Effect of temperature rise on crop growth and productivity

abstract :

Abstract

The present study highlights the effect of temperature rise on crop growth and productivity. Improving crop resilience to temperature stress is a vital step towards ensuring global food and fuel demands are met. Temperature is a critical meteorological determinant of crop development and function. Essential physiological processes including carbon assimilation and leaf chlorophyll content are very sensitive to high temperature extremes. High-temperature stress occurs when morpho-physiological and biochemical attributes of plant development are altered. Flowering optimum temperature was 25-30 °C. higher temperature (both max. and min.) and low diurnal variation in temperature are more conducive for early flowering rice variety. Advances in molecular techniques now allow for swift identification of beneficial traits in wild varieties. It is crucial to adopt advanced agricultural practices worldwide to mitigate the impact of rising global temperatures. This includes implementing climate-smart strategies and employing high-throughput phenotyping methods to identify and utilize resilient traits, thereby safeguarding future food security.

Keywords: crop growth, climate-smart strategies, food security, biochemical attributes

Introduction

Global land surface temperatures are increasing due to rising atmospheric CO_2 from anthropogenic emissions that are causing climate change, and with this comes the challenge of meeting food and fuel supply demands under more stressful crop growing conditions. Despite a drop in emissions associated with the coronavirus pandemic of 2020 (COVID-19; Le quere *et al.,*2020), global emissions are currently tracking the worst-case ‘business as usual’ emissions scenario (RCP 8.5) that will very likely equate to unprecedented warming from pre-industrial (1850–1990) levels of 3–5 °C by 2100 (IPCC, 2014).

A recent IPCC report indicated, with medium confidence, that crop yields will experience ‘severe and widespread impacts’ if global warming exceeds 1.5 °C above pre-industrial levels, but that these impacts can be managed below this warming threshold (IPCC, 2018). Coupled with rising mean global temperature is a projected increase in the frequency, intensity, and duration of extreme heatwave events that have the potential to cripple crop yields (Battisti and Naylor, 2009; Perkins *et al.,*2012; Hatfield and Prueger, 2015; Hoegh-Guldberg *et al.,*2018). Additionally, some cropping areas, such as temperate, high-latitude regions, will likely face even greater warming than tropical regions of the world (Hoegh-Guldberg *et al.,*2018). Therefore, there is an urgent need, first and foremost, for mitigation strategies to reduce fossil fuel emissions to cap warming at 1.5 °C (IPCC, 2018), but also for development of our major cropping systems to be more resilient to hotter growing seasons and extreme temperature events that seem inevitable in the coming century.

Global yield losses in key crops, such as maize and wheat, have been attributed to higher growing season temperatures (Lobell *et al.,*2011; Lobell and Gourdji, 2012; Asseng *et al.,*2015). Without crop improvement strategies, including genetic engineering and adaptation under carbon dioxide (CO2) fertilization, substantial yield declines per °C of warming have been projected for the major cropping systems of maize (7.4%), wheat (6.0%), rice (3.2%), and soybean (3.1%) (Zhao *et al.,*2017). Yet, to keep pace with supplying food and fuel to the growing human population, agricultural production will need to double (based on average yield in 2005) over this century to meet increased caloric demand (Long and Ort, 2010; Ray *et al.,*2013). Additionally, the full theoretical extent of the CO_2 fertilization effect is unlikely to be realized due to the impact of rising temperature (Long *et al.,*2006; Ainsworth and Long, 2020). Thus, improving crop resilience to temperature stress is a vital step towards ensuring global food and fuel demands are met. Temperature is a critical meteorological determinant of crop development and function. Temperature alters enzyme function within a leaf (Bernacchi *et al.,*2001; Walker *et al.,*2013; Florian *et al.,*2014; Kumarathunge *et al.,*2019; Timm *et al.,*2019) and triggers changes in developmental growth stage that are tightly coupled with crop yield (Ruiz-Vera *et al.,*2018; Zhu *et al.,*2018). Furthermore, the amount of water vapour in air at saturation increases exponentially with temperature, raising the vapour pressure deficit (VPD), and driving more potential water loss from plants (Novick *et al.,*2016; Grossiord *et al.,*2020). The result of these broad crop physiological responses to temperature means that any shifts in long-term mean annual temperature and extreme temperature events will be likely to have significant impacts on crop production from the key food and fuel growing regions of the world.

Importance of temperature in plant growth and development

- ✓ Temperature is one of the most important ecological factors.
- ✓ It regulates the many physiological processes of plants like photosynthesis, transpiration.
- ✓ The plant grows best at optimum temperature.
- ✓ Both low and high temperatures have adverse effects on plants.
- ✓ The metabolic processes are low at minimum temperature. It increases at a particular temperature called as optimum temperature.
- ✓ Metabolism again decreases at maximum temperature. the plants cannot survive above this temperature**.**

Cardinal temperature: Every plant community has its own minimum, optimum, maximum temperature range for their growth and development.

table 1 : Cardinal points of important crops.

