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Review Paper

Climate change shocks and crop production: The foodgrain bowl of India as an example

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ABSTRACT

Global warming is causing climate change (CC) characterized by increased frequency of heatwaves, droughts, erratic rains, hailstorms, cloudbursts, floods, landslides etc. The CC has already adversely affected ecosystems. In spite of efforts to mitigate greenhouse gas (GHG) emissions, which lead to warming, the global temperature during 2011–20 was 1.1°C above that during pre-industrial era. The projections are that warming will continue to increase and adverse effects will intensify particularly in developing countries like India. In India a number of studies have recorded wide spatial variability in rainfall, though, many reported a general overall negative trend since mid-20th century. Further, varying pattern of rainfall has been recorded in three agroclimatic regions of Punjab state, the granary of India. Unseasonal rains followed by spiked temperature during winter (*rabi*) season of 2021–22 reduced wheat (*Triticum aestivum* L.) yield in Punjab by 651 kg/ha and by 301 kg/ha in Haryana compared to 2020–21. Further, the grain was of lower quality. During rainy (*kharif*) season of 2022, Southern Rice Black-streaked Dwarf Virus (SRBSDV), appeared for the first time in Punjab and Haryana. Some farmers ploughed the affected fields. Adverse weather during *rabi* 2022–23 also, reduced the wheat yield (143–150 kg/ha) in these states. At the national level, erratic weather during *rabi* 2021–22 and *kharif* 2022 caused losses of about 3 mt of grain of each of wheat and rice (*Oryza sativa* L.). The projected increased adverse effects due to intensified CC include food insecurity. Thus, there is an emergent need to accelerate implementation of adaptation and mitigation strategies in agriculture. The adaptation options include cultivar improvement, conservation agriculture altering growing seasons, crop diversification and sustainable soil, and water resource management. In the process of adaptive management of crop production, adjusting sowing dates and breeding cultivars having varying duration in consonance with CC has been one of the central aspects. Shifting sowing dates to find appropriate crop cultivation season is a low-cost measure. However, cultivar development is time and resource consuming. Novel biotechnological tools enable fast cultivar development with precision, and facilitate mobilization of genes from wild-weedy relatives, which are rich in genes conferring resistance/tolerance to biotic and biotic stresses, required to combat CC challenge. In view of CC stress on water resources, improving water-use efficiency (WUE) has gained importance. Sensor-based micro-irrigation/fertigation has great potential to enhance water and fertilizer-use efficiency. Similarly, the application of other smart technologies like nanotechnology, sensor-based pesticide application, bio-fertilizers and bio-pesticides, need to be mobilised. In view of agro-ecological diversity in India, right-sized region-specific technology packages have to be developed implying that crop research will expand exponentially. This needs strengthening of human resources and institutional infrastructure, expanding and linking basic and applied researches, and fortifying inter-disciplinary/inter-institutional collaborations to develop and diffuse technology innovations. Enabling factors include enhanced funding and international cooperation. All-out efforts are needed to have more climate-resilient agriculture.

Key words: Adaptation, Biotechnology, Climate change, Climate-resilient cultivars, Crop production, Food security, Micro-irrigation, Mitigation

Concerns are being raised since long about the impending climate change (CC) caused by greenhouse gas (GHG) emissions. The incidence of extreme events has become more frequent in recent years. There are heat waves, droughts, wildfires, untimely and heavy rains, reduction of rainy days, hailstorms, cloudbursts, melting of glaciers, decline in snow cover, floods, landslides, tropical storms, incidence of new diseases and insect-pests, loss of biodiversity etc. in many regions of the word. These changes in climate are causing widespread damages and have endangered food security. The projections are that warming will continue to increase and CC impacts will

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intensify. To meet these projected CC challenges, an accelerated action in GHG mitigation and adaption is critical to support sustainable development and secure a liveable and sustainable future for all. To ensure food security, the focus has to be on development and adoption of technological innovations for climate-resilient agriculture. Climate change at global level and its effects on crop production in food bowl in northwestern region of the country are presented here.

