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Review Article

Abiotic Stress in Vegetable Crops: Challenges and Strategies

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Abstract

In view of increasing challenges posed by abiotic factors owing to changing environmental conditions, the total production of vegetables are likely to get significant setback, which has potential to give a ruinous blow to the efforts being taken for food security. In this context, understanding various stresses by vegetable crops and devising and adopting the innovative means for their timely and effective mitigation would be a pragmatic approach in order to better equip farming communities against such impending challenges. The present review is a small yet noteworthy action towards sensitizing the stakeholders about imminent threats proffered by environmental stresses to a successful vegetable crop production.

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Introduction

Abiotic stress is the negative impact of environmental factors on plants. Abiotic stress such as, drought, high soil salinity, high temperature, cold, oxidative stress and heavy metal toxicity are the common adverse environmental conditions (Table 1) that affect and limit crop productivity worldwide [1,2]. In addition, declining water resources, deforestation and inadvertent climate change may further increase the risk of exposure of plants to abiotic stresses. Ever since the industrial revolution started i.e., approximately 200 years ago, global atmospheric CO2 has increased from 270 to 401ppm, whereas the average global temperature has risen by 0.85 °C [3]. It is expected that by the end of this century, CO2 will increase up to 700ppm, and global temperatures are projected to rise by 4 °C or more based on current greenhouse gas emission [3]. Vegetables confer immense health benefits to humans when consumed regularly. Vegetables are an important component of human nutrition that are a rich source of fiber, protein, vitamins, antioxidants, carbohydrates and minerals [4]. Such diverse bioactive compounds confer immunomodulation and prevention against infections and non-communicable diseases. India is the second largest producer of vegetables after China with a production of 197.23 million tons from an area of 10.97 million ha area. In the total horticulture production, 59.58% contribution is from vegetables [5]. Most of the vegetables are sensitive to environmental extremes due to succulent in nature, shallow root system and vulnerability to attack of pests and diseases. Worldwide, increasing temperatures, reduced irrigation water availability, flooding and salinity are major limiting factors for sustaining and increasing vegetable productivity. Abiotic stressors cause morphological, biochemical, physiological and molecular changes in vegetable crops, leading to a significant crop loss. Environmental stresses like drought and flood together inflict huge losses worldwide as per FAO estimates. The global losses due to drought were assessed to be USD 37 billion, while that of flood is USD 21 billion. Other stresses too contribute in varying degrees to total crop losses.

Table 1: Environmental factors affecting vegetable production.

S. No.	Environmental Factors
1	High temperature (heat stress)
2	Low temperature (chilling injury and frost)
3	Water stress (drought /waterlogging or flooding)
4	Salinity and alkalinity
5	Light (high/ low radiations)
6	Nutrient deficiency in soil
7	Chemicals and pollutants (heavy metals, pesticides and aerosols)
8	Extreme weather (avalanche, hail storm, thunder storm, dust storm, cyclones, tidal waves, etc.)
9	High wind velocity

Abiotic stresses may trigger a series of responses in plants including changes in gene expression and cell metabolism. The duration, severity and frequency of stress, and the affected organs and tissues, developmental stage and genotype also influences plant responses to abiotic stresses [6,7] (Saeed et al. 2019). Some environmental factors, such as air temperature can become stressful in just a few minutes; others such as soil water content may take days to weeks, and factors such as soil mineral deficiencies can take months to become stressful. Abiotic factors are the major limitation to crop production worldwide. The abiotic stresses like temperature (heat, cold chilling/frost), water (drought, flooding/ hypoxia), radiation (UV, ionizing radiation), chemicals (mineral deficiency/excess, pollutants heavy metals/ pesticides, gaseous toxins), mechanical (wind, soil movement, submergence), etc. are responsible for over 50% reduction in agricultural production. These comprise mostly of high temperature (40%), salinity (20%), drought (17%), low temperature (15%) and other forms of stresses [8]. It is estimated that less than 10% of the world's arable lands may be free of major environmental stresses, with drought and salinity stresses being the most widespread. As per the ICAR estimates (2010), 120.8 million ha constituting 36.5% of the geographical area in India is degraded due to soil erosion, salinity/alkalinity, soil acidity, waterlogging, and other edaphic problems. In the present manuscript, we have attempted to prepare a comprehensive review based on the available literature on challenges of various abiotic stresses experienced in vegetable cultivation. Besides discourse on such challenges, the present review includes the means of overcoming stress in a holistic manner. Such information is likely to help the readers and growers involved in vegetable production immensely.

