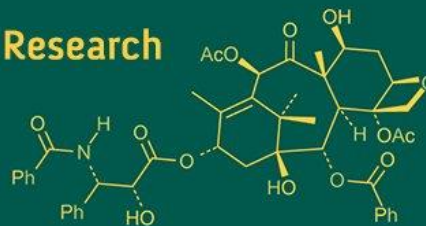


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Climate resilient strategies for vegetable cultivation in a changing climate scenario

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Abstract

Vegetables form the backbone of nutritional and livelihood security across the tropics and sub-tropics, yet their cultivation is disproportionately vulnerable to climate variability because most crops in this group are shallow-rooted, short-duration and sensitive to even brief episodes of heat, moisture stress or waterlogging at critical growth stages. Rising mean temperatures, erratic and intense rainfall, prolonged dry spells, secondary soil salinisation and the poleward and altitudinal shift of insect-pests and pathogens are together eroding yield stability, fruit quality and farm incomes in vegetable-based cropping systems. This review synthesises the physiological basis of climate-induced stress in vegetable crops and consolidates the spectrum of resilience-building strategies available to growers, breeders and policy makers, spanning genetic approaches such as participatory breeding, marker-assisted and genomic selection, genome editing and grafting; agronomic interventions including adjusted sowing windows, mulching, precision and deficit irrigation, protected cultivation and soil-health management; biological tools such as plant growth-promoting microbes and biostimulants; integrated pest and disease management; diversification through intercropping, agroforestry and underutilised species and digital climate-smart advisories. Regional case evidence from South Asia, sub-Saharan Africa and other vegetable-growing tropics is discussed alongside the economic, gender and institutional dimensions that shape adoption. The review concludes that resilience in vegetable production depends less on any single technology than on the deliberate stacking of complementary genetic, agronomic, ecological and digital tools within locally calibrated, farmer-participatory extension systems.

Keywords: Climate change, vegetable cultivation, abiotic stress, climate-resilient varieties, climate-smart agriculture and adaptation strategies

Introduction

Climate change refers to the long-term alteration in climatic variables, including temperature, rainfall, relative humidity and atmospheric gas composition, occurring over time within a specific geographical region (Raza *et al.*, 2019) ^[1]. Climate change has increased the occurrence of extreme environmental conditions, including drought, flooding, heat stress, cold stress and salinity, along with fluctuations in atmospheric carbon dioxide and ozone concentrations. These changes significantly reduce the productivity and quality of vegetable crops (Bulgari *et al.*, 2019) ^[2]. Studies have indicated that global warming contributed to an estimated 41 per cent decline in vegetable crop yields between 1965 and 2016 (Scheelbeek *et al.*, 2018) ^[3]. To meet the growing demand for vegetables and ensure food security for the rapidly increasing global population, it is essential to adopt and develop climate-resilient technologies and management practices that can minimize the negative impacts of environmental stresses (Malhotra and Srivastva, 2014) ^[4].

Impact of Abiotic Stresses on Vegetable Crop Effect of high-temperature stress

Supra-optimal temperature is among the most pervasive constraints to vegetable productivity. Heat stress during the reproductive phase disrupts pollen viability and stigma receptivity in solanaceous and cucurbitaceous vegetables, leading to flower abortion and poor fruit set (Saha *et al.*, 2010) ^[5]. In cole crops such as cabbage, prolonged exposure to drought-associated heat during the vegetative stage reduces leaf size and photosynthetic area, ultimately depressing head weight and marketable yield (Ackah and Kotei, 2021) ^[6].

Heat stress also hastens crop development, reducing the time available for dry matter accumulation. As a result, marketable yield declines even when the plants survive the stress without severe damage. Temperatures above 35°C impair membrane integrity in carrot, resulting in lower cell membrane stability and greater relative cell injury (Nijabat *et al.*, 2020) [7]. Prolonged exposure to high temperatures

induces premature flowering (bolting) in spinach and lettuce, thereby reducing their market quality. Severe heat stress also disrupts enzymatic activities, triggers excessive production of reactive oxygen species, impairs normal metabolic processes and accelerates plant senescence. (Raza, 2022) [8].