Climate change: Global scenario

The GHG emissions are leading to global warming. During 2011–20, the global temperature was 1.1°C above that during the pre-industrial era, 1850–1900 (IPCC, 2023). The temperature has increased faster since 1970 than in any other period of 50 years over at least last 2000 years. In 2019, agriculture, forestry and other land use contributed approximately 22% to GHG emissions and the rest were produced by other sectors source. The global warming is causing CC which has already caused widespread adverse effects on nature and human systems. These effects are unequally distributed across systems, regions and sectors, and the regions and people with development constraints are more vulnerable. As heatwaves, heavy precipitation, floods, droughts and tropical cyclones have further strengthened since AR5 (IPCC, 2014), it is projected that adverse impacts from CC will continue to intensify.

The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and the Paris Agreement focussed on combating global warming and CC. The UNFCCC entered into force in 1994 with an ultimate aim to stabilize GHG concentrations at a level that would prevent "dangerous" human induced interference with the climate system. The Kyoto protocol entered into force in 2005 was the first implementation of measures under the UNFCCC that committed the state parties to reduce GHG emissions to combat the challenge of global warming and achieve the UNFCCC's objective. This protocol was superseded by the historic, legally binding international treaty, the Paris Agreement. The United Nation (UN) Climate Change conference at its 21st meeting of the Conference of Parties (COP21) reached this landmark agreement in 2015 to tackle CC and its negative impacts. It entered into force in 2016 and its long-term goals include substantial reduction in global GHG emissions to limit the rise of global temperature in this century to 2°C above pre-industrial levels while pursuing efforts to limit the increase even further to 1.5°C. It marked the beginning of a shift towards a net zero GHG-emission world. The benchmark of 1.5°C was based on the UN's Intergovernmental Panel on Climate Change (IPCC) suggestion that crossing this threshold risks unleashing severe CC impacts. As of February 2023, 195 (194 states and the EU) of the 198 members of the UNFCCC are parties to the Paris Agreement that certifies near universal participation. This agreement covers climate change mitigation, adaptation, and finance and led to policy development and target-setting at national and subnational levels, particularly with regard to mitigating. Several mitigation options in diverse sectors including improved crop/grassland and forest management and reduced food waste/loss are technically viable, are becoming increasingly cost effective, and are generally getting public support. Many regulatory and economic instruments have also been deployed successfully. There has been reduced or removed emissions in some cases (IPCC, 2023). Yet, it is likely that global warming will exceed 1.5°C. In spite of overwhelming proportion of the funds being devoted to mitigation, insufficient funds are the major constraint. There are gaps in many countries especially in the developing ones. Apparently, there is a need of accelerated implementation of the mitigation options with enhanced funding support to limit warming to below 1.5°C.

There has been progress in adaptation too, and the effectiveness of adaptation in reducing climate risks is documented (IPCC, 2023). Effective adaptation examples include cultivar improvements, on-farm water management and storage, soil moisture conservation, irrigation, farm/landscape agricultural diversification, agroforestry, and sustainable land management. Despite progress, there are gaps which are projected to continue to grow under current levels of implementation of adaptation measures. So far adaptation options got only a small part of available funds and that too predominantly from public sources, and limited funding is the most important constraint particularly in the lower income groups, as in case of mitigation.

