Climate Change Impact on Vegetable Crops and Potential for Adaptation: A Review

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Abstract: Climate change is emerging as one of the major constraints for global food security and will become more prevalent in the coming years. Agriculture is one of the leading sectors to be affected by climate change. This review is concerned with climate change impacts on the production and quality of vegetables and the crucial need for adaptation. Fluctuations in daily mean, minimum and maximum temperature is the primary effect of climate change that unfavorably affects vegetable production since many plant physiological, biochemical and metabolic activities are temperature-dependent. Case studies concerning the effect of elevated temperature on major vegetable crops production were discussed. Increased CO_2 in atmosphere can cause direct effect on growth and development of vegetable plants. Evidence has shown that higher growth rates observed for plants grown under high CO_2 concentrations may result in denser canopies with higher humidity that favor pathogens. It is well documented that the rise in temperature adversely affects the activity of pollinating agents and hence lower seed yield. Climate changes can potentially cause postharvest quality alterations in vegetable crops on both perceived and nutritional quality. Climate change could improve some quality attributes resulting in the improvement of some nutritional traits however, negative effects could be observed on product appearance. In addition, climate change variables may have indirect effects through the incidence of diseases and insect pests. Potential impacts of climate change on agricultural sector will necessitate the need for adaption and mitigation of the adverse effects on agricultural productivity, and particularly on vegetable crops yield and quality. Means for adaption and mitigation may include improving vegetable production systems, better exploitation of biodiversity, applying biotechnology and genomic approaches, genetically engineering different stress tolerance and ultimately develop climate-resilient vegetables. A holistic approach is essential to overcome climate change impact on vegetable crops rather than a single approach.

Keywords: GHGs-Global Warming-CO_2- Climate Resilience- Biodiversity-Vegetables Yield- Vegetables Quality

PREFACE

Over the following decades, it is expected that billions of people, mostly those in developing countries, will face shortages of food as a result of climate change that are currently happening and will worsen in the upcoming decades. Due to its importance to human, agriculture was one of the leading sectors to be studied in terms of potential impacts of climate change (Gornall *et al.,* 2010). The consequences of climate changes on major and stable crops gained a substantial interest; however, vegetable crops did not receive a similar concern. This review is concerned with climate change impacts on the production of vegetables.

INTRODUCTION

Life on earth depends on naturally occurring greenhouse gases (GHGs), particularly carbon dioxide (CO_2) and methane, which are modulated by carbon cycle. Without these GHGs trapping heat, the earth's temperature would be, on average, 35°C colder (Maslin, 2004). The industrial era has interfered with this crucial cycle by consuming the carbon trapped in life to provide power to industries and boost development. Since the 1960s, evidence has been built up linking increased GHGs to increased global average temperatures (IPCC, 2014; Keller, 2007). Since the beginning of twenty one century, each monthly average land and ocean surface temperature has exceeded the average temperatures for the 20th century (Kokic *et al*., 2014) and recent patterns of climate change are contrasting past cycles. Many studies evidently determine that it is exceptionally likely that anthropogenic GHG emissions are the foremost motivation for global warming since the mid-20th century (Maslin, 2004; IPCC, 2014). The consequences of global climate change would have substantial effects on societies, economies and world health (Parise, 2018; Bhattacharyya, 2019).

The global average surface temperature has risen approximately 1.62°F (0.9°C) since the late 19th century, a change driven mainly by elevated carbon dioxide levels and other anthropogenic emissions into the atmosphere. Most of the warming occurred in the past 35 years, with the five warmest years on record taking place since 2010, with 2016 was the warmest year on record. The heat-trapping nature of carbon dioxide and other gases was confirmed in the mid-19th century. There is no question that elevated levels of greenhouse gases must cause the Earth to warm in response.

1. Physiological responses of vegetables to climate change:

1.1. Elevated CO_2:

The Earth's atmosphere consists basically of nitrogen (78.1%) and oxygen (20.9%) and minor amount of carbon dioxide (0.031%). The greenhouse effect is primarily a combination of the effects of water vapor, CO_2 and minute amounts of other gases (methane, nitrous oxide, and ozone) that absorb the

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radiation leaving the Earth´s surface (IPCC, 2001). The warming effect is explained by the fact that CO_2 and other gases absorb the Earth's infrared radiation, trapping heat. Since a significant part of all the energy emanated from Earth occurs in the form of infrared radiation, increased CO_2 concentrations mean that more energy will be retained in the atmosphere, contributing to global warming (Lloyd and Farquhar, 2008). Carbon dioxide concentrations in the atmosphere have increased approximately 35% (to 0.0417%) from pre-industrial times to 2005 (Lindsey, 2020; IPCC, 2007). Besides industrial activities, agriculture also contributes to the emission of greenhouse gases.

Changes in CO_2 concentration in the atmosphere can alter plant tissues in terms of growth and physiological behavior. Many of these effects have been studied in detail for some vegetable crops (Dong *et al*., 2018; Cure and Acock, 1986; Idso and Idso, 1994). These studies concluded, in summary, that increased atmospheric CO_2 alters net photosynthesis, biomass production, proteins, sugars and organic acids contents, stomatal conductance, firmness, seed yield, light, water, and nutrient use efficiency and plant water potential.

1.2. Elevated temperatures:

Elevated temperatures can increase the capability of air to absorb water vapor and, subsequently, create a higher demand for water. Higher evapotranspiration could suppress or deplete the water reservoir in agricultural soils, creating water stress in plants. It is well recognized that water stress not only reduces crop production but also tends to accelerate fruit ripening (Henson, 2008). Exposure to higher temperatures can cause morphological, anatomical, physiological, and, eventually, biochemical alterations in plant tissues and, accordingly, can disturb growth and development of various plant organs. These events can cause extreme reductions in marketable yield.