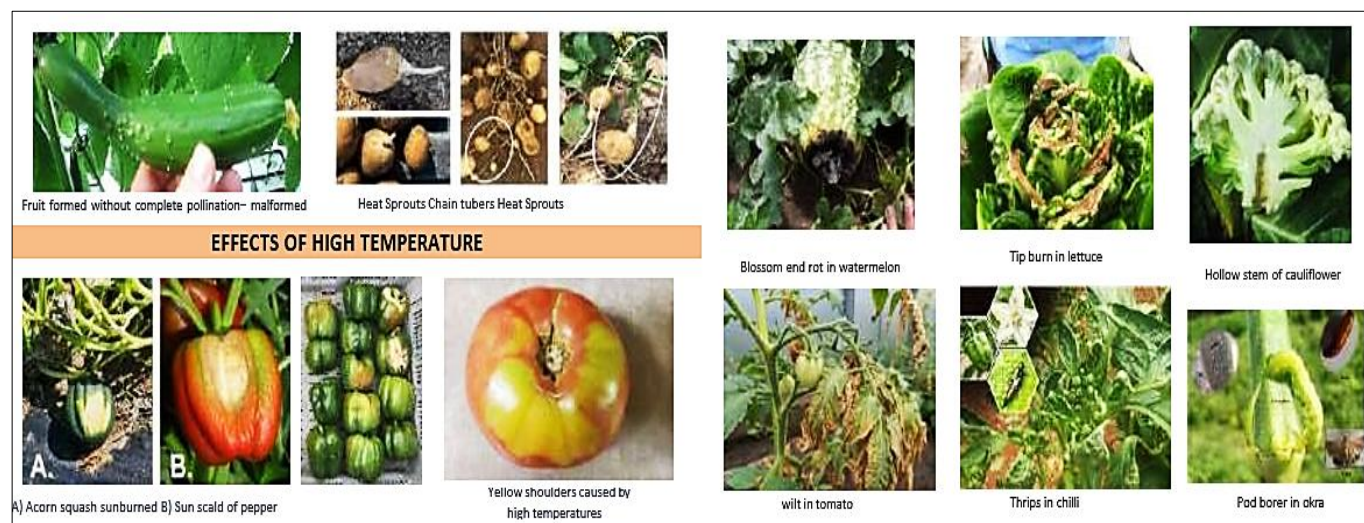


Fig 1: Effects of high temperature stress

Effect of cold (low temperature) stress

The plasma membrane is the primary target of cold stress, as low temperatures alter its integrity and fluidity. These changes disrupt ion transport, promote protein denaturation, and disturb normal cellular metabolism, ultimately impairing plant growth and function (Orzechowski *et al.*, 2021) [9]. Exposure of tomato plants to low temperatures (8-12°C) has been reported to impair seed germination,

vegetative growth, pollen tube development and fruit set. These adverse effects are associated with reduced antioxidant enzyme activity, excessive accumulation of reactive oxygen species (ROS), enhanced lipid peroxidation, disruption of membrane integrity, decreased chlorophyll synthesis and damage to the photosynthetic machinery (Bai *et al.*, 2021) [10].