Temperature stress

High temperature stress: High temperature affects vegetable crops in several ways. Increase in temperatures can reduce crop duration, increase plant respiration, alter photosynthesis process, affect the survival and distribution of pest population, hasten nutrient mineralization in soil, increase evapo-transpiration, etc [9]. Sudden rise in maximum temperatures in India during March 2004 affected mustard, pea, tomato, onion, garlic and other winter season vegetable crops considerably. High temperature (HT) causes reduction in pollen formation or viability in tomatoes at temperature above 37 °C. Fruit set in tomato occurs only when night temperatures ranging between 12.8-24 °C. The typical red colour of most tomato cultivars does not develop when temperatures go above 30 °C, but yellow pigment continues to develop. Fruit cracking in tomato occurs, if high temperature (above 32 °C) is accompanied with high humidity. Also, extreme high or low temperatures which interfere with pollination, low light, excessive nitrogen and heavy rainfall contribute to puffiness in tomatoes. Sun burning in tomato occurs, if fruits are exposed above 45 °C for 4 hours. In sweet pepper, the optimum temperature for growth ranges between 20 and 25 °C. When the temperature falls below 15 °C or exceeds 32 °C, growth is usually retarded and yield decreases. High temperature (29/23 °C D/N) reduces per cent fruit set and size significantly in sweet pepper as compared to optimum (24/18 °C D/N) temperature condition [10]. In pepper, there is blossom drop if day temperature is 33 °C or above or night temperature remain above 26.5 °C. Hot chili does not set fruit well when night temperatures are greater than 24 °C. Moderate HT stress (32/26 °C D/N) in bell pepper, one week before anthesis remarkably reduced the pollen germination and seeds in fruits [11]. HT increases capsaicin biosynthesis in capsicum, but floral abortion occurs when temperatures exceed 30 ºC. During ripening red colour development in capsicum is inhibited above 27 ºC. In common bean, HT stresses (35/20 °C D/N) during anthesis reduce pollen germination, pollen tube growth, fertilization, pod and seed set. In broccoli and cauliflower, temperature above 29 °C can triggered flowers too soon and causes heat injury, yellowing/ browning and loosening of head. If the temperature is more than 25 °C there is bolting in European cauliflowers, Asiatic carrots and broccoli. At HT, poor pollination occurs in many crops grown for seed (lettuce, sweet corn, cucurbits and carrot). HT induces floral differentiation and flower stalk development in lettuce plants, both of which decrease yield and quality of the crop. In onion and garlic, very high temperature (>42 °C) during bulb maturity (April-May) causes reduction in bulb size and poor post-harvest life in storage. In potato, HT brings about marked morphological changes like etiolated growth with smaller size leaflets in addition to reduction in tuber number and size. Tuber productions in potato totally stops at temperature of about 29 °C.

Low temperature stress: Low temperature (chilling / freezing) injury can occur in all plants, but the mechanisms and types of damage vary considerably. Many vegetables of tropical origin experience physiological damage when subjected to temperatures below 12 °C (well above freezing temperatures). Chilling injury is damage to plant parts caused by temperatures above the freezing point (0 °C) [12,13]. Frost and freeze injury are closely related. Frost damage occurs during a radiation freeze, while freeze damage occurs during an advection freeze. In both cases, ice crystals form in plant tissues, dehydrating cells and disrupting membranes. Tropical vegetables can endure temperatures below 10 °C, but above freezing for few hours without any harmful effect, if warm temperatures soon follow the low temperature exposure. In vegetables, susceptibility to cold and chilling temperature varies with species and stage of plant development; flowering and fruit development are highly susceptible [14]. Frost sensitive crops are adversely affected by periods of low temperatures. These conditions can be associated with low night temperatures and warm days. Low temperatures can also adversely affect flowering and fruit set in crops such as beans, tomatoes and most cucurbits [15]. Short term fluctuations in lower temperatures and the associated impact of chilling, frost, fogginess and impaired sun-shine may sometimes cause heavy loss to agriculture, as was case in northern and north-eastern region of India during winter of 2002-2003. As a consequence of this cold wave, about 600ha of fruit orchard (more particularly newly planted) were severely damaged in the Shiwalik belt of Punjab. In Agra region of Uttar Pradesh, there was 100% damage to brinjal, 80% tomato and 25% to potato. Similarly, the occurrence of frost during January 2008 in Rajasthan has resulted in total loss of mustard and cumin. Temperature range below optimum affects both photosynthesis and respiration, but rate of decrease is more for photosynthesis. Further, the rate of protein synthesis in the development of new cells is also decreased. In the upper range of optimum night temperature, vigorous vegetative growth takes place, if there is high rate of photosynthesis and normal rate of respiration during daytime. On the contrary, at lower range of night temperature, moderately vigorous vegetative growth is induced with consequent storing of more carbohydrate. This situation is ideally conceived in potato, sweet potato and yam. Thus, ideal crop growth and yield may be achieved if upper range of optimum night temperature in the early vegetative phase and lower range of the optimum night temperature in the late vegetative phase and reproductive phase of the crop are prevailed. Low temperatures reduce growth rate. In lettuce, temperatures below 13 °C sharply reduce plant growth and N uptake. In addition, many crops experience photomorphogenic changes at low temperatures. In biennials, such as onions and Cole crops, exposure to too low temperatures can lead to premature flowering.