Vegetable growth and development are influenced by different environmental factors. During their development, high temperatures can affect photosynthesis, respiration, aqueous relations and membrane stability as well as levels of plant hormones, primary and secondary metabolites. Seed germination can be reduced or even inhibited by high temperatures, depending on the species and stress level (Motsa *et al.,* 2015; Carter and Vavrina, 2001; Bewley, 1997).

Most of the temperature effects on plants are mediated by their effects on plant biochemistry. Most of the physiological processes go on normally in temperatures ranging from 0°C to 40°C. However, basic temperatures for the development of vegetable crops are much narrower and, depending on the species and ecological origin, it can be pushed towards 0°C for temperate species from cold regions, such as carrots and lettuce. On the other hand, they can reach 40°C in species from tropical regions, such as many cucurbits (Went, 1953).

A general temperature effect in plants involves the ratio between photosynthesis and respiration. For a high yield, not only photosynthesis should be high but also the ratio photosynthesis/ respiration should be much higher than one. At temperatures around 15°C, the above mentioned ratio is usually higher than ten (Went, 1953).

Higher than normal temperatures affect the photosynthetic process through the modulation of enzyme activity as well as the electron transport chain (Sage and Kubien, 2007). Additionally, in an indirect manner, higher temperatures can affect the photosynthetic process increasing leaf temperatures and influencing stomatal conductance (Moore *et al.,* 2021; Lloyd and Farquhar, 2008).

1.3. Photosynthetic activity is proportional to temperature variations

High temperatures can increase the rate of biochemical reactions catalyzed by different enzymes. However, above a certain temperature threshold, many enzymes lose their function, potentially changing plant tissue tolerance to heat stresses.

Temperature is of paramount importance in the establishment of a harvest index. The higher the temperature during the growing season, the sooner the crop will mature. The production and quality of vegetable crops can be directly and indirectly affected by exposure to high temperatures and elevated levels of carbon dioxide and ozone (Mattos *et al.*, 2014). Wurr *et al.* (1996) reported that lettuce, celery and cauliflower grown under higher temperatures matured earlier than that the same crops grown under lower temperatures.

The above mentioned climate changes is evidently cause alterations in vegetable crops. The next article section reviews how changes in climate change can potentially impact the vegetable crops.

1.4. Climate change impacts on vegetable production systems:

Major climatic parameters which affect the vegetable crops production are temperature, CO_2 concentration in atmosphere and drought.

1.5. Temperature:

Fluctuations in daily mean, minimum and maximum temperature is the primary effect of climate change that unfavorably affects vegetable production since many plant physiological, biochemical and metabolic activities are temperature-dependent. Physiological disorders of various vegetable crops caused by high temperature are summarized in Table (1).

Case study of different vegetable crops:

1.5.1. Potato:

Potato is the most vulnerable vegetable crop for climate change due to its strict temperature and day length requirement for tuber formation. Increase in temperature favors the potato cultivation by prolonging the crop growing season in high altitudes and temperate regions of the world such as Europe and Russia, whereas, it disfavors the potato production by shortening the growing period in subtropical regions during winter season (Sandhu *et al.,* 2018; Ayyogari *et al.,* 2014). The optimum tuber formation takes place at 20°C and an increase in temperature of above 21°C causes severe reduction in the potato tuber yield while at 30°C complete inhibition of tuber formation occurs (Sekhawat, 2001). A moderate harvest index is recorded at 20°C night temperatures indicating that temperature stress is limiting the partitioning of photosynthates to the tubers while a low harvest index is recorded at more than 20°C night temperatures (Pandey *et al.,* 2009).

1.5.2. Tomato:

Vegetative and reproductive processes in tomatoes are strongly modulated by temperature only or in combination with other environmental factors (Sadashiva *et al.,* 2016). Elevated temperature can cause significant losses in tomato productivity due to decreased fruit set as well as lower quality fruits. Overall productivity is reduced by high temperatures due to bud drop, abnormal flower development viability, and reduced carbohydrate availability (Hazra *et al.,* 2007). Symptoms of high temperature stress on tomato are sunburn, disruption of lycopene synthesis, appearance of yellow areas in the affected tissues, poor fruit set, delay in ripening, yellow-shouldered fruit, white core and blossom-end rot (Trinklein, 2012; Kader *et al.,* 1974).

Fruit color is having significant importance in assessing the marketable quality of tomato. The optimum temperature for development of lycopene pigment in tomato is 25-30°C. Degradation of lycopene starts at above 27°C and it is completely destroyed at 40°C. Similarly high temperatures above 25°C affect pollination and fruit set in tomato (Kalloo *et al.,* 2001). Abnormal pollen production, abnormal development of the female reproductive tissues, hormonal imbalances and lower levels of carbohydrates and lack of pollination are responsible for the poor reproductive performance of tomatoes at high temperatures (Peet *et al.,* 1997). Lurie *et al.* (1996) reported high temperature inhibits ripening by inhibiting the accumulation of ripening related m-RNAs, thereby inhibits continuous protein synthesis including ethylene production, lycopene accumulation and cell-wall dissolution.

1.5.3. Strawberry:

Strawberry is highly sensitive to day and night temperatures and their interactions with other environmental factors, especially photoperiod. Higher temperatures alter morphological, anatomical, physiological, and ultimately, biochemical and molecular changes in strawberry plants (Palencia *et al.,* 2013). High temperatures reduced strawberry fruit size, weight, and caused irregular shaped fruit (Kadir *et al.,* 2006; Wang and Camp, 2000; Miura *et al.,* 1994). The reduced fruit size and weight can be attributed to lower dry matter accumulation due to higher fruit transpiration rate and decreased photosynthetic rates at higher temperatures (Miura *et al.,* 1994). Generally, cooler day/night temperatures favored plant and fruit growth, while rising temperatures resulted in smaller irregular shaped fruits. Higher temperatures could also affect fruit quality by reducing sweetness (Wang and Camp, 2000). It appears that strawberries grown at warmer day/ night temperatures produce more antioxidants as a defense mechanism in response to the applied stress (Wang and Zheng, 2001). Development of heat-tolerant strawberry will be essential to enable strawberry producers to adapt to the anticipated climatic changes (Gulen and Eris, 2004). Strawberry plants may cope with warmer environments on the basis of gene expressions responsible for the production of enzymatic antioxidants (Kesici *et al.*, 2020).