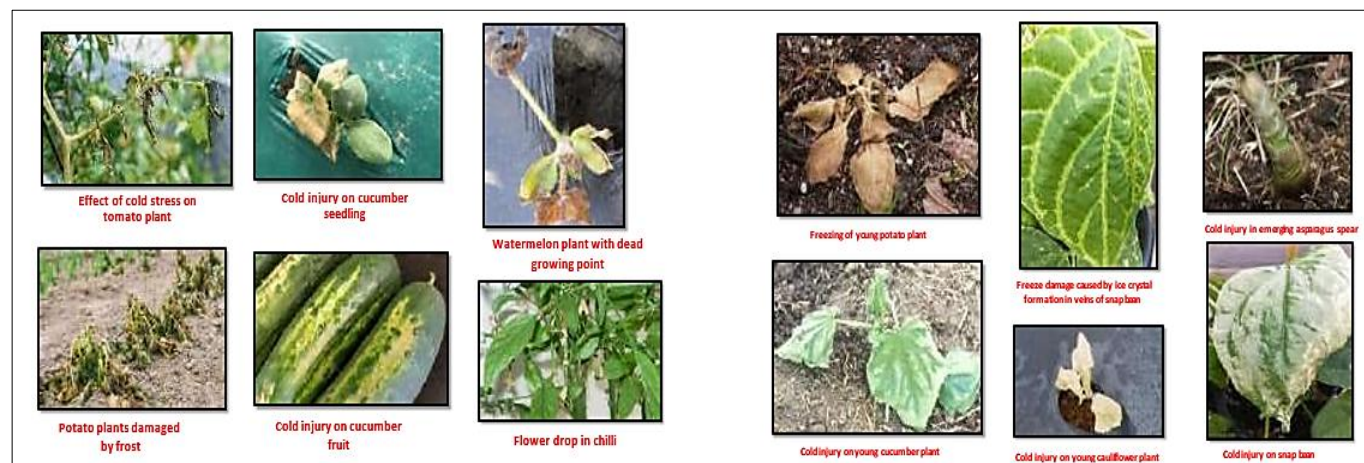


Fig 2: Effects of low temperature stress

Erratic Rainfall and Drought

Irregular patterns in rainfall timing, distribution, and intensity have significantly affected the stability of both rainfed and irrigated vegetable production systems. A delayed onset of the monsoon shortens the period available for nursery establishment and transplanting, whereas prolonged dry spells during the cropping season, particularly at flowering and fruit development stages, adversely affect crops such as pepper, brinjal and cucurbits. Water deficit

during these critical growth phases reduces cell turgor, stomatal conductance and photosynthetic efficiency, ultimately limiting fruit set and yield. In pepper, adequate soil moisture is especially essential during flowering and fruit-set to ensure optimum productivity (Okunlola *et al.*, 2017) [11]. Furthermore, drought stress weakens plant vigor, making crops more vulnerable to secondary stresses such as infestations by sap-sucking insects and infections by soil-borne pathogens, thereby intensifying overall yield losses.

Flooding and Waterlogging

Climate change has also increased the frequency of intense rainfall events, resulting in flooding and temporary waterlogging even in regions that commonly experience drought. Excess water creates oxygen-deficient (anoxic) conditions in the root zone, which most vegetable crops are unable to tolerate. Such conditions impair root respiration, reduce nutrient uptake and hinder overall plant growth. In pepper, even brief periods of waterlogging have been reported to decrease photosynthetic activity, lower chlorophyll content, and accelerate root senescence (Ou *et al.*, 2011) ^[12]. Similar responses have been observed in tomato, chilli and cucurbit crops cultivated in poorly drained soils, leading to reduced plant vigor, impaired fruit development and substantial yield losses.

Soil and Water Salinity

Rising sea levels, seawater intrusion into coastal aquifers, and the increasing use of poor-quality irrigation water have accelerated soil and water salinity in many coastal and canal-irrigated regions. Elevated salinity restricts plant water uptake by creating osmotic stress and causes ionic toxicity due to the excessive accumulation of sodium (Na⁺) and chloride (Cl⁻) ions. These conditions adversely affect plant growth, resulting in reduced germination, stunted development, leaf margin scorching, nutrient imbalance and smaller fruits in salt-sensitive vegetable crops such as okra, French bean, and carrot. The detrimental effects of salinity are often intensified by other climate-related challenges, rising input costs and market uncertainties, collectively reducing the productivity and profitability of vegetable farming in vulnerable regions (Hatfield *et al.*, 2018) ^[13].

Elevated Atmospheric Carbon Dioxide

Higher atmospheric carbon dioxide (CO₂) levels can stimulate photosynthesis and increase biomass production in many C₃ vegetable crops, a phenomenon commonly known as the CO₂ fertilization effect. Nevertheless, under practical field conditions, these positive effects are often reduced because elevated CO₂ frequently occurs alongside high temperatures and water stress. Moreover, research indicates that increased CO₂ concentrations may lower the levels of essential nutrients, including protein, iron, zinc and other micronutrients, in edible plant tissues. This decline in nutritional quality poses a significant challenge for vegetable production under future climate change scenarios.

Shifting Pest and Disease Dynamics

Rising temperatures and increased humidity are changing the distribution, life cycles, and population dynamics of numerous insect pests and plant pathogens affecting vegetable crops. Studies from climate-sensitive Himalayan vegetable-growing regions have shown that greater climatic vulnerability is linked to an increased risk of pest outbreaks and significant alterations in traditional cropping schedules (Singh *et al.*, 2025) ^[14]. These changing pest dynamics make it increasingly difficult to synchronize pest management practices with conventional pest calendars, particularly in solanaceous and cucurbitaceous vegetable production systems, thereby reducing the effectiveness of timely plant protection measures.

Field-level climate-resilient strategies for vegetable cultivation

Developing climate-resilient vegetable production systems requires the integration of genetic improvement, sustainable agronomic practices, biological inputs, ecological management and modern information technologies. Rather than functioning independently, these approaches are most effective when combined into location-specific production packages that address local climatic risks and farming conditions.

