate change, in addition to temperature (high and low temperatures), water (drought and waterlogging), and salt stresses. Since CO₂ is essential to plant metabolism and directly contributes to energy balance by controlling physiological activities like photosynthesis and respiration, the rising CO₂ level has a direct impact on plants' metabolism. By improving plant water consumption efficiency, photosynthetic capability, and a growth process known as the "Carbon fertilization" effect, increasing CO₂ levels typically boosts plant productivity (Rogers and Dahlman 1993; Fleisher *et al.*, 2008) ^[21, 47]. As CO₂ levels rise, C₃ and C₄ plant productivity rises by 15 to 41% and 5 to 10%, respectively (Lotze-Campen and Schellnhuber, 2009; Brand *et al.*, 2016) ^[35, 13].

According to some research, rising CO₂ levels have an impact on product quality by raising the content of sugars, ascorbic acid, flavonoids, phenols, and antioxidant capacity, primarily in leafy vegetables (Bisbis *et al.*, 2018) ^[10]. Red leaf lettuce exhibits a rise in sugars, flavonoids, and derivatives of caffeic acid at a CO₂ concentration of 1000 ppm (Becker and Klaring, 2016) ^[7]. Chinese cabbage, lettuce, and celery cultivated at 800-1000 ppm CO₂ have been found to have higher vitamin C content (Jin *et al.* 2009) ^[29]. At 700 ppm CO₂, lettuce and spinach have been shown to have higher levels of total phenolic compounds, antioxidant capacity, and total chlorophyll content as well as lower levels of various macronutrients and micronutrients (Giri *et al.*, 2016) ^[24].

Protein, vitamin C, minerals (Ca, Mg, Zn, Mn, and Fe), essential fatty acids, and amino acids in tomatoes (Khan *et al.*, 2013) ^[31] and root crops, including carrot, radish, and turnip (Azam *et al.*, 2013) ^[5], are negatively impacted by elevated CO₂ at 1000 ppm. The high atmospheric CO₂ levels (550-680 ppm) in potatoes caused changes in tuber quality, but depending on the quality parameter, these changes could be either positive (increasing dry matter, starch, and vitamin C content and decreasing toxic compounds like total glycoalkaloids, α -chaconine, and nitrate) or negative (reducing protein, macro-micronutrients (N, K, Ca, Mg, and Fe), total amino acids, and citric acid).

Furthermore, according to some research, CO₂ levels between 700 and 1000 ppm enhance characteristics linked to flavor in tomato fruits, including color, sugar/acid ratio, and total sucrose,

glucose, and fructose content (Khan *et al.*, 2013) ^[31]. Furthermore, it is found that increased CO₂ does not affect the quantities of titratable acidity, carotenoids, lycopene, anthocyanins, phosphorus, potassium, sulfur, copper, and manganese (Dong *et al.* 2018) ^[18].

Pests and diseases

The biology of insect pests is likewise impacted by climate change. Some insects with short life cycles, including aphids and diamond back moths, have higher fecundity and an earlier life cycle completion when the temperature rises. As a result, these can generate more generations annually than they typically do. On the other hand, certain insects could take a few years to finish their life cycle. The soil provides an insulating layer that tends to buffer temperature changes more than the air, which affects some insect species that live in soil for all or part of their life cycle, typically suffer more than insects found above the soil surface (Abewoy, 2018) ^[11].

The physiology and resistance of the host plant, as well as the growth stage, development pace, and pathogenicity of infectious pathogens, can all be affected by variations in temperature and precipitation patterns brought on by climate change. Plant pathogens are predicted to be the first species to exhibit the effects of climate change due to their enormous population size and short generation period. Since low temperatures and long winters now lower the survival, annual generations, reproduction rate, and activity of most pathogens affecting crops during the growing season, it is anticipated that the effects of plant infections in northern latitudes may worsen with warming (Mboup *et al.*, 2012; Harvell *et al.*, 2002) ^[27, 38].

The distribution of pathogen species is influenced by temperature and frost sensitivity because, despite their wide host range, soil-borne diseases like *Sclerotium rofsii* and *Macrophomina phaseolina* do not occur in temperate areas because of their high temperature optimum and frost sensitivity. Due to less frost, higher temperatures accelerate the disease cycles of airborne viruses and increase their survival (Boonekamp, 2012) ^[11]. Viral infections of crops like potatoes and sugarbeets are on the rise as a result of the earlier emergence and increased number of insect vectors of viral diseases brought on by the wintertime temperature rise. The elimination of a limiting factor for diseases like Fusarium is implied by the decrease in frost caused by higher average minimum temperatures (Abewoy, 2018) ^[11].

Salinity

Salinity is a severe problem that lowers the growth and productivity of vegetable crops in many salt-affected areas. The majority of vegetables, which are especially susceptible throughout the plant's ontogeny, are among the numerous crops whose yield is decreased by excessive soil salinity. Physiologically, salinity imposes an initial water deficit that derives from the comparatively high solute concentrations in the soil, generates ion-specific stressors resulting from changed K⁺/Na⁺ ratios, and leads to a buildup in Na⁺ and Cl⁻ concentrations that are detrimental to plants.