1.5.4. Cucumber:

In cucumber, rise in temperature has detrimental effect on sex expression, flowering, pollination, and fruit setting. High temperature and long day tend to keep the vines in male phase while encouraged more female flowers in short day low temperature condition. Fruit yield of cucumber decreased under high temperature (Meng *et al.,* 2004). Extremely high temperatures cause early flower drop in cucumber (Kumar *et al.,* 2011). Exposure of cucumber plants to heat stress during fruit development stage causes bitterness of fruits (Kumar *et al.,* 2011).

1.5.5. Other vegetables:

In pepper, exposure to high temperature at post-pollination stage inhibits fruit set (Erickson and Markhart, 2002). High temperature affects red color development in ripen chili fruits and also causes flower drop, ovule abortion, poor fruit set, size of fruits and fruit drop in chili (Saha *et al.,* 2010; Arora *et al.,*1987). During temperature stress, the fruit weight and the number of seeds per sweet pepper fruit were reduced (Thuy and Kenji, 2015).

The temperature fluctuations delay the ripening of fruits and reduce the sweetness in melons. Warm humid climate increase the vegetative growth and result in poor production of female flowers in cucurbitaceous vegetables like bottle gourd, pumpkin which causes low yield (Singh, 2010).

In snap bean, high temperatures will cause enhanced abscission of flower buds, flowers and young pods and reduce pod production, mature pod size and seeds per pod. Onsets of anthesis and pod development stages are most sensitive to high night temperature. Pods larger than 3 cm do not abscise but usually abort and shrivel under high night temperatures (Konsens *et al.,* 1991).

In okra, high temperatures cause poor germination of seed during spring summer season. Flower drop in okra is recorded at high temperatures above 42°C (Dhankhar and Mishra, 2001), whereas flower abscission and ovule abortion in French bean occurs at temperature above 35°C (Prabhakara *et al.,* 2001). Major symptoms of heat and solar injury of selected vegetable crops are summarized in Table (2).

Table (1): Physiological disorders of vegetable crops caused by high temperature (Adapted from Spaldon *et al.,* 2015)

Crop	Disorder	Caused Factor
Asparagus	High fiber in stalks and spheres	High temperature
Asparagus	Feathering Lateral branch growth	Temperature >32°C
Bean	High fiber in pods	High temperature
Carrot	Low carotene content	Temperature >20°C
Cauliflower	Blindness Buttoning Riceyness	Temperature fluctuation
Cauliflower, Broccoli	Hollow Stem Leafy heads No heads Branching	High temperature
Cole crops, Lettuce	Tip burn	High temperature
Tomato, Pepper, watermelon	Blossom end rot	High temperature, especially if combined with drought

Table (2): Major symptoms of heat and solar injury of selected vegetable crops (Adapted from Kader *et al.,* 1974; Woolf and Ferguson, 2000; Moretti *et al.,* 2010)

Snap bean	Brown and reddish spots on the pod; Spots can coalesce to form a water-soaked area.
Cabbage	Outer leaves showing a bleached, Papery appearance; Damaged leaves are more susceptible to decay.
Lettuce	Damaged leaves assume papery aspect; Affected areas are more susceptible to decay; Tipburn is a disorder normally associated with high temperatures in the field; It can cause soft rot development during postharvest.
Muskmelon	**Sunburn**: dry and sunken areas; green color and brown spots are also observed on rind.
Bell pepper	Sunburn: yellowing and, in some cases, a slight wilting.
Potato	**Black heart**: occur during excessively hot weather in saturated soil; symptoms usually occur in the center of the tuber as dark-gray to black discoloration.
Tomato	**Sunburn**: disruption of lycopene synthesis; appearance of yellow areas in the affected tissues.

1.6. Effect of atmospheric CO_2:

Increased CO_2 in atmosphere cause direct effect on growth and development of plants. Physiological parameters in vegetable crops affected by exposure to increased CO_2 levels are summarized in Table (3). Potato plants grown under elevated CO_2 may have larger photosynthetic rates up to some extent, later on with increase in CO_2 concentration the photosynthetic rates will be down (Burke et al., 2001). The high atmospheric CO_2 content inhibits tomato fruit ripening due to the suppression of the expression of ripening associated genes, which is probably related to the stress effect exerted by high CO_2 (Rothan *et al.,* 1997).

Researchers have shown that higher growth rates of leaves and stems observed for plants grown under high CO_2 concentrations may result in denser canopies with higher humidity that favor pathogens. Lower plant decomposition rates observed in high CO_2 situations could increase the crop residue on which disease organisms can overwinter, resulting in higher inoculum levels at the beginning of the growing season, and earlier and faster disease epidemics. Pathogen growth can be affected by higher CO_2 concentrations resulting in greater fungal spore production. However, increased CO_2 can result in physiological changes to the host plant that can increase host resistance to pathogens (Coakley *et al.,* 1999).