Crops	Germination (°C)			Growth (°C)		
	minimum	optimum	maximum	minimum	optimum	maximum
Rice	10	28	40	13-14	32	36-38
Wheat	4-405	25	30-32	4.5	20	30-32
Maize	8-10	31-35	40-44	8-10	23-30	40-43
Sorghum	8-10	31-35	40-44	12-13	25	40

Effect of high temperature on plant Photosynthesis and growth

C3 plants are more susceptible to high-temperature stress than C_4 plants because C_3 plants convert CO2 into a 3-carbon compound (PGA) with Rubisco. On the other hand, C4 plants convert CO2 into a 4-carbon intermediate (OAA) by using PEPC. CA carbonic anhydrase, PGA phosphoglyceric acid, RuBP ribulose-1,5-bisphosphate, PEP phosphoenolpyruvate, Rubisco ribulose-1,5-bisphosphate carboxylase/oxygenase, PEPC phosphoenolpyruvate carboxylase, NAD(P)-ME NAD(P)-malic enzyme, PCK phosphoenolpyruvate carboxykinase, PPDK pyruvate phosphate dikinase, NAD(P)-MDH NAD(P)-malate dehydrogenase (OAA) with substrates of phosphoenolpyruvate (PEP) by phosphoenolpyruvate carboxylase (PEPC) located in the cytosol. PEP is produced from pyruvate and ATP, catalyzed by pyruvate phosphate dikinase (PPDK) located in the chloroplast. Among C4 plants, there are three subtypes, based on the C4 acid decarboxylation enzyme: NADP-malic enzyme (NADP-ME) type, NAD-malic enzyme (NAD-ME) type, and phosphoenol-pyruvate carboxykinase (PCK) type. Malate (or aspartate) is transported to the vascular bundle sheath cells and is finally decarboxylated, producing CO2 and pyruvate. CO2 is then fixed by Rubisco in the chloroplasts of the bundle sheath cells, which have a normal Calvin cycle, as in C3 plants (Yamori *et al.,*2014).

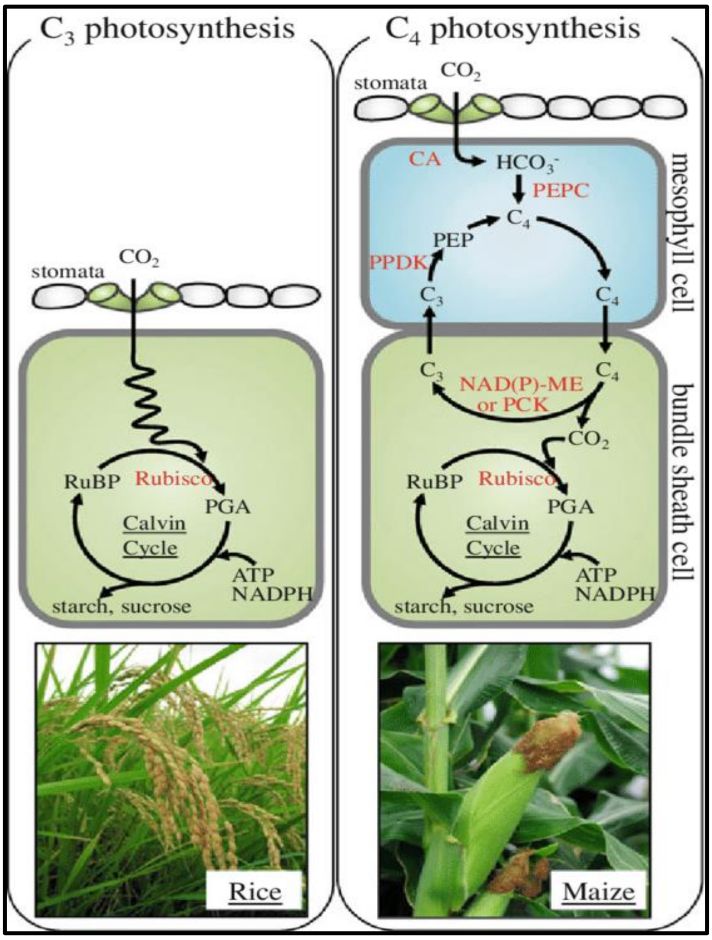

Fig. 1. Effect of high temperature on plant Photosynthesis and growth

Effect of high temperature on plant metabolism

Essential physiological processes including carbon assimilation and leaf chlorophyll content are very sensitive to high temperature extremes. High-temperature stress occurs when morpho-physiological and biochemical attributes of plant development are altered. Air temperatures above 30 °C reduce photosynthesis in plants. Temperature beyond 35 °C restricts the elongation of sympodial branches in cotton (Ekinci *et al.,* 2017). Signal transduction networks form a large proportion of the complex machinery that provokes several self-activated and hormone-dependent mechanisms in plants under temperature stress (Awasthi *et al.,* 2015; Pandey *et al.,*2016). Heat stress affects cell biochemistry by enhancing ROS production. Heat stress causes an alteration in mitochondrial function, leading to the induction of oxidative damage by lipid peroxidation (Davidson and Schiestl 2001; Vacca *et al.,*2004). Numerous studies revealed enhanced lipid peroxidation under heat stress (Wu *et al.,*2010). Temperature extremes lead to ROS production, including OH^-, H_2O_2, and $O2^-$, thus causing oxidative stress (Yin *et al.,*2008). During heat stress, rubisco speeds up the production of $H2O2$ due to its oxygenase activity (Kim and Portis 2004). ROS provokes autocatalytic peroxidation of lipids in cell membranes and pigments, thus affecting the permeability of the membrane and its function (Xu *et al.,*2006).