The projections are that global warming will continue to increase (mainly due to increased cumulative CO_2 emissions) and will very certainly exceed 1.5°C in the near future, probably during 2021–40 (AR 6). According to Cuff (2023), year 2023 could be the hottest year encountered so far, as extraordinary levels of high temperature are being observed in global weather: the first 11 days of June registered the highest global temperatures for this time of the year and May was second-warmest, and April was the fourth-warmest month on record. The peak occurred on 9 June, when the average global air temperature was 16.7°C, just 0.1°C below the warmest ever recorded on 13 August 2016. Evidently, the adverse effects of CC will continue to intensify, that is, rainfall, temperature and seasons may become erratic, and heatwaves, droughts, and tropical storms, more intense and frequent. Aridity is also projected to increase. The likelihood of abrupt and/or irreversible changes, such as irreversible loss of biodiversity (species extinction) in ecosystems will also increase. The loss of biodiversity has multiple implications for ecosystem and agriculture including erosion of the foundation of crop improvement. These risks will become increasingly complex and more difficult to manage with every increment of global warming. Further, global warming above 1.5°C is bound to adversely affect the efficacy of the options feasible and effective today, and adaptation limits may be reached in some cases (such as freshwater resources). The human and natural ecosystems are projected to face further increased risks and damages with severe consequences. These risks and damages are expected to include sharp reduction in food production leading to acute food insecurity and reduced water security. As per IPCC (2023) an acceleration of GHG mitigation and adaptation actions for sustainable development is more urgent than previously assessed in AR5 (IPCC, 2014). Global warming may decline back to below 1.5°C by the end of the 21st century (IPCC 2023).

Greenhouse gas emissions and crop performance

Temperature is a major factor affecting the crop growth and yield. Increased temperature is associated with faster growth. In most agro-ecologies, it shortens duration of plant growing period causing yield losses at the global level (Asseng *et al*., 2015; Zhao *et al*., 2017; Kahiluoto *et al*., 2019). There are projections for average yield to decrease by 3.7% per 1°C rise in day temperature and by 4% per 1°C rise in night temperature at global level (Lobell *et al*., 2011; Hatfeld *et al*., 2011, Hays *et al*., 2022). However, the effect of rising temperature will vary depending on the prevalent temperature. An increase of temperature will reduce crop yield in an agro-ecology having optimal temperature, and if the region already has temperature near upper limit (e.g., in tropical areas), economically viable crop cultivation may become difficult. Whereas increased temperature will enhance the performance in the area having low temperature and may make the cultivation of a crop possible in an area wherein the crop cannot be cultivated due to low temperature (e.g., in temperate areas). During past 50 years, the growth of crop productivity has slowed down mainly in mid-and low latitude regions, but is positively affected in some high latitude regions. It is also worth noting that maize (*Zea mays* L.) yields in the USA have increased in spite of warming climate, partially owing to earlier sowing and longer-duration varieties (Butler *et al*., 2018) and were projected to increase in Europe (Parent *et al*., 2018). Further, shortening of crop growing period may open up possibilities of adopting new cropping system. Short duration summer/spring mungbean [*Vigna radiata* (L.) R. Wilczek] is being cultivated on a small scale as a *zaid* crop in-between *rabi* (winter) and *kharif* (rainy) seasons in northwestern India. The area under its cultivation may increase. The incorporation of another crop in a cropping system will provide a cushion to the farmers against the losses due to erratic weather on per year basis, and will also widen their economic base. However, it will depend on the water resources as increased temperature and raising an additional crop, that too during summer season, will considerably enhance the irrigation water demand of a cropping system.

The effect of GHG emissions on crop production is more than that of simply increased global warming, though, temperature is an extremely important factor. The dominant GHG emitted is CO_2 (the two other main gases being methane and nitrous oxide) and an increasing concentration of CO_2 is expected to increase photosynthetic rate of plants and crop yield. The variable reduction in maize yields in different regions of the world, in response to changing temperature, precipitation, solar radiation, humidity, etc. in irrigated areas is shown in AR6 (IPCC, 2023). It is added that during past 50 years, the growth of crop productivity has slowed down but, on the whole, global crop productivity has increased.