Table (3): Physiological parameters in vegetable crops affected by exposure to increased CO_2 levels (Adapted from Moretti *et al.,* 2010)

Parameter	Effect of high CO_2	Crop	Reference
Photosynthesis	up	Potato; spinach	Katnya *et al.* (2005), Jain *et al.* (2007)
Respiration	down	Asparagus; broccoli; mungbean sprout; tomato	Peppelenbos and Leven (1996)
	up	Potato; lettuce; eggplant; cucumber	Pal and Buescher (1993), Fonseca *et al.* (2002)
Stomatal conductance	down	Spinach	Jain *et al.* (2007)

1.7. Effect of Drought:

As average temperatures have risen due to climate change, an increase in the rate of evaporation from soil and transpiration from plants causing a drought condition has been recorded (EPA, 2021). Major morphological and physiological symptoms of selected vegetable crops caused by water stress are presented in Table (4). The prevalence of drought conditions adversely affects the germination of seeds in vegetable crops like onion and okra and sprouting of tubers in potato (Arora *et al.,* 1987). Potato is highly sensitive to drought. A moderate level of water stress can also cause reductions in tuber yield (Jefferies and Mackerron, 1993; Romero *et al.*, 2017). As succulent leaves are commercial products in leafy vegetables like spinach, the drought conditions reduce their water content thereby reduces their quality (Ors *et al*., 2017). Drought increases the salt concentration in the soil and affects the reverse osmosis of loss of water from plant cells. This leads to an increased water loss in plant cells and inhibition of several physiological and biochemical processes such as photosynthesis, respiration etc., thereby reduces productivity of most vegetables (Pena and Hughes, 2007).

Table (4): Morphological and physiological symptoms of vegetable crops caused by water stress (Adapted from Yadav *et al.,* 2012)

Vegetable	Symptoms
Eggplant	Reduced main stem Reduced no. of branches
Beans	Reduced no. of flowers Delayed flowering Reduction in seed yield Decreased starch content Decreased seed protein content
Potato	Yield loss Decreased starch content Increase in reducing sugars
Cauliflower	Ricey, leafy, loose, yellow, small and hard curds
Chard	Quick Bolting
Tomato	Blossom end rot Accumulation of free proline
Lettuce	Bitter taste Tipburn

2. Climate change impacts on vegetable pollination:

Pollination is a crucial stage in the reproduction of most flowering plants, including vegetable crops (Espíndola, 2021; Kearns *et al*., 1998). Change in the climate may be threatening to pollination activities due to altered behavior of pollinating agents (Memmott *et al*., 2007, Hegland *et al*., 2009, Schweiger *et al*., 2010). Among all the climatic factors, an increase in temperature has the highest adverse effect on pollinator interactions.

Rise in temperature adversely affects the activity of pollinating agents and hence lower seed yield. Climatic change, including global warming and increased variability of environmental hazards require improved analyses that can be used to assess the risk of the existing and the newly developed pollinators management strategies and techniques, and to define the impact of these techniques on environment, productivity and profitability (Lee *et al*., 2009). Many bee species are able to control the temperatures in their flight muscles before, during and after the flight, by physiological and behavior means (Willmer and Stone, 1997). With respect to the potential effects of future global warming, behavior responses of pollinator to avoid extreme temperatures have the potential effect on significant reduction of pollination services (Corbet *et al*., 1993). Examples of behavior strategies for thermal regulation include long periods of basking in the sun to warm up and shade seeking or nest returning to cool down, which reduces the floral visiting time of pollinators, thereby subsequent pollination and fruit or seed set (Willmer and Stone, 2004).

This topic was previously reviewed (Moretti *et al*., 2010; de La Peña and Hughes, 2007; Prasad and Chakravorty, 2015; Ayyogari *et al*., 2014; de La Peña *et al*., 2011; Bisbis *et al*., 2018; Mattos *et al*., 2014; Abou-Hussein, 2012; Srivarsha *et al*., 2018; Abewoy, 2018; McDonald and Warland, 2018; Spaldon *et al*., 2015; Ebert, 2017; Solankey *et al*., 2019).

3. Climate change impacts on vegetable quality:

3.1. Effect of Temperature:

The visible effects of high temperature on apparent and nutritional quality in selected vegetable crops are presented in Table (5). Sunburn is the most common temperature-induced disorder reported in vegetable crops (Woolf and Ferguson, 2000). Tissues exposed directly to sunlight can develop sunburn symptoms even in relatively low temperatures (25-30°C).

In certain vegetable crops, increased temperatures due to climate change could decrease the duration of their biological cycle resulting in deterioration of the quality related to the appearance-size of the marketable product. Common beans grown at temperatures exceeding 27/22°C (day/night) during seed development produced smaller seeds in contrast to beans grown at 21/16°C (Abdus Siddique and Goodwin, 1980). Short periods of excessive temperature were reported to accelerate the maturity of pea plants accompanied by reduced seed size (Bisbis *et al*., 2018). In head lettuce temperatures beyond 17-28/3-12°C (day/night) increased the portion of loose and puffy heads, tipburn and leaf chlorosis with an accumulation of bitter compounds (Wien, 1997). A reduced size of onions was reported when grown at 32°C instead of 27°C (Coolong and Randle, 2003). In leafy and brassica vegetables an increase in the tipburn disorder has been reported at high night temperatures (Saure, 1998). In tomato plant, high temperatures have been shown to lower macronutrients and carotene, lycopene and antioxidant content (Rosales *et al*., 2011). In asparagus the increased air temperature damages apparent quality and were associated with rapid head opening, purple discoloration, and undesirable fibers in asparagus spears (Peet and Wolfe, 2000).

Under certain conditions, increased temperatures due to climate change could result in an enhancement in the apparent and nutritional quality of vegetable crops. In carrots, antioxidants, components of essential oils related to flavoring attributes, are accumulated in high temperatures (Ibrahim *et al*., 2006). The carotene and antioxidant content in tomatoes has been found to increase at higher temperatures in comparison with tomatoes harvested at lower temperature periods (Rosales *et al*., 2011), and in lettuce the heat stress enhanced the tocopherol and antioxidants content (Oh *et al*., 2009).