Tolerance to oxidative damage is directly correlated with antioxidant production in crop plants (Almeselmani *et al.,* 2009). Elevated protein levels from ROS scavenging enzymes are observed under high temperatures (Rainwater *et al.,* 1996; Rizhsky *et al.,* 2002). Moreover, plants can evolve heat tolerance defence mechanisms to prevent oxidative damage under high-temperature stress (Bergmuller *et al.,* 2003). Zhang *et al.,* (2016) reported increased ROS production in cotton during reproductive stages, i.e., an increase in the lipid peroxidation byproduct malondialdehyde (MDA) that affects all cellular organelles. The cotton plant was unable to scavenge ROS under high-temperature stress. The antioxidant enzymes SOD and CAT were up-regulated in cotton leaves but were unable to protect cells from oxidative damage (Snider *et al.,* 2009). Temperature stress reduced the number of sympodial branches and boll weight in cotton as reported by Singh *et al.,* (2007) that might be due to hindrance in the supply of assimilates to developing bolls. In summary, antioxidant enzymes in cotton are elevated but failed to scavenge ROS due to more pressure on organelles under heat stress (Snider *et al.,* 2009). Recent studies demonstrated the effect of a foliar spray of H2O2 to induce thermo-tolerance (Gao *et al.,* 2010; Hossain *et al.,* 2015). Exogenous application of H2O2 improved plant growth and reduced oxidative stress by protecting DNA structures from damage. Moringa leaf extract (MLE) and AA are also considered to be essential for the enhancement of antioxidative activity (Fahad *et al.,* 2016). H2O2 acts as a signaling molecule that increases chlorophyll content under high temperature stress. Similarly, moringa leaf extract is rich in zeatin which protects the cell from oxidative stress. Studies have shown that these growth regulators (H_2O_2, ASA and MLE) increased cotton fiber length. H2O2 played an essential role in cell expansion and differentiation of cotton fibers (Li *et al.,* 2007). Moringa leaf extract was abundant in cytokinins that enhanced fiber quality components (Ali *et al.,* 2011).

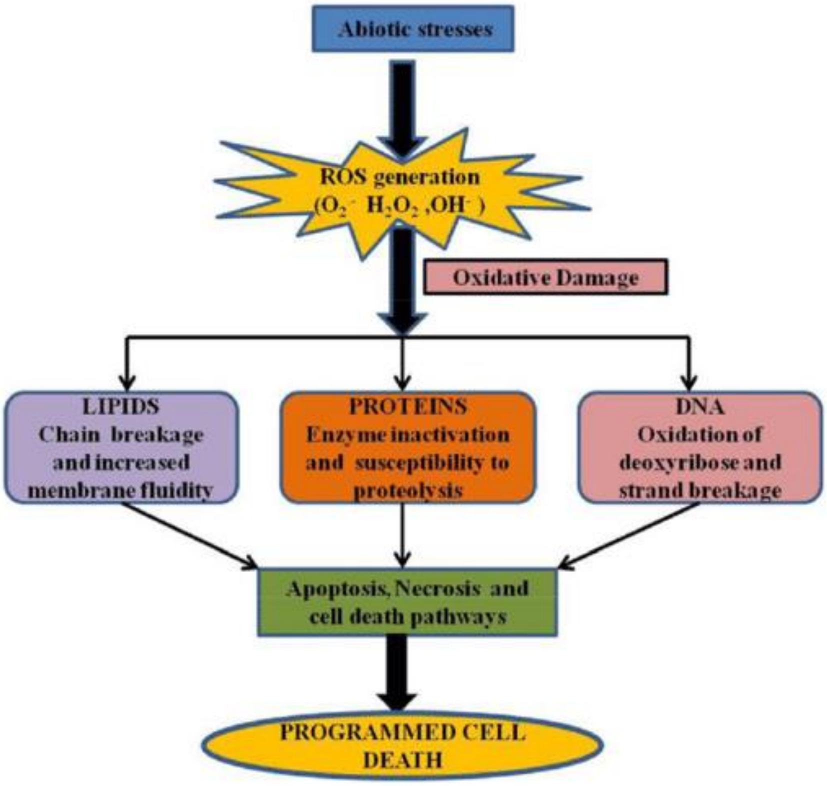

Fig. 2. Effect of high temperature on plant metabolism

Effect of temperature on plant growth and development in rice crop

There is main three stage

1.Vegetative Stage

2. Reproductive Stage

3. Ripening Stage

(1) Vegetative stage effect of temperature on germination, seedling growth (shoot and root elongation), leaf emergence, plant height and last one is tillering.