Breeding and genetic approaches

Conventional and Participatory Plant Breeding

Conventional breeding, based on hybridization and selection, continues to play a fundamental role in developing vegetable cultivars capable of tolerating heat, drought, flooding and salinity. Studies indicate that drought tolerance and improved water-use efficiency are the most widely adopted traits in climate-resilient crop breeding programmes (Acevedo *et al.*, 2020) ^[15]. Farmer participation through participatory varietal selection further enhances the adoption of improved cultivars by allowing growers to evaluate breeding lines under their own environmental and management conditions. This collaborative approach ensures that newly developed varieties satisfy local production requirements, market demand, and consumer preferences. In addition, access to extension support and farmer training significantly influences the successful adoption of climate-resilient cultivars.

Marker-Assisted Selection and Genomic Tools

Recent advances in molecular genetics and genome sequencing have accelerated the breeding of stress-tolerant vegetable crops. Modern breeding strategies combine genomic selection, high-throughput phenotyping, and molecular markers to identify and transfer favourable genes associated with abiotic stress tolerance. Marker-assisted selection enables breeders to incorporate valuable alleles from wild relatives and traditional landraces into elite cultivars more efficiently, substantially reducing the time required compared with conventional breeding (Naqvi *et al.*, 2022) ^[16].

Genome Editing

Genome-editing technologies, particularly CRISPR/Cas systems, provide precise tools for modifying genes involved in drought and heat tolerance. Targeted editing of genes regulating stomatal behaviour, abscisic acid signalling and antioxidant defence mechanisms has demonstrated promising improvements in stress adaptation in vegetable crops such as tomato under controlled conditions (Park *et al.*, 2025) ^[17]. However, the practical adoption of gene-edited vegetables depends not only on scientific advances but also on national biosafety regulations, public acceptance and policy frameworks governing these technologies.

Grafting Technology

Grafting is an effective non-transgenic strategy for enhancing stress tolerance in vegetable crops. Susceptible scions of tomato, brinjal, chilli, and cucurbits are grafted onto vigorous rootstocks possessing superior tolerance to drought, salinity, heat and other environmental stresses.

Improved root architecture, enhanced uptake of water and nutrients, and favourable hormonal interactions between the rootstock and scion contribute to increased resilience under adverse conditions. Furthermore, grafting cucumber and watermelon onto drought-tolerant rootstocks has been reported to improve antioxidant activity and osmotic regulation, thereby sustaining growth and productivity during water-limited conditions (Yang *et al.*, 2022) ^[18].

Agronomic and Crop Management Practices Mulching and Soil Moisture Conservation

Mulching plays a vital role in conserving soil moisture and creating a favourable root-zone environment. Organic materials such as straw, crop residues and dried leaves, together with synthetic mulches including black and silver-black polyethylene films, reduce evaporation, suppress weed growth and moderate soil temperature. Climate-smart production systems increasingly advocate the combined use of mulching, conservation tillage, residue retention and balanced nutrient management to improve resource-use efficiency and enhance the resilience of vegetable crops to moisture stress.

Precision Water Management

Efficient irrigation management is essential for sustaining vegetable production under conditions of increasing water

scarcity. Drip irrigation integrated with fertigation supplies water and nutrients directly to the root zone, thereby minimizing conveyance losses and improving nutrient-use efficiency compared with conventional surface irrigation. Modern irrigation systems equipped with soil moisture sensors and automated scheduling technologies further optimize water application based on crop requirements (Bwambale *et al.*, 2022) ^[19]. In addition, regulated deficit irrigation during less sensitive growth stages and the use of raised beds with proper drainage help conserve water while reducing the risks associated with drought and temporary waterlogging.

Protected Cultivation

Protected cultivation provides an effective means of shielding vegetable crops from adverse weather conditions. Structures such as shade nets, low tunnels, rain shelters and naturally ventilated polyhouses help regulate temperature, reduce rainfall damage and protect crops from strong winds. These systems create a more favourable microclimate, extend the cropping season, improve productivity, and enhance produce quality, particularly for high-value vegetable crops cultivated in peri-urban and intensive production systems (Gruda *et al.*, 2019) ^[20].