Common injury symptoms in edible part of vegetables exposed to freezing: Asparagus: Tip becomes limp and dark; the rest of the spear is water-soaked. Thawed spears become mushy.

a) **Beet:** External and internal water-soaking; sometimes blackening of conducting tissue.

Broccoli: The youngest florets in the center of the curd are most sensitive to freezing injury. They turn brown and give off strong odors upon thawing.

b) **Cabbage:** Leaves become water-soaked, translucent, and limp upon thawing; epidermis separates.

Carrot: Blistered appearance, jagged lengthwise cracks. The interior becomes water-soaked and darkened upon thawing.

c) **Cauliflower:** Curds turn brown and have a strong off-odor when cooked.

d) **Celery:** Leaves and petioles appear wilted and water-soaked upon thawing. Petioles freeze more readily than leaves.

e) **Garlic:** Thawed cloves appear greyish-yellow and water-soaked.

f) **Lettuce:** Blistering; dead cells of the separated epidermis on outer leaves become tan; increased susceptibility to physical damage and decay.

g) **Onion:** Thawed bulbs are soft, greyish-yellow, and water-soaked in cross-section; often limited to individual scales.

h) **Potato**: Freezing injury may not be externally evident but shows grey or bluish-grey patches beneath the sink. Thawed tubers become soft and watery.

i) **Radish:** Thawed tissues appear translucent; roots soften and shrivel.

j) **Sweet pepper:** Dead, water-soaked tissue in part or all of pericarp surface; pitting, shriveling and decay follow thawing.

k) **Tomato:** Water soaked and soft upon thawing. In partially frozen fruits, the margin between healthy and dead tissue is distinct, especially in green fruits.

l) **Turnip:** Small water-soaked spots or pitting on the surface. Injured tissues appear tan or grey and give off an objectionable odor.

Water stress

Water stress denotes both drought stress and flooding or waterlogging situations. Indian agriculture is highly prone to drought, as almost two-third of the agricultural lands in India is rainfed. India has experienced droughts in 2002, 2004, 2006, 2009, 2010 and 2012, while floods in 2005, 2006, 2008, 2010, 2013, 2017 and 2022. Waterlogging/ flooding is also a major problem in many part of the country, particularly in the eastern part.

Drought stress: Water is important for all physiological processes of plants as it is a medium for transporting metabolites and nutrients. Drought is a situation that lowers plant water potential and turgor to the extent that plants face difficulties in executing normal physiological functions [16]. Unpredictable drought is the most important factor affecting world food security and the catalyst of the great famines of the past. Drought occurs in many parts of the world every year, frequently experienced in the field grown plants under arid and semi-arid climates. Regions with adequate but non-uniform precipitation also experience water limiting environments. Vegetables consist of more than 90% water, and drought stress at any stage greatly influence vegetable productivity and quality. Drought stress causes an increase of solute concentration in the soil environment, leading to an osmotic flow of water out of plant cells. This leads to an increase of the solute concentration in plant cells, thereby lowering the water potential and disrupting membranes and cell processes such as photosynthesis [17]. The timing, intensity, and duration of drought spells determine the magnitude of the effect of drought. Soil moisture deficit at critical growth stages such as active growth, flowering and fruit enlargement greatly reduces vegetable production and product quality. Low fruit set in tomato and chili, splitting in tomato, cabbage, nitrate toxicity in root vegetables and watermelon, bitterness, and crooked fruits in cucumber, etc. are some important consequence of drought stresses. In vegetable crops, there are critical phases of plant growth when irrigation cannot be avoided; otherwise, higher yield loss and quality may be expected. The critical period of water requirement and its impact on important vegetable crops have been summarized in Table 2 [18].