Table (5): Effects of elevated temperatures on the perceived and nutritional quality of selected vegetables (Adapted from: Christopoulos and Ouzounidou, 2021)

Vegetable	Perceived Traits*	Nutritional Traits*	Literature
Asparagus	↓appearance (malformation, texture, browning)		Peet and Wolfe (2000)
Beans	↓appearance (size)		Abdus Siddique and Goodwin (1980)
Broccoli	↓appearance (skin disorders)		Saure (1998)
Cabbage	↓appearance (skin disorders)		Saure (1998)
Carrot		↑antioxidants	Ibrahim *et al.* (2006)
Lettuce	↓appearance (malformation, color), ↓taste	↑antioxidants	Oh *et al.* (2009), Saure (1998), Wien (1997)
Onion	↓appearance (size)		Coolong and Randle (2003)
Tomato		↓↑antioxidants, ↓macronutrients	Rosales *et al.* (2011)

*The symbol ↓denotes deterioration in the quality trait; the symbol ↑denotes improvement in the quality trait.

3.2. Effect of CO_2

Reports on the effects of elevated CO_2 concentrations on the apparent and nutritional quality of vegetable crops are relatively limited. The probable effects of elevated CO_2 levels on perceived and nutritional quality in selected vegetables are presented in Table (6).

Several studies, mostly with leafy vegetables, on the enriched CO_2 effects on product quality indicate a possible nutritional improvement resulting in enrichment in sugars, ascorbic acid, phenols, flavonoids, and antioxidants content (Bisbis *et al.*, 2018). In red leaf lettuce grown at 1000 ppm CO_2, increased sugars, flavonoids and caffeic acid derivatives were reported to increase (Becker Klaring, 2016). Higher vitamin C content has been observed in lettuce, celery, and Chinese cabbage grown at 800-1000 ppm CO_2 (Jin *et al.*, 2009).

Table (6): Effects of elevated atmospheric CO_2 on the perceived and nutritional quality of various vegetables (Adapted from: Christopoulos and Ouzounidou (2021), Moretti *et al.* (2010))

Vegetable	Perceived Traits*	Nutritional Traits*	Literature
Cabbage	↓taste (sugars)	↑vitamin C	Jin *et al.* (2009)
Chinese cabbage		↓nitrate	Jin *et al.* (2009)
Carrot		↓protein, ↓vitamin C, ↓macronutrients, ↓micronutrients, ↓fatty acids, ↓amino acids	Azam*et al.* (2013)
Celery		↑vitamin C ↓nitrate	Jin *et al.* (2009)
Lettuce	↑appearance (color)	↑antioxidants, ↑vitamin C, ↓macronutrients, ↓micronutrients ↓nitrate	Becker and Kläring (2016), Giri*et al.* (2016), Jin *et al.* (2009)
Potato	↓appearance (shape), ↑appearance (colorgreening), ↑taste (carbohydrates)	↑alkaloids, ↑nitrates, ↑vitamin C, ↓protein, ↓macronutrients, ↓micronutrients, ↓amino acids, ↑↓sugars	Högy and Fangmeier (2009), Kumari and Agrawal (2014), Vorne*et al.* (2002)
Radish		↓protein, ↓vitamin C, ↓macronutrients, ↓micronutrients, ↓fatty acids, ↓amino acids	Azam*et al.* (2013)
Spinach		↑antioxidants, ↓macronutrients, ↓micronutrients	(Giri*et al.*, 2016).
Tomato	↑taste (carbohydrates, sugars)	↓protein, ↑↓vitamin C, ↓macronutrients, ↓micronutrients, ↓organic acids	Behboudian and Tod (1995), Islam *et al.*, (1996), Khan *et al.*, (2013),Moretti*et al.*, (2010); Wei *et al.*, (2018)
Strawberry	↑firmness	↑ascorbic acid ↑total phenolics ↑anthocyanins ↓antioxidant capacity	Siriphanich et al., (1998), Wang et al., (2003) Shin et al., (2008)
Turnip		↓protein, ↓vitamin C, ↓macronutrients, ↓micronutrients, ↓fatty acids, ↓amino acids	(Azam*et al.*, 2013)

*The symbol ↓denotes deterioration in the quality trait; the symbol ↑denotes improvement in the quality trait.

However, in the same study, altered responses among vegetable species were shown for other quality characters. Elevated CO_2 at 700 ppm during growth of lettuce and spinach resulted in an increased total phenolic content and antioxidant capacity, increased total chlorophyll content in lettuce, but a significant reduction of several macro- and micronutrients in the edible parts of both species (Giri *et al.*, 2016). In root vegetables (carrot, radish and turnip), elevated CO_2 (1000 ppm) caused several main nutritional parameters deteriorate, including protein, vitamin C, minerals, essential fatty acids and amino acids, which were decreased (Azam *et al.*, 2013). In potato plants the effects of high CO_2 (550-680 ppm) caused modification in tuber quality (Hogy Fangmeier, 2009). Regarding the appearance, high CO_2 levels increased tuber malformation and common scab but decreased tuber greening.

The high CO_2 resulted in positive effects related to decreased nitrate content, which have negative effects on both taste and the toxicological potential of potato tubers, and increased dry matter, starch and the vitamin C content (Hogy Fangmeier, 2009; Kumari Agrawal, 2014; Vorne *et al.*, 2002). Conversely, deterioration in the nutritional quality of tubers was detected due to high CO_2, in form of a decreased content of protein, macro-micronutrients, both total, and individual, amino acids and citric acid (Hogy Fangmeier, 2009; Kumari Agrawal, 2014; Vorne *et al.*, 2002).