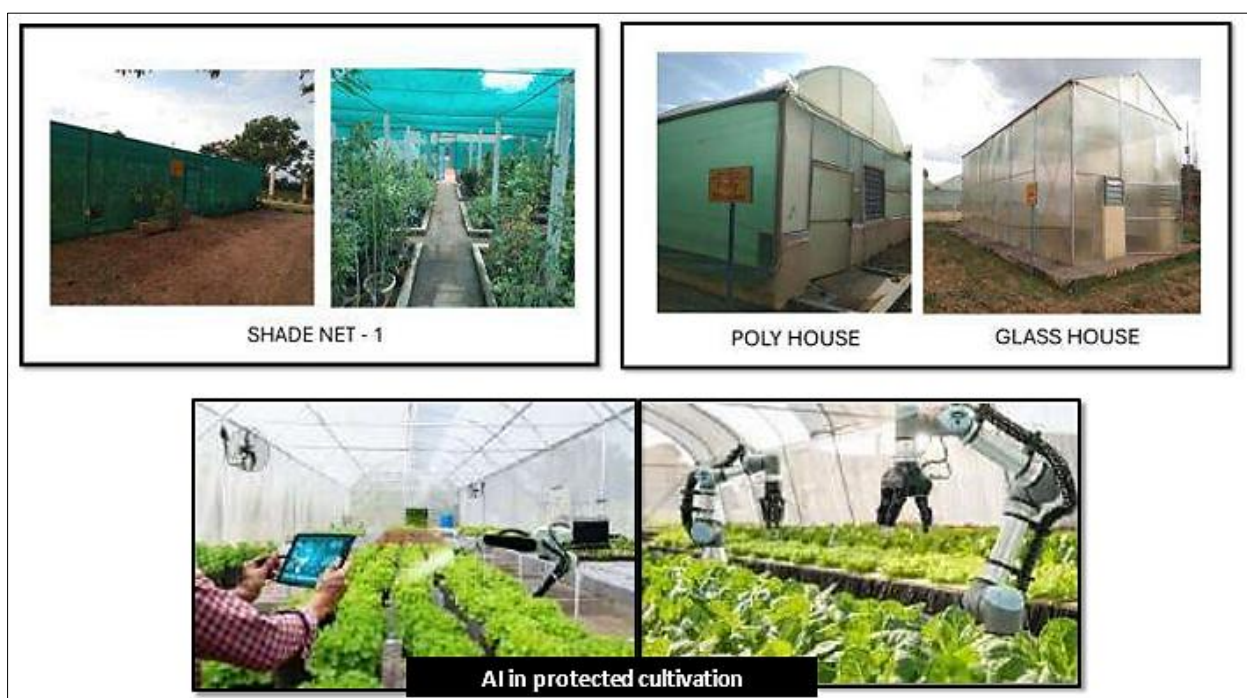


Fig 3: Protected Cultivation

Soil Health and Nutrient Management

Maintaining healthy soils is fundamental to improving crop resilience under climate change. Practices such as compost application, green manuring, conservation tillage and the incorporation of organic amendments increase soil organic matter, improve moisture retention and promote beneficial microbial activity involved in nutrient cycling. Studies have

demonstrated that integrating rainwater harvesting techniques with amendments such as biochar enhances soil fertility and significantly increases crop productivity compared with the adoption of either practice alone (Debebe *et al.*, 2025) ^[21]. These findings emphasize the importance of integrated soil and water management strategies for sustainable vegetable production.



Fig 4: Soil nutrient management

Biological and Biostimulant Approaches

Beneficial microorganisms and naturally derived biostimulants offer environmentally sustainable options for improving crop tolerance to abiotic stress. Plant growth-promoting rhizobacteria (PGPR) enhance nutrient availability through nitrogen fixation and phosphate solubilization while producing phytohormones that stimulate plant growth and strengthen antioxidant defence

systems (Ruzzi and Aroca, 2015) [22]. They also improve drought tolerance by modifying root architecture, lowering stress-induced ethylene levels through ACC-deaminase activity, and producing osmoprotective compounds that help maintain soil moisture around plant roots (Vurukonda *et al.*, 2016) [23].