Table 2: Critical stages of drought stress and its impact on vegetable crops Adopted from Bahadur et al. [18].

Vegetable	Critical Stage of Water Requirement	Impact of Water Deficit
Tomato	Flowering and period of rapid fruit enlargement	Flower shedding, lack of fertilization, reduced fruit size, fruit splitting and development of calcium deficient disorder blossom end rot (BER)
Brinjal	Flowering and fruit development	Reduced yield with poor colour development in fruits
Chilli and capsicum	Flowering and fruit set	Shedding of flowers and young fruits, reduction in dry matter production and nutrient uptake
Cabbage and cauliflower	Head/ curd formation and enlargement	Tip burning and splitting of head in cabbage; browning and buttoning in cauliflower
Carrot, radish and turnip	Root enlargement	Distorted, rough and poor growth of roots, strong and pungent odor in carrot, accumulation of harmful nitrates in root
Cucumber	Flowering as well as throughout fruit development	Deformed and non-viable pollen grains, bitterness and deformity in fruits
Onion	Bulb formation and enlargement	Splitting and doubling of bulb, poor storage life
Okra	Flowering and pod development	Considerable yield loss, development of fibers, high infestation of mites
Melons	Flowering and evenly throughout fruit development	Poor fruit quality in muskmelon due to decrease in TSS, reducing sugar and ascorbic acid, increase nitrate content in watermelon fruit
Lettuce	Consistently throughout development	Toughness of leaves, poor plant growth, tip burning
Pea	Flowering and pod filling	Reduction in root nodulation and plant growth, poor grain fill
Potato	Tuberization and tuber enlargement	Poor tuber growth and yield, splitting
Leafy vegetables	Throughout growth and development of plant	Toughness of leaves, poor foliage growth, accumulation of nitrates

Waterlogging or flooding stress: More erratic and uneven distribution of rainfall would cause drought and flooding as well. Vegetable production in the tropics is often limited during the rainy season due to excessive moisture brought about by heavy rain. Waterlogging is one of the most hazardous natural occurrences, which can also be called as flood, submergence, soil saturation, anoxia and hypoxia, which are generally used to describe waterlogging conditions depending upon the moisture or water level on the field [19]. Waterlogging and flooding are common in rain-fed ecosystems, especially in soils with poor drainage. In India, about 12m ha area is waterlogged and floods prone, where the productivity of arable crops gets severely affected. Both flooding and waterlogging can seriously reduce yield. Flooding can result in yield reduction from 10% up to 40% in severe cases [20]. Most vegetables are highly sensitive to flooding and genetic variation with respect to this character is limited. In general, damage to vegetables by excessive soil moisture is due to the reduction of oxygen in the root zone which inhibits aerobic processes. Flooded tomato plants accumulate endogenous ethylene that causes damage to the plants. Low oxygen levels stimulate an increased production of the ethylene precursor, 1-aminocyclopropane-1-carboxylic acid (ACC) in the roots. The rapid development of epinasty growth of leaves is a characteristic response of tomato to waterlogged conditions and the role of ethylene accumulation has been implicated. The severity of flooding symptoms increases with rising temperatures; rapid wilting and death of tomato plants is usually observed following a short period of flooding at high temperatures [21].

In general, if flooding or waterlogging lasts for less than 48 hours, most vegetable crops can recover. Longer periods will lead to high amounts of root death and lower chances of recovery. There has not been much research on flooding effects in vegetables; however, some physiological effects that have been documented are given as follows:

A. Oxygen starvation in tuber crops such as potato leads to cell death in tubers and storage roots. This appears as dark or discolored areas in the tubers or roots. In carrots and other root vegetables, the tap roots often die leading to the formation of unmarketable fibrous roots.