In germination the optimum temperature is 20-30 °C. low temperature depresses the rate of germination and prolongs it beyond the desirable span of 6 days. High temperature 35 °C or more halted the germination because of high respiration rate. Seedling growth rate increase linearly between 22-31 °C, suggesting that chemical reaction dominate growth and above 40 °C the plant may die. Shoot and root elongation critical minimum temperature is 7-16 and 12-16 °C respectively. Elongation is a combination of two components; cell division and cell enlargement and for which extreme temperature are 15 °C and 40 °C. Leaf emergence; before panicle initiation, leaf emerges about every 4-5 days, afterwards about 7-8 days. Temperature affects the rate of leaf emergence. Example rice plant is grown at 20 °C leaves emergence every 5 days, when grown in 25°C leaves emergence is every 4 days before panicle initiation. Plant height increased with the rise of temperature within the range of 30-35 °C. the plant elongate vigorously until 30 DAT, then slowly ceases to elongate at the heading stage. Tillering, optimum temperature for 25-31°C, tillering rate is inhibited by low temperature but the period of tillering is prolonged. The mean temp. exceeded 26 °C the tiller production stopped abruptly by 5 weeks after transplanting and whenever it falls below 26°C the duration of tillering increased to 7-8 week after transplanting. Temperature above 28 °C during vegetative phase reduce the day to heading and shorter the life cycle.

(2) Reproductive stage the temperature effect on panical initiation, booting & heading, flowering and emergence of flag leaf. After the tillering stage high temperature decrease the number of panicles, panicle weight at maturity Booting and heading stage when the rice plant subjected to low temperature for 3 days it is more sensitive at the booting stage than heading stage as indicated by higher percentage of spikelet sterility. Flowering optimum temperature was 25-30 °C. higher temperature (both max. and min.) and low diurnal variation in temperature are more conducive for early flowering rice variety.

(3) Ripening stage the temperature effect on grain filling grain quality and yield. Optimum temperature for ripening is 20-25 °C. low temperature reduced the grain dry matter increasing rate, extends the grain filling delay grain maturation although moderate cool temperature sometimes benefits grain yield. Higher temperature decreased the grain yield significantly due to the reduction of percentage of ripened grain.

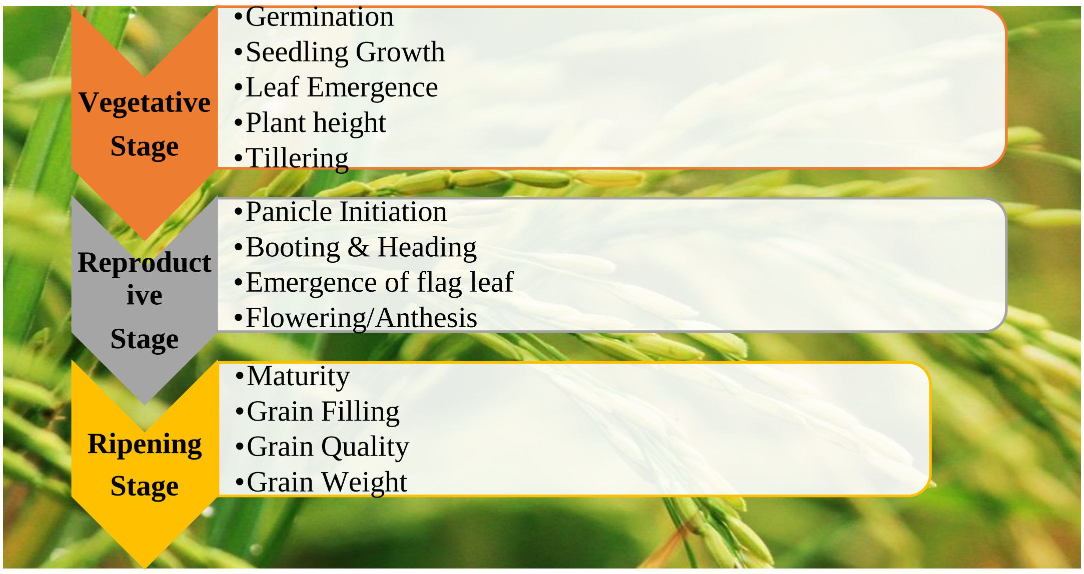

Fig. 3. Effect of temperature on plant growth and development in rice crop

Adaptive mechanisms of plants under high temperature

- ### Avoidance Mechanism

Under HT conditions, plants exhibit various mechanisms for surviving which include long-term evolutionary phenological and morphological adaptations and short-term avoidance or acclimation mechanisms such as changing leaf orientation, transpirational cooling, or alteration of membrane lipid compositions. Closure of stomata and reduced water loss, increased stomatal and trachomatous densities, and larger xylem vessels are common heat induced features in plant (Srivastava *et al.,*2012). In many crop plants, early maturation is closely correlated with smaller yield losses under HT, which may be attributed to the engagement of an escape mechanism (Rodriguez *et al.,*2005; Adams *et al.,*2001). Plants growing in a hot climate avoid heat stress by reducing the absorption of solar radiation. This ability is supported by the presence of small hairs (tomentose) that form a thick coat on the surface of the leaf as well as cuticles, protective waxy covering. In such plants, leaf blades often turn away from light and orient themselves parallel to sun rays (para heliotropism). Solar radiation may also be reduced by rolling leaf blades. Plants with small leaves are also more likely to avoid heat stress: they evacuate heat to ambient more quickly due to smaller resistance of the air boundary layer in comparison with large leaves. Plants rely on the same anatomical and physiological adaptive mechanisms those are deployed in a water deficit to limit transpiration. In well-hydrated plants, intensive transpiration prevents leaves from heat stress, and leaf temperature may be 6 °C or even 10–15 °C lower than ambient temperature. Many species have evolved life histories which permit them to avoid the hottest period of the year. This can be achieved by leaf abscission, leaving heat resistant buds, or in desert annuals, by completing the entire reproductive cycle during the cooler months (Fitter and Hay 2012). Such morphological and phenological adaptations are commonly associated with biochemical adaptations favoring net photosynthesis at HT (in particular C4 and CAM photosynthetic pathways), although C3 plants are also common in desert floras (Fitter and Hay 2012). High temperature can affect the degree of leaf rolling in many plants. Physiological role of leaf rolling was the maintenance of adaptation potential by increasing the efficiency of water metabolism in the flag leaves of wheat under HT (Sarieva *et al.,*2010). During active growth, all plants are highly sensitive to temperature stress. Selected species of land plants increase their resistance to heat only in the summer, while others demonstrate the highest level of tolerance during winter dormancy. Dormant plants become resistant to stress upon reaching a developmental stage induced by factors other than high environmental temperature. In many land plant species, noticeable changes in heat tolerance are not observed. Due to the close correlation between drought and HT, the effects of each stressor on field-grown plants can be difficult to distinguish, and adaptations to arid environments can be effective only if they lead to avoidance or tolerance of both stresses floras (Fitter and Hay 2012).