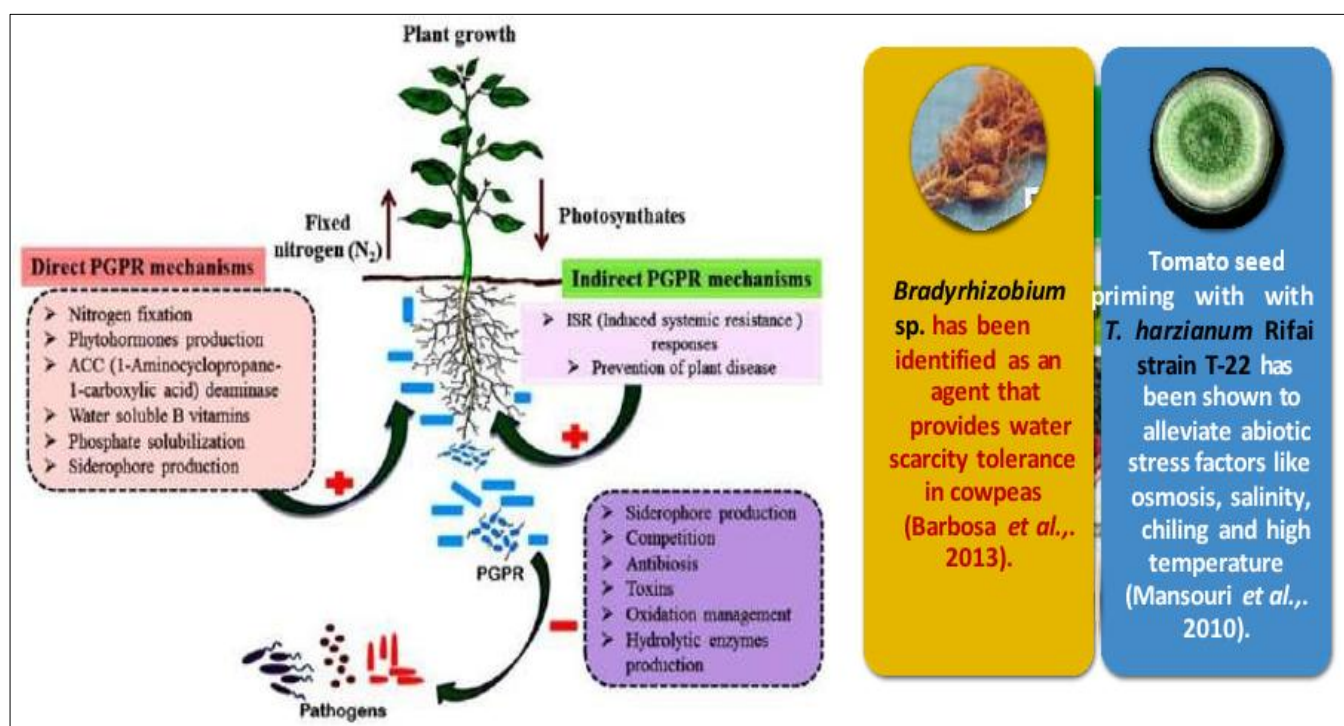


Fig 5: Plant growth-promoting rhizobacteria (PGPR)

Similarly, biostimulants derived from seaweed extracts, humic substances, and amino acids improve nutrient uptake, enhance water-use efficiency, and support primary and secondary metabolic processes under stress conditions (Bulgari *et al.*, 2015) [24]. Humic substances additionally stimulate root development and nutrient absorption, thereby

indirectly improving stress tolerant (Nardi, 2010) [25]. Foliar application of osmoprotectants such as potassium nitrate, salicylic acid and proline has also proven effective in strengthening membrane stability and antioxidant activity, enabling vegetable crops to better withstand heat and drought stress.