B. Lack of root function and movement of water and calcium in the plant leads to calcium related disorders; most notably incidence of blossom end rot (BER) in tomato, pepper, watermelon, and several other susceptible crops.

C. Leaching and denitrification losses of nitrogen and limited nitrogen uptake in flooded soils also lead to nitrogen deficiency in most vegetable crops.

D. In bean crops, flooding or waterlogging has been shown to decrease flower production and increase flower and young fruit abscission or abortion.

E. Ethylene buildup in saturated soil conditions can cause leaf drop, flower drop, fruit drop, or early plant decline in many vegetable crops.

F. In tomato and other vegetables, flooding stress causes deleterious symptoms such as epinasty, leaf chlorosis, necrosis and reduced fruit yield.

Light stress: Light intensity is the number of quanta or photon light falling on any surface. In general, 10000 lux is regarded as low light intensity, whereas; 50000 lux or more is known as high intensity. The rate of photosynthesis of plants is proportional to the intensity of light up to about 1200ft-c. Photosynthesis is negligible at about 5 lux, and the light compensation points for many crop species is about 1000 lux or 1200-foot candles. At this light intensity, the rate of net photosynthesis is zero. Optimum light intensity is the range in which rate of gross photosynthesis is high and rate of respiration is normal, resulting in higher net photosynthesis in particular crop (Table 3). Most of the vegetables, including root crops require high light intensity of 3000-8000-foot candles. Leafy vegetables can be grown in partial shading, but vegetables producing fruits requires full sunlight. Consequences of growing vegetables under the light intensity below the optimum range are:

Table 3: Physiological response of plant to certain light wavelengths.

Wavelength (nm)	Effect
720-1000	Stem elongation, germination inhibition of certain seeds, stimulation of onion bulging
650-690	Suppression of onion bulging, lycopene synthesis in tomato, flower initiation in long day plants, flower inhibition of short-day plant, promotion of germination, promotion of anthocyanins
440-655	Photosynthesis occurs
445-660	Chlorophyll formation takes place
350-500	Phototropism response

a) Reduction in chlorophyll content of the leaves.

b) Reduction in the number of palisade cells in the leaves.

c) Reduction in the rate of photosynthesis.

d) Reduction in growth and yield.

Similarly, when the vegetable crops are grown in excess light intensity above the optimum range the probable consequences are:

a) Reduction in chlorophyll content of the leaves.

b) Reduction in the rate of photosynthesis.

c) In most cases, high light intensity is of little use photosynthetically because light harvesting system captures light energy much faster than its utilization for transformation to chemical energy.

d) Increase in rate of respiration resulting in less net photosynthesis.

e) Increase in leaf temperature induces high rate of transpiration resulting in high water demand.

f) In some cases, strong irradiance inactivates some enzyme system.

g) Reduction of yield in most cases.

h) Increase in the number of male flowers in monoecious cucurbits.

The duration of light (photoperiodism) is also important for the performance of some vegetable crops. Photoperiod influences growth and development of the crop in various ways like induction of flowering, carbohydrate production, development of storage organs and sex expression in cucurbits. Relative length of light and dark period determines the flowering in some vegetable crops, while in others; photoperiod has no effect on flowering.

Salinity stress: As per FAO (2008) estimate, over 6% of the world's land is salt affected. In addition, out of 230 million hectares of irrigated land, 45 million hectares (≈20%) are salt affected. In India, the crop productivity of 6.73m ha land is limited by the existence of salinity/alkalinity. Similarly, about 12m ha of acidic soils (pH <5.5) suffer from deficiencies as well as toxicities of certain nutrients and have very low productivity. Generally, dryland salinity has categorized into three different types: low salinity (ECe 2-4dS/m), moderate salinity (ECe 4-8dS/m) and high salinity (ECe > 8dS/m). Excessive soil salinity reduces productivity of many agricultural crops, including most of the vegetables [22]. Salinity fluctuates with the season, being generally high in the dry season and low during rainy season when freshwater flushing is prevalent. In hot and dry environments, high evapotranspiration results in substantial water loss, thus leaving salt around the plant roots which interferes with the plant's ability to uptake water. Physiologically, salinity imposes an initial water deficit that results from the relatively high solute concentrations in the soil, causes ion-specific stresses resulting from altered K^+/Na^+ ratio, and leads to a buildup in Na^+ and Cl^- concentrations that are detrimental to plants [23,24]. Plant sensitivity to salt stress is reflected in the loss of turgor, growth reduction, wilting, leaf curling and epinasty, leaf abscission, decreased photosynthesis, respiratory changes, loss of cellular integrity, tissue necrosis, and potentially death of the plant [25]. The threshold salinity level and salt tolerance ability of different vegetables has been summarized under Table 4.