High temperature stress can also be avoided by crop management practices such as selecting proper sowing methods, choice of sowing date, cultivars, irrigation methods, etc. For instance, in subtropical zones, cool-season annuals such as lettuce when sown in the late summer may show incomplete germination and emergence due to high soil temperature (Hall, 2011). The incomplete emergence problem can be overcome by sowing the lettuce seed into dry beds during the day and then sprinkle irrigating the beds during the late afternoon. Seed priming is another potential solution to this problem which involves placing the seed in an osmotic solution for several days at moderate temperatures and then drying them. In contrast, tropical crops may face inadequate plant emergence and establishment can limit the productivity of several warm-season annual crops due to very hot soil surface. In such cases, deep placement can overcome the problem. In temperate or subtropical climatic zones, which have seasonal variations in temperature, sowing date can be varied to increase the probability that annual crop species will escape stressfully HTs during subsequent sensitive stages of development. In some cases, HT and intense direct solar radiation can cause damage to fruit. This can be avoided if fruit is shaded by foliage (Hall, 2011).

Tolerance Mechanisms

Heat tolerance is generally defined as the ability of the plant to grow and produce economic yield under HT. This is a highly specific trait, and closely related species, even different organs and tissues of the same plant, may vary significantly in this respect. Plants have evolved various mechanisms for thriving under higher prevailing temperatures. They include short term avoidance/acclimation mechanism or long-term evolutionary adaptations. Some major tolerance mechanisms, including ion transporters, late embryogenesis abundant (LEA) proteins, Osmoprotectants, antioxidant defence, and factors involved in signaling cascades and transcriptional control are essentially significant to counteract the stress effects (Rodriguez *et al.,*2005; Wang *et al.,*2004). In case of sudden heat stress, short term response, i.e., leaf orientation, transpirational cooling and changes in membrane lipid composition are more important for survival (Rodriguez *et al.,*2005; Radin *et al.,*1994). Smaller yield losses due to early maturation in summer shows possible involvement of an escape mechanism in heat stress tolerance (Adams *et al.,*2001). Different tissues in plants show variations in terms of developmental complexity, exposure and responses towards the prevailing or applied stress types (Queitsch *et al.,*2000). The stress responsive mechanism is established by an initial stress signal that may be in the form of ionic and osmotic effect or changes in the membrane fluidity. This helps to reestablish homeostasis and to protect and repair damaged proteins and membranes (Vinocur and Altman, 2005).