Climate change-Indian scenario

Weather data in India are available since 1901. Using different temporal and spatial datasets, innumerable studies have been conducted on climate in India and its different regions. The studies revealed that CC, besides causing an increase in average temperature, has also altered rainfall pattern in India. However, projections for rainfall are not as reliable as for temperature. In general, negative trend of rainfall has been recorded since the middle of the 20th century or recent temporal parts thereof for most of the country or specific regions (Bollasina *et al*., 2011; Mishra *et al*., 2012; Oza and Kishtawal, 2014; Mondal *et al*., 2015; Radhakrishnan *et al*., 2017; Xu *et al*., 2018; Praveen *et al*., 2020). On the other hand, wide spatial variability was observed in many studies (Guhathakurta and Rajeevan, 2008; Jain and Kumar, 2012; Rathore *et al*., 2013; Saha *et al*., 2018; Praveen *et al*., 2020; Maharana *et al*., 2021). Further, in the studies wherein a homogenous response was reported, the rate of change varied within the regions. Saha *et al*., (2018) reported reduction in wetness trend over north mountainous region, and an increasing trend over southern peninsula, whereas the opposite was observed by Maharana *et al*., (2021) for the southern India. Maharana *et al*., (2021) also recorded reduced rainfall over northeastern region and Indo-Gangetic Plains (IGP) but higher rainfall over northwestern India. It is interesting to note that northeastern region, that was once high rainfall zone in the world, is now receiving lower rainfall, whereas, western region is receiving higher than normal rainfall that supports possible greening of Thar region.

On the whole, the conclusions were highly variable for different regions of the country which is not unexpected for such a vast and diverse country, such as India. This high variability in spatial domain makes it difficult to draw reliable and practical conclusions at the national level and underscores planning at regional level instead of national level.

The changes in rainfall, as reported by Maharana *et al*., (2021), have been causing a shift of IGP towards a relatively arid regime. Sandhu and Kaur (2023) recently studied the changing pattern of monsoon rainfall in different agroclimatic regions of Punjab, a state which is part of IGP. The state has three major agro-ecological regions identified on the basis of physiography, rainfall and underground water quality and quantity. These are northeastern submountainous and undulating plain region, central plain region and southwestern region having >800–900, 500–800 and <200 mm average annual rainfall, respectively. During the first 2 decades of the present century, rainfall has decreased in the state, though, the duration of the monsoon season has increased. However, the change in rainfall differed among three zones. The rainfall declined in northeastern and southwestern regions while central plain region registered an increase. Further, the decrease in the rainfall in the state was mainly due to a decline in rainfall in the sub-mountainous north-eastern region, the region having the highest rainfall. The distribution of the change in the monthly rainfall during monsoon season was also variable in three regions. Evidently, the impact of CC needs to be considered for different agro-ecologies even in a small state like Punjab, which occupies only 1.53% area of the country.

Punjab- Rabi *2021–22, 2022–23 and* kharif *2022 crop seasons*

Punjab is playing a leading and dependable role in national food security by being the largest contributor to central pool of foodgrain (wheat and rice) reserves since 1970s. Thereby, the state has come to be known as 'foodgrain bowl of India'. During 2022, there have been extreme weather conditions, viz. high temperature and droughts coupled with unseasonal and erratic rains that have direct adverse impact on crop production. Wheat is the main crop during *rabi* season in Punjab. The *rabi* 2021–22 crop (sown during October-November 2021) was having normal growth. However, the weather became highly erratic in 2022. During the first fortnight of January 2022, 99.4 mm rainfall was received at Punjab Agricultural University, Ludhiana as compared to the normal weekly rainfall of 8.6 mm for this period. Again, 31 mm of rainfall was received from 29 January to 4 February (5 standard week), against 5.6 mm normal rainfall. Further, during January 2022 cloudiness reduced the duration of sunshine to 1.9 hr compared to normal of 6.1 hr per day. Heavy rains in January 2022 resulted in stress on the crop plants due to water stagnation, the problem being more serious in heavy soils. The rains accompanied by reduced sunshine duration (caused by cloudiness) adversely affected the photosynthesis and crop growth. The long spell of rains from January-end to early-February also negatively impacted the pollination.