Table 4: Salt tolerance index of vegetables.

Crop		Salt Tolerance Parameters		
Vegetables Common name	Botanical name	Threshold ECe (dS m^{-1})a	Slope (% decline per dS m^{-1})	Rating
Sugar beet	*Beta vulgaris L.*	7	5.9	T
Broad bean	*Vicia faba L.*	1.6	9.6	MS
Indian bean	*Lablab purpureus (L.) Sweet*	-	-	MS
Asparagus	*Asparagus officinalis L.*	4.1	2	T
Common Bean	*Phaseolus vulgaris L.*	1	19	S
Lima Bean	*P. lunatus L.*	-	-	MT*

Broccoli	*Brassica oleracea L. (botrytis group)*	2.8	9.2	MS
Brussels sprouts	*B. oleracea L. (gemmifera group)*	-	-	MS*
Cabbage	*B. oleracea L. (capitata group)*	1.8	9.7	MS
Carrot	*Daucus carota L.*	1	14	S
Cauliflower	*Brassica oleracea L. (botrytis group)*	-	-	MS*
Celery	*Apium graveolens L. var. dulce*	1.8	6.2	MS
Cowpea	*Vigna unguiculata (L.) Walp.*	4.9	12	MT
Cucumber	*Cucumis sativus L*	2.5	13	MS
Brinjal	*Solanum melongena L.*	1.1	6.9	MS
Garlic	*Allium sativum L.*	1.7	10	MS
Lettuce	*Lactuca sativa L*	1.3	13	MS
Muskmelon	*Cucumis melo L. (reticulatus group)*	1	8.4	MS
Okra	*Abelmoschus esculentus (L.) Moench*	-	-	MS
Onion	*Allium cepa L.*	1.2	16	S
Pea	*Pisum sativum L.*	3.4	10.6	MS
Pepper	*Capsicum annuum L.*	1.5	14	MS
Potato	*Solanum tuberosum L.*	1.7	12	MS
Pumpkin	*Cucurbita pepo L.var. Pepo*	-	-	MS*
Radish	*Raphanus sativus L.*	1.2	13	MS
Spinach	*Spinacia oleracea L.*	2	7.6	MS
Sweet potato	*Ipomoea batatas (L.) Lam.*	1.5	11	MS
Tomato	*Solanum lycopersicum (L.)*	2.5	9.9	MS
Turnip	*Brassica rapa L. (rapifera group)*	0.9	9	MS

S: Sensitive; MS: Moderately sensitive; MT: Moderately tolerant; T: Tolerant.

[a]In gypsiferous soils, plants tolerate EC_e about $2dSm^{-1}$ higher than indicated.

[1]Pessarakli M (Ed.), 1999. Handbook of plant and crop stress. Marcel Dekker, Inc. NY. pp: 177-183.

Elevated CO_2 stress: Carbon is a principal element of life, as it comprises a major part of the dry mass in living organisms. Carbon is required by green plants, taking up CO_2 from the surrounding air. The average atmospheric CO_2 concentration is around 350µmol mol^{-1} and has increased by about 70µmol mol^{-1} in the last 200 years. In the future, owing to anthropogenic processes (mainly fossil fuel combustion and forest destruction), the CO_2 concentration is expected to continue to rise (the recent rate of the increasing CO_2 concentration is about 1.8µmol mol^{-1} $year^{-1}$. Crops may be benefited from increased CO_2 concentration as results of global warming. Exposure of the crop with elevated CO_2 levels (carbon fertilization) may stimulate crop growth. Crop growing in enriched CO_2 levels exhibits increased rate of photosynthesis, higher leaf area, water use efficiency and ultimately higher crop yields [26]. In cassava, elevated CO_2 levels (700ppm) increased dry weight of tuber by 8 folds while WUE by two times. The carotene, starch and glucose content of sweet potato are observed to increase with enhanced CO_2 levels. Similarly, in tomato and eggplant, an increase of 25-30% in yields was noticed with an increase CO_2 concentration in polyhouse. CO_2 concentration at supra-optimal level may limit vegetable production. The optimal CO_2 concentration for the growth and yield lies between 700 at 900µl L^{-1}. A healthy crop growth in greenhouses can be achieved by injecting 1000-1500ppm CO_2 using propane burners or other CO_2 generators. Lettuce yield is known to increase by more than 30% at 1600ppm CO_2 [27,28]. The significant positive effects of CO_2 have been reported as increased plant height, number of leaves, lateral branching, advanced flowering date, high fruit numbers and fruit yield, and better-quality fruits (Figure 1).