Loss of turgor, reduced growth, wilting, leaf abscission, reduced respiration and photosynthesis, loss of cellular integrity, tissue necrosis, and ultimately plant death are brought on by salt stress. Cucumber, tomato, pepper, and eggplant are relatively sensitive to salty soils, whereas onions are vulnerable. In cabbage, salinity significantly lowers the germination rate, germination percentage, root and shoot length, and fresh root and shoot weight. Due to the damage caused by the salt accumulation

avoidance mechanism in young expanding potato leaves, the combined stress of heat and salinity causes vegetative growth recovery to fail, which in turn reduces the leaf area index and canopy functioning (Abewoy, 2018) ^[11].

Salinity lowers dry matter production, leaf area, relative growth rate, and net absorption rate in chili. Also, the salinity has a greater impact on the quantity of fruits per plant than on the weight of each fruit. All cucurbits lose weight, both fresh and dry, when the concentration of salt is high (Kaymakanova *et al.*, 2008) ^[30]. These alterations are linked to a drop in both total chlorophyll content and relative water content. In bean plants, salt stress results in altered stomata conductance, quantity, and size as well as a reduction of growth and photosynthetic activity. It lowers transpiration and the cell water potential in salt-affected bean plants. Numerous physiological and metabolic processes are known to be impacted by the high saline levels of soil and irrigation water, which might result in a decrease in cell development.

Effect of Ozone (O₃)

In addition to the effects of CO₂, increasing levels of tropospheric ozone (O₃), a secondary air pollutant linked to industrial activity and vehicle emissions, are also a threat to the quality and marketability of vegetables. High O₃ exposure can cause obvious foliar damage, surface imperfections, and physiological stress in vegetables. Even when total biomass is essentially unaltered, these stresses cause significant financial losses for farmers by lowering market value and compromising visual quality (Scheelbeek *et al.*, 2018) ^[49].

In India's most fertile agricultural districts, rising tropospheric O₃ levels have a negative impact on plant development and reduce vegetable yield (Mukherjee *et al.*, 2020) ^[40]. Over the northern, western, and peninsular parts of India, the O₃ concentration pattern exhibits a 40-60 ppb (higher) range during the pre-monsoon/summer season and a 15-20 ppb (lower) range during the monsoon months (Kunchala *et al.*, 2021) ^[33]. Instead of direct plant surface deposition, stomatal uptake of O₃ into the leaf interior is the primary cause of O₃-induced plant damage (Nouchi, 2002) ^[43].

The amount of O₃ absorbed by crop plants and its capacity to react with cellular components to produce reactive oxygen species that cause damage to the cell at the molecular, biochemical, and physiological levels and speed up leaf senescence, which lowers crop yield (Yadav *et al.*, 2019; Sicard *et al.*, 2020) ^[50, 56]. When potatoes (*Solanum tuberosum* L.) are exposed to high levels of surface O₃ at the tuber initiation stage at a high altitude in Western Ghats, their yield decreases from 4.56 to 25.5% (Suganthi and Udayasoorian, 2020) ^[53]. Elevated O₃ in tomatoes (*S. lycopersicum* L.) reduces yield more in the late vegetative phase than in the early vegetative and fruiting phases (Mina *et al.*, 2010) ^[39].

Palak (*Beta vulgaris* L.), a green leaf vegetable, is particularly vulnerable to O₃ and exhibits yield reductions of up to 25% at high O₃ levels. Similar findings have also been documented in *Rapahanus sativus* L., *Daucus carota* L., and *Amaranthus hypochondriacus* L. In soybeans, elevated O₃ reduces seed protein, which is linked to a negative response to nitrogen fixation. Common beans exposed to 40 ppb of O₃ throughout the growth season have higher levels of total lipids, phytosterols, dietary fiber, total phenolics, and antioxidant capacity, but lower levels of total amino acids, total anthocyanins, certain flavonols, and hydroxyl cinnamates (Laxman *et al.*, 2024) ^[34].

In potatoes, dry weight, proteins, and amino acids are reduced by the elevated atmospheric O₃ level (50-70 ppb), which also

lowers the tuber's sugar and micronutrient content (Kumari & Agrawal, 2014). Furthermore, it has been noted that when daily ozone concentrations exceed 50 ppb, vegetable yields can drop by 5 to 15%. Therefore, increased O₃ has a negative effect on the quantity and quality of vegetables.

Management strategies to overcome Climate change

The creation of climate-resilient cultivars and suitable crop management techniques would greatly aid in mitigating the negative effects of numerous abiotic stresses.

Grafting Technology

One effective way to manage biotic and abiotic challenges and improve the yield and quality of vegetable crops is to graft vegetable plants onto resistant rootstocks. Grafting started in 1950s with brinjal, while the 1960s and 1970s saw the grafting of tomatoes and cucumbers. Melons grafted onto hybrid squash rootstocks were found to be more salt-tolerant than melons that were not grafted. However, different species have very different levels of salt tolerance; for example, rootstocks from *Cucurbita* spp. are more salt-tolerant than rootstocks from *Lagenaria siceraria* (Abewoy, 2018) ^[4].