In tomatoes, most reports reported that CO_2 at 700- 1000 ppm increased the carbohydrate and sugar content, traits related to taste, in tomato fruits (Behboudian and Tod, 1995; Islam *et al.*, 1996; Khan *et al.*, 2013; Moretti *et al.*, 2010; Wei *et al.*, 2018). An improved sugar to acid ration and coloration were also reported (Islam *et al.*, 1996; Wei *et al.*, 2018). Decreases in protein, organic acids and macronutrients were detected in tomato fruits through increased CO_2 levels during growth (Behboudian and Tod, 1995; Islam *et al.*, 1996; Khan *et al.*, 2013), whereas tomato fruit firmness was not affected by elevated CO_2 (Islam *et al.*, 1996; Wei *et al.*, 2018). The high CO_2 could increase (Islam *et al.*, 1996; Moretti *et al.*, 2010) or decrease (Khan *et al.*, 2013) the vitamin C content of tomato fruits, suggesting that some responses of elevated CO_2 could interact with many other factors.

7.3. Effect of drought and salinity:

The exposure of the plants to high salinity and drought considerably restricted growth, photosynthesis, biochemistry, as well as the texture and quality of cucumber fruits (Ouzounidou *et al.*, 2016). Application of 150 mMNaCl induced significant growth reduction in plant biomass and total pigment concentration in cucumber cultivars as well as in broad beans (Ouzounidou *et al.*, 2014). Moreover, drought has been related to quality maintenance during the storage of vegetables, however contrasting responses has been shown for other crops. In tomatoes grown under water stress, shelf-life was extended and weight loss reduced (Conesa *et al.*, 2014). In contrast, drought stress during growth in carrots resulted in higher water loss during storage and an increased susceptibility to chilling damage during cooling (Toivonen Hodges, 2011).

4. Climate change impacts on vegetable pests and diseases:

Climate change variables may have a direct impact on plant yield and quality, or might have indirect effects through the incidence of diseases and insect pests (Newton *et al.*, 2011). The performance of vegetables across changing environments due to shifts in climate is linked to ecological interactions with other organisms in the ecosystem (Beed *et al.*, 2015). While certain climate changes will make some environments more favorable to pests and diseases, others will promote the proliferation of natural enemies and facilitate disease management through biological control.

Extensive research has shown that increased levels of CO_2 enhance photosynthesis and water use efficiency, which may lead to higher biomass and yield and an increase in canopy size in most crop plants (Pangga *et al.*, 2013). Canopy size has a large impact on the microclimate within the plant canopy, resulting in a decrease in light levels, reduction of air circulation, and an increase in relative humidity, which may enhance the proliferation and spread of many fungal diseases.

While higher temperatures and CO_2 levels can affect many physiological and biochemical processes of crop plants, of particular concern are the possible negative effects on host disease resistance. For example, several genes involved in host defense responses have been shown to be down-regulated by higher temperatures resulting in increased disease severity (Sun *et al.*, 2011). In general, crop plants that are exposed to stress conditions will be more susceptible to pathogens than crop plants growing under normal conditions (Desprez-Loustau *et al.*, 2006). An increase in rainfall combined with elevated temperatures can enhance the development of certain bacterial and fungal pathogens. For instance, increased duration of surface wetness of plant green foliage in addition to elevated temperatures could increase the severity of fungal diseases such as anthracnose caused by *Colletotrichum* spp., in pepper (Park *et al.*, 2009; Than *et al.*, 2008). Warmer temperatures also seem to favor the incidence of the late blight caused by (*Phytophthora capsici*) in pepper. The emergence of a new, more virulent A2 type of late blight with a higher optimum growth temperature than the A1 type has been observed in pepper (Sheu *et al.*, 2009).

Invasive species and other species with high fertility and dispersal capabilities can easily adapt to variable climatic conditions. As a result, such species may rapidly disseminate worldwide as evidenced by the rapid spread of the tomato pinworm, *Tuta absoluta* (Desneux *et al*., 2011). Elevated CO_2 conditions seem to enhance the feeding of the common army worm (*Spodoptera litura*) on mungbean plants because of increased sugar levels (Srivastava *et al*., 2002). Reproduction of green peach aphid (*Myzus persicae*) on *Brassica oleracea* plants was significantly accelerated under elevated CO_2 (Bezemer *et al*., 1999). Increases in temperature favor rapid multiplication of whitefly (*Bemisia tabaci*) that pose a major threat to solanaceous crops as vectors for the virus diseases such as tomato leaf curl disease (Hanson *et al*., 2011).

Increasing temperatures up to 30°C enhanced the development and fertility of *Aphis gossypii* on cucumber, while temperatures over 30°C prolonged development, increased mortality of immature stages, shortened adult longevity and reduced fertility of the species (Satar *et al*., 2005).

The incidence of viroids is another more recent, but serious concern for the cultivation of solanaceous crops. Viroid multiplication at temperatures above 25°C is inhibited at lower temperatures. Thus, increasing temperatures may also favor the incidence of viroids in major vegetable crops such as tomatoes and pepper.

While increasing temperatures may enhance reproduction rate of insect pests, very high temperatures are often detrimental. Constant temperatures of 35°C were lethal to immature stages of *A. gossypii* (Satar *et al*., 2005), while high temperature (40-47°C) heat-shock treatments damaged pod borers (*Helicoverpa armigera*) (Mironidis and Savopoulou-Soultani, 2010). Unfortunately, such high temperatures are also very damaging to many vegetable crops, causing flower drop, and reducing pollen viability and fruit set (de la Pen˜a *et al*., 2011; Hanson *et al*., 2011).

5. The Need for Adaptation to Climate Change:

Potential impacts of climate change on agricultural sector will depend in part on ability to adapt to the changes (FAO, 2001). There is a need for means to adapt and mitigate the adverse effects of climate change on agricultural productivity, and particularly on vegetable crops growth, quality and yield. Germplasm of the main vegetable crops that are tolerant to high temperatures and drought has been identified and advanced breeding lines are being developed. In addition, development of production systems with improved water-use efficiency that expected to mitigate the effects of hot and dry conditions in vegetable production systems are the focus of current research.

6.1. Enhancing Vegetable Production Systems:

Various management practices have the potential to raise the yield of vegetables crops grown under hot condition. Strategies include adjusting fertilizer application, direct and precise delivery of water to root zone, grafting to increase disease tolerance, and use of soil amendments.