The temperature witnessed extraordinary spikes in March 2022. It suddenly rose after 5 March. It was 2.2°C above normal during 5–11 March (10 standard week). The temperature rose further thereafter, the weekly temperatures being 5.5–7.1°C above normal between 12 March to 15 April, i.e. 11 to 15 weeks except that it was 4.6°C above normal during 2–8 April. High temperature was accompanied by no rainfall from 5 March to 15 April against the normal of 29.7 mm. The sudden rise in temperature in March 2022 coincided with grain development as wheat crop is very sensitive to high temperature. It adversely affected grain yield components, such as ear length, grain number and grain boldness. Further, high temperature forced advanced maturity by about 10 days and the grains produced were shrivelled and had poor lustre. Thus, wheat yield in Punjab dropped to 4217 kg/ha during *rabi* 2021–22 from 4868 kg/ha in 2020–21. In the neighboring state of Haryana also, wheat yield went down from 4834 kg/ha during 2020–21 to 4533 kg/ha during 2021–22. Further, the grain was of lower quality.

During *kharif* season, rice is the main crop in Punjab. Even though, there was a deficient monsoon, rice transplanting was not delayed and had normal plant growth since it is cultivated under irrigated conditions. However, a new viral disease of rice, Southern Rice Black-streaked Dwarf Virus, also known as dwarf disease, transmitted by white-backed planthopper, appeared in some parts of the state (and also in the adjoining districts of Haryana) in July 2022. This disease has been first reported from southern China, and is the first viral disease of rice in Punjab and Haryana. The disease incidence was reported on *parmal* in about 34 thousand ha in Punjab (Department of Agriculture and Farmers Welfare, Govt of Punjab). The severity was relatively high in the districts in northeastern region. There was stunting of 5–15% plants during initial vegetative phase and later on, even some plants having nearly normal growth did not flower. Some farmers ploughed the affected fields. The *parmal* yield was practically the same during *kharif* 2022 (4564 kg/ha) and *kharif* 2021 (4578 kg/ha), though area was a little less during 2022 (2.67 mha) than the previous year (2.71 mha) which may be owing to ploughing of diseased fields or other factors. In Haryana, however, rice yield dropped to 3558 kg/ha during *kharif*

2022 from 3650 kg/ha during *kharif* 2021.

The extreme weather during 2022, adversely affected the health and performance of livestock too. There was also an epidemic of Lumpy Skin Disease in livestock caused by the Capripoxvirus (transmitted by mosquitoes, biting flies, ticks). This disease was endemic in Africa, but had appeared in the southern states of India during last 2–3 years. It affected mainly cows and to a lesser extent buffaloes. In Punjab it was first reported in June, peaked in July and its spell continued till November (The Tribune, 2022). There were 1.74 lakh cases and 17,932 deaths, the deaths being third highest after Rajasthan and Maharashtra. The milk yield of the affected cattle in Punjab dropped by 10–15%.

A knock of impending erratic climate came quite early in 2023, that is in the month of February, which is technically a part of the regular winter season in north India. Average temperatures started rising in early February, and weekly temperature from 5 February to 18 March remained above normal by 2.2–4.4°C. Thereafter, the temperatures dipped due to unseasonal rains in March and April. Consequently, wheat crop was not much affected by early spike in temperature and untimely rains thereafter. Though, rains caused crop lodging, but these two erratic weather events worked in opposite directions with respect to the effect of temperature on wheat crop. Thus, adverse effect of erratic weather was partially nullified and the resultant wheat yield loss was smaller than that during 2021–22. The estimated wheat yield during *rabi* 2022–23 was 4725 kg/ha in Punjab and 4684 kg/ha in Haryana, these yield levels being higher than that during 2021–22 but lower than that during 2020–21 in both states.