According to several reports, waterlogging stress was reduced when tomatoes were grafted onto eggplant rootstocks. Eggplant rootstocks Arka Keshav, Arka Neelkanth, IC-354557, and IC-111056 have been found to provide tomatoes with flooding tolerance (Laxman *et al.*, 2024) ^[34]. Eggplant rootstocks can offer protection against restricted soil moisture stress in addition to flood protection because some eggplant genotypes are drought-tolerant. While grafted vegetables are grown commercially in more than 20 nations globally, the majority of greenhouse-grown cucurbits are grafted in China, Japan, Korea, Turkey, and Israel. For increased resistance to biotic stress, nutritional deficiency/toxicity, abiotic stress, and heavy metal toxicity, grafted seedlings are used in the cultivation of nearly 99% of watermelons in Korea, 94% in Japan, and 40% in China. Plant response to heat stress conditions is improved by grafting temperature-sensitive tomatoes onto more resilient rootstock cultivars. According to reports, grafted tomato plants outperform ungrafted ones in heat-stressed environments.

Changing management practices

In areas where periods of high temperatures and heavy rains are predicted, changing the dates of planting can be a fast adaptation method to counteract yield losses. In regions with limited water availability, water-saving irrigation techniques like sprinkler (for crops like onion, carrot, radish, and beetroot) and drip (for crops like cucurbits, tomato, pepper, capsicum, and brinjal) irrigation systems can be used. In regions that are vulnerable to water shortage stress, agronomic techniques such as contour cultivation, contour strip cropping, mixed cropping, and low tillage can be used to preserve the in-situ soil moisture. Growing green manure crops and adding farm yard manure can increase the soil's organic matter content, which can also increase the soil's ability to retain moisture. Using plastic mulches offers a low-cost technology to conserve soil moisture.

Employing clear plastic rain shelters for vegetable cultivation can lessen the direct influence on fruit development and field waterlogging during the rainy season. Vegetables grown in raised beds during the rainy season will yield more because of better drainage, which lessens anoxic stress on the root system (Welbaum, 2015) ^[55].

Protected cultivation

Crop production is increased when crops are grown in protected cultivation structures such as greenhouses, polyhouses, and net houses. These structures shield the crops from adverse climatic

conditions like extreme temperatures, drought, and flooding. Likewise, sheltered growing of tomatoes, capsicums, and parthenocarpic cucumbers yields higher-quality fruits.

Biotechnology

Modern technology will be needed to supplement conventional approaches, which are insufficient to prevent yield losses brought on by environmental pressures. The roles of genes have been identified, which has made it possible to genetically modify genes linked to stress tolerance. These tools need large amounts of investment but promise faster and even spectacular results. There are numerous initiatives utilizing these genetic and molecular technologies, some of which have been successful. There is little molecular marker analysis of vegetable stress tolerance, although work is being done to find the QTLs that underlie stress tolerance (Laxman *et al.*, 2024) ^[34].

Future prospects

In order to fulfill the demands of a constantly expanding population, global agriculture, particularly the production of vegetables, is currently facing challenges related to food and nutritional security. Growing biotic and abiotic pressures, deteriorating environmental quality, and the threat of rising global warming brought on by greenhouse gases made the issue worse. Studying how climate change affects agricultural growth, development, yield, and quality is therefore critically important. Adapting present vegetable systems to the possible effects of climate change will be necessary to reduce hunger and alleviate poverty in developing nations through enhanced production and consumption of safe vegetables. Developing effective adaptation techniques is necessary to lessen the negative effects of climate change on vegetable crop productivity and quality. The development of manufacturing technologies for increased water use efficiency that can be adapted to the hot and dry conditions should be the main focus. Soil moisture conservation is aided by crop management techniques such as mulching with crop waste and artificial mulches. Growing crops on raised beds can help address the major issue of excessive soil moisture caused by high rainfall.

Genetic communities are being produced to identify genes tolerant to climate stress, and at the same time generate tools for gene isolation, characterization, and genetic engineering. Additionally, farmers in underdeveloped nations need to have easy access to agronomic techniques that preserve water and shield vegetable crops from unfavorable environmental conditions. Technical, socioeconomic, and political factors must be taken into account in an efficient extension strategy. The two most important elements that need to be focused on for a sustainable climate change adaptation strategy are education and capacity building.

Conclusion

Extreme weather events such as heat, cold, drought, flooding, salinity stress, and variations in atmospheric CO₂ and ozone levels have become more often as a result of climate change. When vegetable crops are subjected to various kinds of abiotic stresses, their production and quality are decreased. Membrane damage, oxidative burst, decreased chlorophyll content, and decreased photosynthetic rate are some of the major physiological and biochemical impacts of abiotic stress. Therefore, both adaptation and mitigation strategies are required to maintain vegetable crop productivity under changing climate scenarios. It is necessary to employ climate-smart production techniques, climate-resilient cultivars, appropriate cultural

practices, diverse cropping systems, and mulching. A cost-effective mix of adaptation options must be developed for various crops and geographies. Therefore, all of the strategies discussed can help farmers to maintain the production of vegetable crops while helping them overcome abiotic challenges.

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