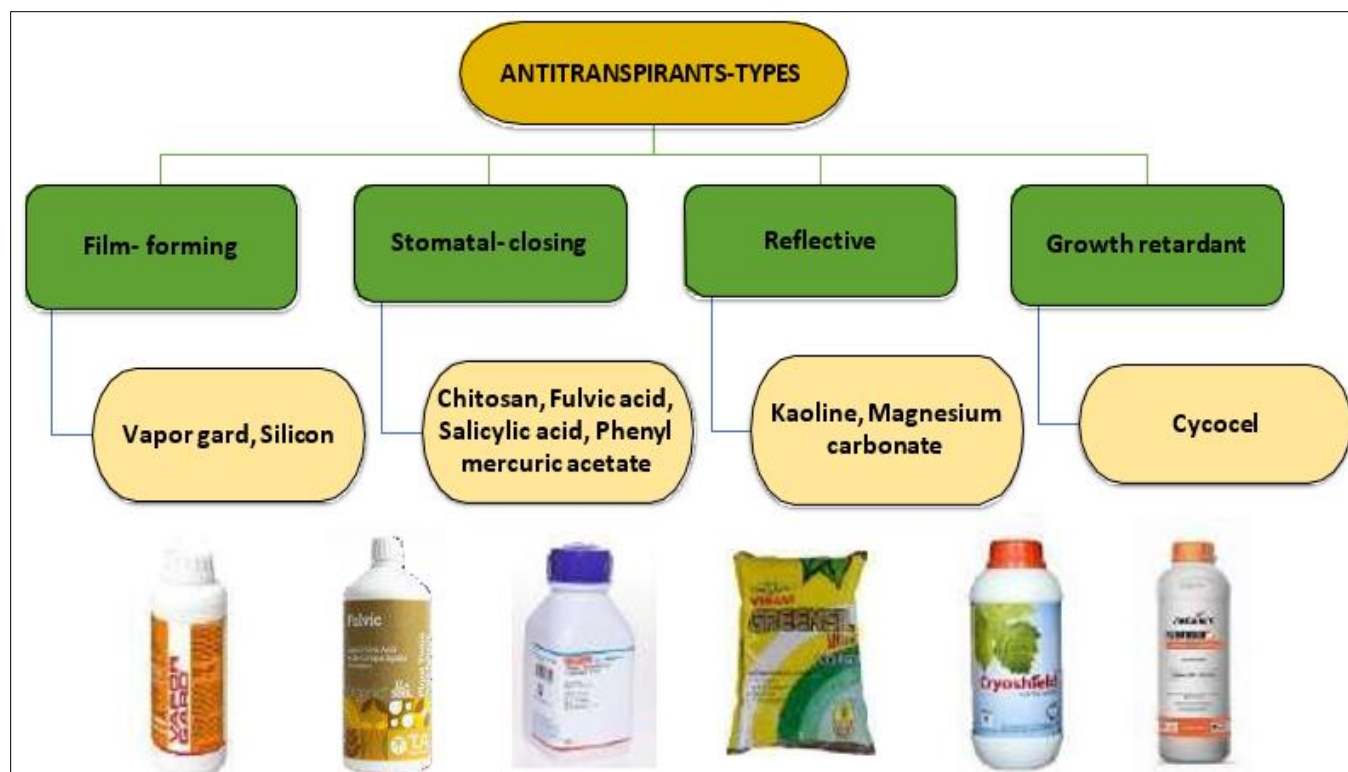


Fig 6: Different types of antitranspirants

Integrated Pest and Disease Management

Climate change has altered the seasonal occurrence and intensity of many insect pests and plant diseases, making conventional pest management schedules less reliable. Consequently, climate-resilient production systems increasingly rely on integrated pest management (IPM), which combines resistant cultivars, biological control agents, pheromone traps, and the judicious use of pesticides based on monitoring and economic threshold levels. Community-based pest surveillance and early warning systems further enable farmers to detect emerging outbreaks promptly and implement timely control measures before significant crop damage occurs.

Diversification and Cropping System Approaches Intercropping and Crop Rotation

Diversifying cropping systems through intercropping and crop rotation reduces climatic risk while improving soil health and biological stability. Intercropping vegetables with legumes enhances soil fertility through biological nitrogen fixation, whereas crop rotation with cereals or fodder crops interrupts pest and disease cycles associated with continuous monoculture. Climate-resilient legumes such as grass pea are increasingly recommended as intercrops or rotational crops because of their tolerance to drought, waterlogging and nutrient-deficient soils (Gonçalves *et al.*, 2022) ^[26].

Agroforestry and Homestead Systems

Agroforestry-based vegetable production integrates trees, shrubs, and vegetable crops to create a more favourable microclimate. Shade provided by trees reduces evapotranspiration and moderates the temperature, while windbreak effects minimize crop damage caused by strong winds. In addition to improving soil fertility and moisture conservation, these systems diversify farm income and

reduce the economic risks associated with climate-induced crop failures. Integrating agroforestry with rainwater harvesting and soil improvement measures has also been shown to enhance both crop productivity and soil nutrient status in dryland agriculture (Debebe *et al.*, 2025) ^[21].

Underutilised and Traditional Vegetable Species

Many indigenous and underutilized vegetable species possess natural tolerance to harsh environmental conditions, making them valuable resources for climate-resilient agriculture. Crops such as amaranth, moringa, cluster bean, ridge gourd and several traditional leafy vegetables perform well under high temperatures, drought and low-fertility soils compared with many commercially bred cultivars. Promoting these resilient species through extension programmes and improved market access not only strengthens climate adaptation but also enhances nutritional diversity and supports sustainable farming systems (Kugedera and Naik, 2026) ^[27].

Digital and Climate-Smart Agriculture Tools

The adoption of digital technologies is transforming climate adaptation in vegetable cultivation by providing farmers with timely and location-specific decision support. Mobile-based weather forecasting services, remote sensing technologies for monitoring soil moisture and crop health and decision-support systems for irrigation scheduling, sowing time and pest management enable growers to make informed management decisions under variable climatic conditions. When effectively delivered through agricultural extension services and farmer producer organizations, these climate-smart digital tools enhance the practical application of research findings at the farm level.