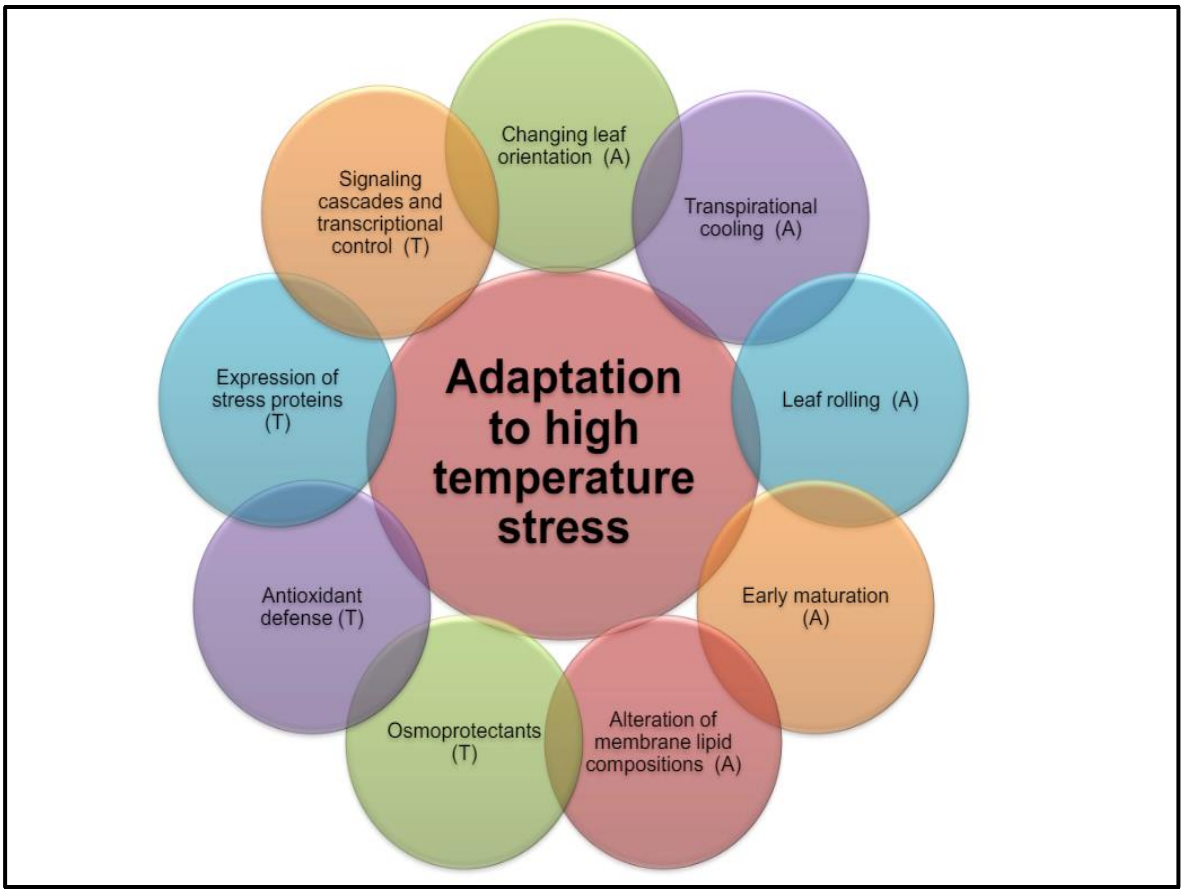

Fig. 4. Adaptive mechanisms of plants under high temperature

table 2 : **Physiological disorder due to high temperature**

Crop	Malady
Rice	Severe chlorosis of leaves
	Irregular flowering and chaffiness, multiple deficiency Of nutrients
	Tip drying and marginal scorching and browning
Maize	Chlorosis
	Yellowing in the bud leaves only (white bud)
	Tip drying and pinkish colouration of lower leaves
	Marginal scorching and yellowing
	Irregular drying of tips and margins
Sorghum	Chlorosis of younger leaves

Leaf chlorosis in rice

Maize: Marginal scorching

Conclusion

High temperatures are a critical environmental factor that impacts crop growth and yield by influencing various mechanisms. This issue is alarming because it directly affects yield at a time when there is a pressing need to increase agricultural output to alleviate global hunger and ensure food security. Developing resilience to high temperatures is crucial not only for current conditions but also for the future, given predictions of increasing temperatures that will significantly impact yield. Therefore, it is essential to explore new strategies to bolster or enhance tolerance to high temperatures. Although numerous studies have examined the effects of high temperatures on crops, many wild types remain unexplored. Exploring these untouched wild types could uncover valuable insights into managing high temperatures through novel genes that confer tolerance. Advances in molecular techniques now allow for swift identification of beneficial traits in wild varieties. It is crucial to adopt advanced agricultural practices worldwide to mitigate the impact of rising global temperatures. This includes implementing climate-smart strategies and employing high-throughput phenotyping methods to identify and utilize resilient traits, thereby safeguarding future food security.

References

Adams, S. R., Cockshull, K. E., & Cave, C. R. J. (2001). Effect of temperature on the growth and development of tomato fruits. *Annals of botany*, 88 (5), 869-877.

Ainsworth, E. A., & Long, S. P. (2021). 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global change biology*, 27 (1), 27-49.

Ali, Z., Basra, S. M. A., Munir, H. A. S. S. A. N., Mahmood, A. R. S. H. A. D., & Yousaf, S. H. A. H. I. D. A. (2011). Mitigation of drought stress in maize by natural and synthetic growth promoters. *Journal of agriculture & social sciences,* Sci, 7 (2), 56-62.

Almeselmani, M., Deshmukh, P., & Sairam, R. (2009). High temperature stress tolerance in wheat genotypes: role of antioxidant defence enzymes. *Acta Agronomica Hungarica,* 57 (1), 1-14.

Asseng, S., Ewert, F., Martre, P., Rotter, R. P., Lobell, D. B., Cammarano, D., & Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature climate change*, 5 (2), 143-147.

Awasthi, R., Bhandari, K., & Nayyar, H. (2015). Temperature stress and redox homeostasis in agricultural crops. *Frontiers in Environmental Science*, 11 (3).

Battisti, D. S., & Naylor, R. L. (2009). Historical warnings of future food insecurity with unprecedented seasonal heat. *Science,* 323(5911), 240-244.

Bergmuller, E., Porfirova, S., & Dormann, P. (2003). Characterization of an Arabidopsis mutant deficient in γ-tocopherol methyltransferase. *Plant Molecular Biology*, 52, 1181-1190.

Bernacchi, C. J., Singsaas, E. L., Pimentel, C. A. R. L. O. S., Portis Jr, A. R., & Long, S. P. (2001). Improved temperature response functions for models of Rubisco-limited photosynthesis. *Plant, Cell & Environment*, 24 (2), 253-259.