India-Rabi *and* kharif *crop seasons, 2022*

Erratic weather during 2022 played havoc at the national level too. There was unusually high temperature in northwestern and central India during March-April and consequently an early onslaught of heat waves. Thus, the performance of wheat crop was adversely affected. The national wheat yield during *rabi* 2021–22 was 3507 kg/ha compared to 3521 kg/ha in 2020–21, and the national wheat production was 106.8 and 109.6 mt during these two years, respectively. Thus, about 3 mt of wheat grain was lost due to heat stress source.

The heat wave was followed by the failure of monsoon in June, when the sowing of *kharif* crops starts. It resulted in a drop of area sown compared to June 2021. Thereafter, the progress of monsoon was smooth in most parts of the country. By mid-September 2022, as per Union Ministry of Agriculture and Farmers Welfare, the monsoon at the national level was 'above normal' by 6% (Directorate of Economics and Statistics, 2022). But the distribution was uneven. East, northeast and northwest (except Punjab) received 8 to 17% less rains and Uttar Pradesh, Bihar, Jharkhand, West Bengal, Punjab and parts of northeast received 20 to 59% less rains. Resultantly, the area under *kharif* rice reduced to 40.45 mha during 2022 compared to 41.04 during 2021, and the yield to 2672 Kg/ha from 2705 kg/ha during the respective years (CACP, 2023). The production was lower by about 3 mt (108.08 mt during 2022 vs 111.00 mt during 2021).

Mitigation and adaptation

The adverse impacts of CC caused by increasing global warming on human and natural systems include reduced crop productivity and thereby threat to food security. In addition, poor crop performance directly and immediately impacts the livelihood of farmers. India is specifically vulnerable as it has burgeoning population and large number of farmers and others in low-income group. It must also be appreciated that agriculture (food production), being a climate-exposed sector, is most vulnerable to adverse impacts of CC. Thus, there is an emergent need to intensify two-pronged strategy of mitigation and adaptation to meet the expanding qualitative and quantitative food requirements of the ever-increasing population from limited land and water resources.

The strategies and action plans must integrate adaptation and mitigation employing innovative technologies to harness synergies and reduce trade-offs between adaptation and mitigation. Many feasible, effective, and low-cost options for mitigation and adaptation are available in agriculture that could be upscaled in the near-term (IPCC, 2023). However, it is to be noted that for mitigation, the causative factors of CC have to be offset, and some agricultural practices can contribute to the reduction of GHG emissions, though, it is hard to abate the emissions. Further, adaptation does not prevent all adverse effects, even with effective adaptation and before reaching limits. In spite of these limitations, agriculture will continue to be indispensable because food is the most basic need of human being. Further, agriculture offers an important natural solution to global warming as crop plant pull CO_2 from the air and sequester, and store carbon in soil.

In agriculture, the correction of market-led unsustainable land use and land-use changes, choice of different crops/cropping systems and the cultivation protocols including soil-water management practices help reducing the GHG emissions. Conservation agriculture (CA), based on the inter-related principles of minimal mechanical soil disturbance; permanent soil covers with living or dead plant material; and crop diversification through rotation or intercropping, helps conserve land and water resources, environment and biodiversity. It increases available soil water, saves irrigation water, reduces heat and drought stresses, reduces GHG emissions, captures carbon and improves soil health in the long term, and thereby, responds to the challenges of CC (Pathak *et al*., 2021; Sharma, 2021). There are also significant benefits of CA towards mitigation (reduction in global warming potential by 12–33%) as well as adaptation to excess rainfall and heat stress.