Grafting has been used mainly to control soil-borne diseases affecting the production of fruit vegetables such as solanaceous crops and cucurbits (Edelstein, 2004). However, it can provide tolerance to soil-related environmental stresses such as drought, salinity and low soil temperature if appropriate tolerant rootstocks have been used. Grafted plants were more able to tolerate low soil temperatures. *Solanum lycopersicum x S. habrochaites* rootstocks provide tolerance of low soil temperatures (10°C to 13°C) for their grafted tomato scions, while eggplants grafted onto *S. integrifolium x S. melongena* rootstocks grew better at lower temperatures (18°C to 21°C) than non-grafted plants (Okimura *et al*.,1986). Grafted watermelon plants were relatively tolerant to sub-optimal temperature than un-grafted ones which could enable the production under stress condition (Mohamed *et al*., 2018).Grafting benefits in improving tolerance of vegetables to abiotic stresses was previously review in several articles (Rouphael *et al*., 2018; Kumar *et al*., 2018; Penella and Calatayud, 2018; Schwarz *et al*., 2010; Agnello, 2018).

6.2. Biodiversity

Climate change revealed the crucial need to breed new vegetable varieties for improved resistance to abiotic and biotic stresses. Local and traditional varieties as well as the genetic diversity in the wild relatives of domesticated vegetables provide rich resources for breeding programmes for climate change-tolerant vegetables.

It became extremely vital to collect, conserve, and characterize traditional varieties (landraces) and wild relatives to have them available for use in mitigating the effects of biotic and abiotic stresses caused by climate change (Lane and Jarvis, 2007). Wild relatives are key resources for adaptation to climate change, as they provide plant breeders with genes and traits for developing plants resistant to biotic and abiotic stresses (Lane and Jarvis, 2007). Besides wild relatives, farmers' fields and bio-reserves hold agrobiodiversity that also represents gene pool that may already reflect species responses to changing climate. The gene banks of the world hold large numbers of genetically diverse plant collections, improved crop varieties, traditional landraces and wild crop species.

6.3. The Role of Biotechnology and Genomics:

Increasing crop production in unfavorable environments will necessitate innovative technologies to complement traditional breeding methods. Recent advances in field of biotechnology have provided plant breeders with several tools to enhance phenotypic screening, ranging from *in vitro* screening, molecular markers, marker-assisted selection and genetic engineering. Current research is using these tools to develop enhanced stress tolerant plants that potently combat climate change (Arora *et al*., 2011; Collard *et al*., 2005; Mtui, 2011).

Examining the field performance of genotypes under a particular stress is the usual method for evaluation however; Field evaluation requires considerable space, time, labor, equipment and planting material resources. Fortunately, *in-vitro* screening can provide alternative method that eliminate above mention drawbacks**.** *In vitro* screening of 30 potato genotypes for heat stress was useful to identify few genotypes that showed superior growth and microtuberization under heat stress condition that may be used as stock genetic material in breeding programs for producing elite potato genotypes adapted to heat stress (Mohamed *et al*., 2016).

Currently, genomics has emerged through whole genome sequencing and the discovery of novel and high throughput genetic and molecular technologies. This has paved the way to genetic manipulation of genes associated with tolerance to environmental stresses. Plant molecular genetic research has enhanced traditional plant breeding to increase and sustain crop productivity. Combining novel knowledge from genomic research with traditional breeding methods improves the ability to enhance crop plants.

6.4. Quantitative trait loci (QTLs) and gene discovery:

Quantitative trait loci (QTL) are the individual genes that influence complex traits which are controlled by several to many genes. DNA marker technology provides the framework to map QTL to chromosomal regions in segregating plant population (Dudley, 1993; Ibrahim, 2007). QTL analysis looks for the association between quantitative trait phenotypes and marker alleles segregating in a population (Collard *et al.,* 2005; Mauricio, 2001).

Lin *et al.* (2006) identified random amplified polymorphic DNA (RAPD) markers linked to heat tolerance in tomato line CL5915. In addition, QTLs were identified for a number of traits underlying reproductive success, *i.e.* pollen viability under continuous mild heat conditions (Xu *et al*., 2017). These results may support development of more heat-tolerant tomato varieties. An association mapping approach was undertaken using high-throughput genomic array to enhance heat-tolerance in tomato (Ruggieri *et al*., 2019). The results identified a total of 15 common markers associated with the studied traits. These promising candidate genes can be transferred to a cultivated tomato to improve its performance under high temperatures (Ruggieri *et al*., 2019).

Integration of QTL analysis with gene discovery will facilitate a comprehensive understanding of stress tolerance, permit the development of useful and effective markers for marker-assisted selection, and identify candidate genes for genetic engineering.

6.5. Engineering climate change-related stresses tolerance:

Although the function of stress response genes has been revealed, particularly in *Arabidposis thaliana*, only a few genes have contributed to a tolerant phenotype when over-expressed in vegetables (Zhang *et al.,* 2004). Expression of *AVP1*, a vacuolar H+ pyrophosphatase from *A. thaliana*, in tomato resulted in enhanced performance under soil water deficit (Park *et al*., 2005). The engineered tomato has a stronger, larger root system that allows the roots to make better use of limited water. The *CBF/DREB1* genes have been used successfully to engineer drought tolerance in tomato and other crops (Hsieh *et al*., 2002). Stress-associated genes such as *ROB5* - a stress inducible gene isolated from bromegrass- enhanced performance of transgenic potato at high temperatures (Gusta, 2012). The integration of genetic engineering with conventional plant breeding methods will likely accelerate the development and adoption of vegetable cultivars with enhanced adaptation to climate change-related stresses (Varshney *et al*., 2011). For further review on how genetic engineering can reduce the effect of climate change through adaptation can be found in several articles (Ortiz *et al*., 2014; Ortiz, 2008; Yadav *et al*., 2013).