Sensor-based smart irrigation systems, for example, have been reported to improve irrigation efficiency and resource

utilization in precision agriculture (Bwambale *et al.*, 2022)^[19]. Nevertheless, bibliometric studies indicate that research on institutional support systems and digital advisory services remains comparatively limited when compared with technological innovations, highlighting the need for greater investment in these areas to strengthen climate resilience (Kori *et al.*, 2024)^[28].

Regional case studies and evidence of impact

Field evidence from diverse agroecological regions demonstrates that farmers are increasingly adopting multiple adaptation strategies to cope with climate variability in vegetable production. In the Himalayan region of South Asia, growers have responded to changing rainfall patterns and rising temperatures by integrating crop diversification, improved nutrient management, drought-tolerant varieties and water conservation practices. Among these measures, crop diversification has emerged as the most widely adopted strategy, while increased climatic vulnerability has been associated with reduced farm profitability (Singh *et al.*, 2025)^[14].

Similarly, studies conducted in the dryland regions of eastern and southern Africa have shown that combining rainwater harvesting, in-situ soil moisture conservation and drought-tolerant crops such as sorghum, cowpea and millet within vegetable-based cropping systems substantially improves productivity compared with conventional farming practices. These findings emphasize that integrating complementary agronomic and varietal interventions provides greater resilience than implementing individual measures in isolation (Kugedera and Naik, 2026)^[27].

A systematic review of climate adaptation practices in African vegetable farming systems further revealed that technological interventions, particularly improved irrigation systems and stress-tolerant cultivars, represent the most widely adopted adaptation measures. Behavioural and ecosystem-based approaches are also gaining importance, whereas institutional support mechanisms remain

comparatively underrepresented. The review additionally identified urban and peri-urban vegetable production as an important yet relatively neglected area of climate adaptation research. Likewise, bibliometric analyses of climate adaptation research among smallholder farmers in southern Africa indicate that technological and agronomic solutions have received considerably greater attention than institutional, financial and digital extension strategies (Kori *et al.*, 2024)^[28]. Strengthening these underexplored areas will be essential for achieving comprehensive and sustainable climate resilience in vegetable production systems.

Conclusion

Vegetable production is highly susceptible to the impacts of climate change while remaining indispensable for ensuring food, nutritional and livelihood security. This dual significance highlights the need for the rapid development and widespread adoption of climate-resilient production systems. Sustainable resilience cannot be achieved through a single practice alone; rather, it depends on the coordinated application of multiple approaches, including climate-resilient cultivars, improved crop and water management, biological inputs, ecological farming practices, efficient post-harvest technologies and supportive economic and policy interventions. These strategies should be adapted to specific agro-climatic conditions and aligned with the socio-economic realities of farming communities. Furthermore, strengthening seed production and distribution systems, enhancing extension services, expanding post-harvest infrastructure, promoting climate risk management tools and encouraging participatory and gender-inclusive research is equally important. When combined with continuous scientific innovation, these integrated measures will play a vital role in maintaining vegetable productivity, improving produce quality and securing farmers' livelihoods in the face of ongoing climate change.

Table 1: Major climatic stresses in vegetable cultivation and corresponding resilience strategies

Climatic Stress	Principal Effects on Vegetable Crops	Representative Resilience Strategies
Heat stress	Pollen sterility, flower/fruit drop, premature bolting, reduced fruit set and quality	Heat-tolerant cultivars, shade nets, adjusted transplanting dates, foliar potassium/salicylic acid sprays
Drought	Reduced turgor, stomatal closure, lower photosynthesis, yield and quality decline	Drip irrigation, mulching, drought-tolerant rootstocks and varieties, PGPR/biostimulant seed and soil treatment
Waterlogging	Root anoxia, nutrient uptake failure, wilting, increased soil-borne disease incidence	Raised beds, sub-surface drainage, flood-tolerant rootstocks, timely field drainage
Salinity	Osmotic stress, ionic toxicity, leaf scorch, stunted growth, reduced fruit size	Salt-tolerant varieties/rootstocks, gypsum and organic amendments, controlled fertigation
Elevated CO ₂	Transient biomass gain offset by micronutrient dilution in edible parts	Balanced nutrient management, biofortified and nutrient-dense cultivars
Shifting pest/disease pressure	Range expansion of vectors and pathogens, altered outbreak timing	IPM, resistant varieties, pheromone traps, community pest surveillance and early warning

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Consent for publication

All authors consent the publication of the current article.

Competing Interests

The authors declare no competing interests.

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