The adaptation strategies include improving cultivars and crop production practices, shifting crop production areas, altering cropping systems and growing seasons, crop diversification, sustainable soil and water resource management, improving water use efficiency and soil moisture conservation. Some adaptation strategies which minimise food loss/waste (development of crop cultivars and production technology that support transportation, processing, etc.) and promote balanced healthy diet based on diverse plant-food items produced locally in resilient and sustainable systems (development of improved production practices for crops grown in stressed ecologies, development of high yielding and nutritionally rich cultivars, etc.), contribute to nutrition, biodiversity and other environmental benefits. Development of sustainable soil and water resource management practices and cultivation of new cultivars in new areas, and altered cropping systems necessitates a total remodeling of production technology packages, that will include the quantity of irrigation water and fertilizers, and their application schedules. Further, the spectrum of insect-pests, diseases and weeds may change due to CC, warranting a revision of the plant protection measures.

The development of crop production practices is not a new phenomenon. This phenomenon has been operating for thousands of years, and in fact it gave birth to agriculture. These practices have evolved over time through adjustments and optimization of the cropping systems to local agro-ecological conditions and incremental climatic changes (Hill and Li, 2016; Kahiluoto *et al*., 2019; Fatima *et al*., 2020; Karapinar and Ozertan, 2020; Minoli *et al*., 2022). Through these efforts, human being has been able to identify and expand the areas of crop cultivation. In this process of adaptive management of crop production systems, adjustment of sowing dates and choice/breeding of cultivars in consonance with rising temperature and other changes in climate has been one of the central aspects. Shifting sowing dates to find appropriate season for crop growing period is an easy and low-cost measure to combat CC. On the other hand, breeding varieties is time and resource consuming.

Some agronomic interventions (besides CA) for adaptation/mitigation, especially for the food bowl, are given as:

Optimum sowing time: It is very crucial for higher yield and adaptation to climatic variations. The sowing of long duration wheat varieties should commence from end of October (Ram *et al*., 2017), that of medium duration varieties from 1st week of November whereas sowing of short duration variety Unnat PBW 550 should commence from 2nd week of November. Long duration wheat varieties sown in end of November or later are expected to face terminal heat stress. Thus, in case wheat crop is to be planted late, only heat tolerant varieties are recommended. For saving underground water and maximizing yield of rice, the optimum time to transplant seedlings is from 20 June to 10 July.

Water-saving technologies: The techniques, like laser land levelling, bed planting, drip irrigation, etc. are valuable measures to adapt to CC (Dar *et al*., 2019; Sharma, 2021).

Application of irrigation to wheat crop in the end of March: If temperature rises above the normal, then one additional irrigation to timely sown wheat crop may be applied in end of March (Jesse *et al*., 2017) to protect the crop form terminal heat stress. Wheat crop sown on 10 November under bed planting with one additional irrigation in last week of March had higher dry-matter accumulation, leaf area index, number of effective tillers, ear length, grains/ear, 1,000-grain weight, PAR (photosynthetically active radiation) interception and radiation use efficiency as compared to three post-sowing irrigations (at crown-root initiation, flag-leaf emergence and soft dough stages), although the water-use efficiency was better in the later (Dhaliwal *et al*., 2020).

Application of bioregulators: Application of 2% KNO_3 at boot leaf and anthesis stage or salicylic acid @75 ppm at boot leaf and early milk stage helps to mitigate the effect of high temperature and enhance the wheat yield (Jatana *et al*., 2021; Tanin *et al*., 2023). These foliar applications also increase days to maturity and keep the leaves green for longer duration. Similarly, foliar spray of 1.5% potassium nitrate at boot stage (Dhillon *et al*., 2021) reduces sterility in rice, and protects rice crop from high temperature stress and drought stress. Application of salicylic acid @200 ppm to wheat crop sown at 18, 20 and 22°C resulted in significant improvement in grain yield, harvest index and nutrient (N, P and K) uptake (Lakhran *et al*., 2021).