6. Develop climate-resilient vegetables:

Climate-resilience is the ability to anticipate, prepare for, and respond to hazardous events, trends, or disturbances regarding climate. Improving climate resilience includes assessing how climate change will create new, or alters current, climate-related risks, and taking steps to better cope with these risks.

Climate-resilient agriculture focuses on reducing poverty and hunger in the face of climate change for future generations. Climate-resilient agriculture is emphasizing on transforming the current agricultural systems with wider perspective than increased production only. It supports food production systems at local, regional and global level that are socially, economically and environmentally sustainable.

The goal of developing climate-resilient vegetables is to help vegetable producers adapt to climate change and enhance vegetable production through developing heat, drought and disease tolerant vegetable varieties, soil health, irrigation and water management in vegetable production systems. Additionally, screening and selecting vegetable varieties for adaptation to increasing temperature, drought, and pest and diseases incidence.

Vegetable breeders need to urgently turn their attention to the introduction of climate-resilient vegetables to reduce losses due to climate change impacts. Furthermore, improved vegetable varieties for the climate changed-future should be adapted to low-input cultivation without the need for inputs that are scarce (water) or costly and environmentally damaging (chemicals).

CONCLUSION AND FUTURE PROSPECTS

Climate change is emerging one of the major constraints for global food security and will become more prevalent in the coming years. Effects of temperature generated by global warming on field crops and vegetables are the major among all the climate change effects. Climate change as well is responsible for other stresses such as drought, salinity and others.

A holistic approach is essential to overcome climate change impact on vegetable crops rather than a single method. A cohesive approach, where all available alternatives are considered in an integrated manner, will be the most effective and sustainable conduct under a vast changing climate. Reduction of climate change impact on vegetable crops must involve adaptation of current vegetable production systems to the potential impact of climate change. The emphasis should be on development of production systems for improved water use efficiency that can be adopted for heat and drought stresses. Moreover, agronomic practices that protect vegetable crops from sub-optimal environmental conditions must be continuously enhanced and practiced at farmer fields particularly in the developing countries.

Vegetable breeders need to focus on evaluating the enormous genetic resources in gene banks as well as in the wild that possess potential for adaptation to a changing climate The rich genetic diversity that exists in landraces and wild species should be exploited to serve as sources of selection in vegetable breeding programmes. Ultimately, genetic populations should be developed to introgress and identify genes conferring tolerance to stresses in addition to gene isolation, characterization, and genetic engineering.

This paper has provided a brief review of the state of knowledge in the key areas of climate change impact on vegetable crops and the crucial approaches to adaptation. Climate change impact requires integrating and applying effective and promising approaches, tools and efforts.

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تأثير التغيرات المناخية على محاصيل الخضر وإمكانية التأقلم

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يعد تغير المناخ واحدا من المعوقات الرئيسية للأمن الغذائي العالمي وسيصبح أكثر تأثيرا في السنوات القادمة. وتعد الزراعة أحد القطاعات الرئيسية التي سوف تتأثر بتغير المناخ. تهتم هذه المقالة المرجعية بتأثيرات تغير المناخ على إنتاج الخضر وجودتها والحاجة الماسة للتكيف مع تغير المناخ. التقلبات في المتوسط اليومي، الحد الأدنى والحد الأقصى لدرجة الحرارة هي التأثير الأساسي لتغير المناخ الذي يؤثر بشكل سلبي على إنتاج الخضر لأن العديد من الأنشطة الفسيولوجية والكيميائية الحيوية والتمثيل الغذائي للنبات تعتمد على درجة الحرارة. تتضمن هذه المقالة مناقشة دراسات حالة متعلقة بتأثير درجات الحرارة المرتفعة على إنتاج محاصيل الخضر الرئيسية. يمكن أن تؤدي زيادة ثاني أكسيد الكربون في الغلاف الجوي إلى تأثير مباشر على نمو نباتات الخضر وتطورها. أظهرت الأدلة أن معدلات النمو المرتفعة التي لوحظت للنباتات النامية تحت تركيزات عالية من ثاني أكسيد الكربون قد تؤدي إلى مجموع خضري أكثر كثافة مع رطوبة أعلى تفضلها مسببات الأمراض. من الموثق جيدًا أن ارتفاع درجة الحرارة يؤثر سلبًا على نشاط الحشرات الملقحة وبالتالي انخفاض محصول البذور. يمكن أن تتسبب التغيرات المناخية في حدوث تغييرات في جودة ما بعد الحصاد في محاصيل الخضر من حيث الجودة الظاهرية والقيمة الغذائية. يمكن أن يؤدي تغير المناخ إلى تحسين بعض صفات الجودة مما يؤدي إلى تحسين القيمة الغذائية ومع ذلك، يمكن أيضا ملاحظة الآثار السلبية على مظهر المنتج. بالإضافة إلى ذلك، قد يكون لتغير المناخ آثار غير مباشرة من خلال الإصابة بالأمراض والآفات الحشرية. سوف تستلزم الآثار المحتملة لتغير المناخ على القطاع الزراعي الحاجة إلى التكيف والتخفيف من الآثار السلبية على الإنتاجية الزراعية، وخاصة على محاصيل الخضر وجودتها. قد تشمل وسائل التكيف والتخفيف تحسين أنظمة الإنتاج، والاستغلال الأفضل للتنوع البيولوجي، وتطبيق التكنولوجيا الحيوية وتقنيات الجينوم، والهندسة الوراثية لتحمل مختلف صور الإجهاد، وفي نهاية المطاف تطوير خضر مرنة الاستجابة لتغير المناخ. يعد النهج الشامل للتكيف أمرًا ضروريًا للتغلب على تأثير تغير المناخ على محاصيل الخضر بدلاً من إتباع نهج واحد.