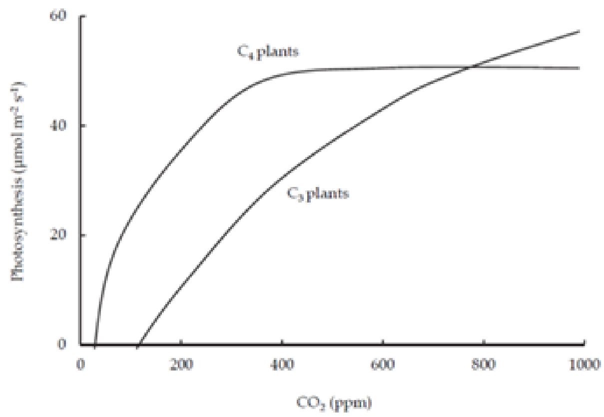

Figure 1: Effect of elevated CO_2 on photosynthesis of C_3 and C_4 plants [29].

Strategies to Alleviate the Effect of Abiotic Stresses

Plants exposed to abiotic stresses produce Reactive Oxygen Species (ROS) or free radicals as a byproduct in various cellular parts, especially mitochondria and chloroplasts in association with different kinds of oxidases [30,31]. These ROS are important for signaling in several growth and developmental processes and in severe abiotic stresses programmed cell death occurs [32]. But when ROS are present in excess quantities, they cause severe damage to cellular structure and macromolecules. There are many scavenging systems comprising of antioxidants and enzymes counter these ROS and convert them into less toxic products in the cell [33]. Measures to adapt abiotic stresses are critical for sustainable vegetable production. Until now, the scientific information on the effect of environmental stresses on vegetables is overwhelmingly on tomatoes. There is a need to do more research on how other vegetable crops are affected by increased abiotic stresses as a direct potential threat from climate change. Farmers in developing countries of the tropics need tools to adapt and mitigate the adverse effects of abiotic stresses on agricultural productivity, and particularly on vegetable production, yield and quality. However, farmers in developing countries are usually small holders, 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 used to increase the resilience of farms in less developed countries.

Plant's strategies to cope with drought normally involve a mixture of stress avoidance and tolerance strategies. Early responses of plants to drought stress usually help the plant to survive for some time. The acclimation of the plant to drought is indicated by the accumulation of certain new metabolites associated with the structural capabilities to improve plant functioning under drought stress. Drought avoidance is usually achieved through morphological changes in the plant, such as reduced stomatal conductance, decreased leaf area, development of extensive root systems and increased root/shoot ratios. On the other hand, drought tolerance is achieved by cell and tissue specific physiological, biochemical and molecular mechanisms, which include specific gene expression and accumulation of specific proteins. Drought stress can be mitigated by making provision of water harvesting in micro and/ or macro catchments, supplemental irrigations at critical crop stages (flowering and fruit enlargement), minimum or zero tillage, furrow irrigated raised bed practice, drip irrigation, mulching and growing of drought tolerant/ escaped vegetable cultivars. Experimental findings obtained at ICAR-IIVR revealed that growing tomato on raised bed and mulching with paddy straw mulch (7.5 tones/ha) can save around 49% water and enhance yield by 55% [34]. Use of organic mulches (7.5-10 tones/ha) or plastic mulch, particularly of black polythene (25-40 microns) can reduce the water requirements of the crop by 20-35%, and thereby drought tolerance. Growing vegetable crops on raised bed, light soils and under rain shelter structures are some measures to mitigate the effect of food or water stagnation. Grafting can provide tolerance to flooding if appropriate tolerant rootstocks are used. Grafting experiments related to waterlogging tolerance were conducted at ICAR-IIVR, Varanasi revealed that using brinjal as rootstocks (IC 111056 and IC 354557), the high yielding tomato scions (Arka Rakshak, Arka Samrat and Kashi Aman) can survive waterlogging condition 48HR during early growth stage and 96-120HR during reproductive stage without significant reduction in yield [35,36].