Davidson, J. F., & Schiestl, R. H. (2001). Mitochondrial respiratory electron carriers are involved in oxidative stress during heat stress in Saccharomyces cerevisiae. *Molecular and cellular biology*, 21 (24), 8483–8489.

Ekinci, R., Basbag, S., & Karademir, E. (2017). The effects of high temperature stress on some agronomic characters in cotton. *Pakistan Journal of Botany*, 49 (2), 503–508.

Fahad, S., Hussain, S., Saud, S., Khan, F., Hassan, S., Amanullah, ... & Huang, J. (2016). Exogenously applied plant growth regulators affect heat-stressed rice pollens. *Journal of agronomy and crop science,* 202 (2), 139-150.

Fitter, A. H., & Hay, R. K. (2012). *Environmental physiology of plants*. Academic press.

Florian, A., Nikoloski, Z., Sulpice, R., Timm, S., Araújo, W. L., Tohge, T., & Fernie, A. R. (2014). Analysis of short-term metabolic alterations in Arabidopsis following changes in the prevailing environmental conditions. *Molecular Plant*, 7 (5), 893-911.

Gao, Y., Guo, Y. K., Lin, S. H., Fang, Y. Y., & Bai, J. G. (2010). Hydrogen peroxide pretreatment alters the activity of antioxidant enzymes and protects chloroplast ultrastructure in heat-stressed cucumber leaves. *Scientia Horticulturae,* 126 (1), 20-26.

Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T., & McDowell, N. G. (2020). Plant responses to rising vapor pressure deficit. *New phytologist*, 226 (6), 1550-1566.

Hall, A. E. (2011). Accessed on 3rd June. *The mitigation of heat stress. Available online: http://www. planstress. com*.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and climate extremes,* 10, 4-10.

Hoegh Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I. A., & Zhou, G. (2018). Impacts of 1.5 °C global warming on natural and human systems. *Global warming of 1.5 °C. Geneva, Switzerland,* IPCC, 177–311.

Hossain, M. A., Bhattacharjee, S., Armin, S. M., Qian, P., Xin, W., Li, H. Y., ... & Tran, L. S. P. (2015). Hydrogen peroxide priming modulates abiotic oxidative stress tolerance: insights from ROS detoxification and scavenging. *Frontiers in plant science,* 6, 420.

Kim, K., & Portis, A. R. (2004). Oxygen-dependent H2O2 production by Rubisco. *Febs Letters*, 571(1-3), 124-128.

Kumarathunge, D. P., Medlyn, B. E., Drake, J. E., Tjoelker, M. G., Aspinwall, M. J., Battaglia, M., & Way, D. A. (2019). Acclimation and adaptation components of the temperature dependence of plant photosynthesis at the global scale. *New Phytologist*, 222 (2), 768-784.

Le Quere, C., Jackson, R. B., Jones, M. W., Smith, A. J., Abernethy, S., Andrew, R. M., & Peters, G. P. (2020). Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nature climate change*, 10 (7), 647-653.

Li, H. B., Qin, Y. M., Pang, Y., Song, W. Q., Mei, W. Q., & Zhu, Y. X. (2007). A cotton ascorbate peroxidase is involved in hydrogen peroxide homeostasis during fibre cell development. *New Phytologist,* 175 (3), 462-471.

Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. *Plant physiology,* 160 (4), 1686-1697.

Lobell, D. B., Roberts, M. J., Schlenker, W., Braun, N., Little, B. B., Rejesus, R. M., & Hammer, G. L. (2014). Greater sensitivity to drought accompanies maize yield increase in the US Midwest. *Science,* 344 (6183), 516-519.

Long, S. P., & Ort, D. R. (2010). More than taking the heat: crops and global change. *Current opinion in plant biology*, 13 (3), 240-247.

Long, S. P., Ainsworth, E. A., Leakey, A. D., Nosberger, J., & Ort, D. R. (2006). Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. *science,* 312 (5782), 1918-1921.

Masson-Delmotte, V., Zhai, P., Portner, H. O., Roberts, D., Skea, J., Shukla, P. R., & Waterfield, T. (2019). Global warming of 1.5 C. *An IPCC Special Report on the impacts of global warming of,* 1, 93-174.

Novick, K. A., Ficklin, D. L., Stoy, P. C., Williams, C. A., Bohrer, G., Oishi, A. C., & Phillips, R. P. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature climate change*, 6 (11), 1023-1027.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., & van Ypserle, J. P. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). IPCC.

Pandey, G. K., Pandey, A., Prasad, M., & Bohmer, M. (2016). Abiotic stress signaling in plants: functional genomic intervention. *Frontiers in plant science,* 7 (4), 289-312.

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters,* 39 (20).

Queitsch, C., Hong, S. W., Vierling, E., & Lindquist, S. (2000). Heat shock protein 101 plays a crucial role in thermotolerance in Arabidopsis. *The Plant Cell*, 12 (4), 479-492.

Radin, J. W., Lu, Z., Percy, R. G., & Zeiger, E. (1994). Genetic variability for stomatal conductance in Pima cotton and its relation to improvements of heat adaptation. *Proceedings of the National Academy of Sciences*, 91 (15), 7217-7221.

Rainwater, D. T., Gossetp, D. R., Millhollon, E. P., Hanna, H. Y., Banks, S. W., & Lucas, M. C. (1996). The relationship between yield and the antioxidant defence system in tomatoes grown under heat stress. *Free Radical Research*, 25 (5), 421-435.

Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PloS one*, 8 (6), e66428.

Rizhsky, L., Liang, H., & Mittler, R. (2002). The combined effect of drought stress and heat shock on gene expression in tobacco. *Plant physiology*, 130 (3), 1143-1151.

Rodriguez, M., Canales, E., & Borras-Hidalgo, O. (2005). Molecular aspects of abiotic stress in plants. *Biotecnologia Aplicada*, 22 (1), 1-10.

Ruiz-Vera, U. M., Siebers, M. H., Jaiswal, D., Ort, D. R., & Bernacchi, C. J. (2018). Canopy warming accelerates development in soybean and maize, offsetting the delay in soybean reproductive development by elevated CO2 concentrations. *Plant, Cell & Environment*, 41 (12), 2806-2820.

Sarieva, G. E., Kenzhebaeva, S. S., & Lichtenthaler, H. K. (2010). Adaptation potential of photosynthesis in wheat cultivars with a capability of leaf rolling under high temperature conditions. *Russian Journal of Plant Physiology*, 57, 28-36.

Singh, R. P., Prasad, P. V., Sunita, K., Giri, S. N., & Reddy, K. R. (2007). Influence of high temperature and breeding for heat tolerance in cotton: a review. *Advances in agronomy,* 93, 313-385.

Snider, J. L., Oosterhuis, D. M., Skulman, B. W., & Kawakami, E. M. (2009). Heat stress-induced limitations to reproductive success in Gossypium hirsutum. *Physiologia plantarum*, 137 (2), 125-138.

Srivastava, S., Pathak, A. D., Gupta, P. S., Shrivastava, A. K., & Srivastava, A. K. (2012). Hydrogen peroxide-scavenging enzymes impart tolerance to high temperature induced oxidative stress in sugarcane. *Journal of Environmental Biology*, 33 (3), 657.

Timm, S., Woitschach, F., Heise, C., Hagemann, M., & Bauwe, H. (2019). Faster removal of 2-phosphoglycolate through photorespiration improves abiotic stress tolerance of Arabidopsis. *Plants*, 8 (12), 563.

Vacca, R. A., de Pinto, M. C., Valenti, D., Passarella, S., Marra, E., & De Gara, L. (2004). Production of reactive oxygen species, alteration of cytosolic ascorbate peroxidase, and impairment of mitochondrial metabolism are early events in heat shock-induced programmed cell death in tobacco Bright-Yellow 2 cells. *Plant physiology,* 134 (3), 1100-1112.

Vinocur, B., & Altman, A. (2005). Recent advances in engineering plant tolerance to abiotic stress: achievements and limitations. *Current opinion in biotechnology*, 16 (2), 123-132.

Walker, B., Ariza, L. S., Kaines, S., Badger, M. R., & Cousins, A. B. (2013). Temperature response of in vivo Rubisco kinetics and mesophyll conductance in Arabidopsis thaliana: comparisons to Nicotiana tabacum. *Plant, Cell & Environment*, 36 (12), 2108-2119.

Wang, W., Vinocur, B., Shoseyov, O., & Altman, A. (2004). Role of plant heat-shock proteins and molecular chaperones in the abiotic stress response. *Trends in plant science*, 9 (5), 244-252.

Wu Bin, W. B., Jiang Qiu Wei, J. Q., Gu TingTing, G. T., Zhao Mei, Z. M., & Liu Li Wang, L. L. (2010). Physiological response to high temperature stress in radish seedlings with different heat tolerance. *China Vegetables,* 10, 25–8.

Xu, S., Li, J., Zhang, X., Wei, H., & Cui, L. (2006). Effects of heat acclimation pretreatment on changes of membrane lipid peroxidation, antioxidant metabolites, and ultrastructure of chloroplasts in two cool-season turfgrass species under heat stress. *Environmental and Experimental Botany,* 56 (3), 274-285.

Yamori, W., Hikosaka, K., & Way, D. A. (2014). Temperature response of photosynthesis in C_3, C_4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynthesis research*, 119, 101-117.

Yin, H., Chen, Q., & Yi, M. (2008). Effects of short-term heat stress on oxidative damage and responses of antioxidant system in *Lilium longiflorum*. *Plant Growth Regulation*, 54, 45-54.

Zhang, J., Chen, H., Wang, H., Li, B., Yi, Y., Kong, F., & Zhang, H. (2016). Constitutive expression of a tomato small heat shock protein gene LeHSP21 improves tolerance to high-temperature stress by enhancing antioxidation capacity in tobacco. *Plant molecular biology reporter,* 34, 399-409.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., ... & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of sciences,* 114 (35), 9326-9331.

Zhao, W. L., Siddiq, Z., Fu, P. L., Zhang, J. L., & Cao, K. F. (2017). Stable stomatal number per minor vein length indicates the coordination between leaf water supply and demand in three leguminous species. *Scientific Reports,* 7 (1), 2211.

Zhu, P., Jin, Z., Zhuang, Q., Ciais, P., Bernacchi, C., Wang, X., & Lobell, D. (2018). The important but weakening maize yield benefit of grain filling prolongation in the US Midwest. *Global change biology*, 24 (10), 4718-4730.