The detrimental effect of high temperature and light can manage through making provision of various protective structures such as shading net, green house, appropriate irrigation scheduling, development of tolerant vegetable cultivars, etc. At ICAR-IIVR, Varanasi 250 lines (cultivated and wild) evaluated for heat tolerance both in field and temperature gradient tunnels condition. Among these, 9 lines, EC-538380, CLN-1621, EC-620421, EC-620419, EC-620438, CLN-2026, EC-538441, VRT-101A and Sun-cherry were able set fruits at maximum temperature ranging between 35-38 °C [37]. Low temperature (frost, freeze and cold) effect may be counter by proper selection of vegetable varieties, use of hot caps and clothes, row cover, poly tunnels, plastic mulch, wind breaks or shelter belt, smokes, air mixing, frequent or sprinkler irrigation, etc. [38-43] (Table 5).

Table 5: Vegetables and their cultivars tolerance to drought stress condition in India.

Vegetable	Cultivars
Tomato (*Solanum lycopersicum*)	Pusa Ruby, Pusa Early Dwarf, S-12, Sel. 7
Chilli (*Capsicum annuum*)	Pusa Jwala, Sindhur, Pant C-1, Arka Mohini, Arka Gaurav, Arka Basant, Bharat, Indira, NP-46A, Titan
Cowpea (*Vigna unguiculata*)	Pusa Dofasali, Pusa Phalguni, Pusa Barsati, Pusa Rituraj, Kashi Kanchan, Kashi Shyamal, Kashi Gauri
Cluster bean (*Cyamopsis tetragonoloba*)	Pusa Sadabahar, Pusa Mausami, Pusa Navbahar, Durga Bahar
Brinjal (*Solanum melongena*)	Pusa Purple Long, Pusa Kranti, Pusa Anmol, Punjab Sadabahar, Arka Sheel, Arka Kusumakar, Arka Navneet, Arka Shirish
Okra (*Abelmoschus esculentus*)	Kashi Pragati, Kashi Vibhuti, Varsha Uphar, Hisar Unnat
Pumpkin (*Cucurbita maxima*)	Arka Chandan, Kashi Harit, Narendra Amrit, CO-1, CO-2
Amaranth (*Amaranthus spp.*)	Chhoti Chaulai, Badi Chaulai, CO-1, CO-2, CO-3
Muskmelon (*Cucumis melo*)	Pusa Sharbati, Pusa Madhuras, Hara Madhu, Punjab Sunehari, Durgapur Madhu, Kashi Madhu, Arka Rajhans, Arka Jeet, MHY-5
Watermelon (*Citrullus lanatus*)	Sugar Baby, Arka Manik, Arka Jyoti, Durgapur Meetha, Durgapur Kesar, Mateera
Ash gourd (*Benincasa hispida*)	Pusa Ujjwal, Kashi Dhawal
Pointed gourd (*Trichosanthes dioica*)	Narendra Parwal-260, Narendra Parwal-307, Rajendra Parwal-1, Rajendra Parwal -2
Snap melon (*Cucumis melo var. Momordica*)	Pusa Shandar
Long melon (*Cucumis melo var. utilissimus*)	Arka Sheetal, Punjab Long Melon-1, Pant Kakri-1
Round melon (*Praecitrullus fistulosus*)	Arka Tinda, Hisar Tinda, Punjab Tinda, Kashi Hari
Drumstick (*Moringa oleifera*)	PKM-1, PKM-2, Kokan Ruchira

Conclusion

In view of increasing challenges posed by abiotic factors owing to changing environmental conditions, the total production of vegetables are likely to get significant setback, which has potential to give a ruinous blow to the efforts being taken for food security. In this context, understanding various stresses by vegetable crops and devising and adopting the innovative means for their timely and effective mitigation would be a pragmatic approach in order to better equip farming communities against such impending challenges. The present review is a small yet noteworthy action towards sensitizing the stakeholders about imminent threats proffered by environmental stresses to a successful vegetable crop production.

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