Mulching/Happy seeder sowing: Mulch retained or applied to the soil modifies crop microclimatic aspects, viz. solar radiation, reflection and absorption, shading, temperature, humidity, wind/air movement, evaporation, soil moisture and crop growth (Stigter *et al*., 2018). Mulching helps to confer tolerance to terminal heat stress in wheat as it reduces the canopy temperature by maintaining the optimum water potential in the plant leaves (Ram, 2020). The happy seeder and zero till drill with mulching technologies gave the similar advantage to reduce the adverse effect of high temperature effect on wheat (Sidhu *et al*., 2015). In a study on *Bt*-cotton hybrids in Punjab, rice-straw mulching in cotton crop saved one irrigation and 50 kg N/ha with yield gain of about 10% for seed cotton yield as compared to no mulch (Joshi and Singh, 2021).

Improving soil health: Enhancing and maintaining soil organic carbon (SOC) concentration to above the critical threshold (1.5% in the 0–20 cm depth) is essential to improving soil quality, increasing use efficiency of nutrients and water, minimizing vulnerability to extreme climatic events, and sustaining crop production (Lal, 2013). Improvement of SOC stock can be achieved through use of organic amendments (biochar, manures), diversification of farming system and conservation agriculture (Benbi, 2022).

Intercropping: It is an efficient strategy to safeguard against climate aberrations. Grain-legume intercrops have many potential benefits such as stable yields, better use of resources, weeds, pest and disease reductions, increased protein content of cereals, reduced N-leaching as compared to sole cropping systems (Venkateswarlu and Shanker, 2009).

To meet the challenge of CC, new cultivars should possess a higher degree of heat and drought tolerance, disease and insect-pest resistance/tolerance, and other desirable agronomic traits besides variable growing-period durations. There is large genetic variability for these traits in germplasm of crop species available with the plant scientists as well as conserved in gene-banks. Further, wild and weedy relatives of crop plants are richer for these traits. Novel biotechnological tools enable faster transfer of desirable genes with greater precision than conventional breeding methods, and are of greater importance in channelizing the desirable traits from wild and weedy species. Crop germplasm explorations for collecting and conserving seeds, plants and plant parts exhibiting desirable traits particularly tolerance to temperature, water and other atmospheric stresses caused by climate change needs to get greater attention as these would constitute the most important cost effective basic raw material for crop breeding which will allow agriculture to adapt to climate change (Venkateswarlu and Shanker, 2009).

Crop improvement programmes are continuously developing varieties having tolerance/resistance to abiotic/biotic stresses besides high yield and other desirable traits. To tolerate or escape stresses, improved crop varieties of variable growing-period durations are also being developed. In wheat long duration varieties are more susceptible to terminal heat stress than medium and short duration varieties (Kaur and Ram, 2023). Medium duration wheat varieties like DBW 187, DBW 222, PBW 826, PBW 869, PBW 766 and short duration variety 'Unnat PBW 550' have the ability to tolerate or escape the high temperature stress during March. In rice, the water requirement increases with its growing-period duration. Short duration rice PR 126, a very popular variety (Burman *et al*., 2020), has significantly less irrigation water needs than other varieties, which is expected to lower methane emission.

Human being is already facing a major challenge on water front that has been accentuated by CC. Besides reduction in the amount of rainfall, intense rains are leading to higher runoff losses and reduced recharging of aquifers, and rising temperature is increasing crop water demand. Further, groundwater resources are depleting because of over-pumping of water required for present-day intensive agriculture being practised to meet our needs. Thus, already scarce water resources are getting stressed. In this situation, enhancing water- use efficiency in agriculture, a major user of water, through improving/adopting better irrigation strategies has gained top-most urgency. Sensor-based micro-irrigation and fertigation protocols have great potential to enhance water and fertilizer-use efficiency, and make optimal use of stressed water resources. Accurate weather forecasting on short-as well as long-term basis, is gaining importance day-by-day. Similarly, the application of other smart technologies like nanotechnology, sensor-based nutrient and pesticide application, artificial intelligence and plant bio-regulators, bio-fertilizers and bio-regulators and digitalization, most of which are financial-resource intensive, needs to be mobilized. Multi-disciplinary teams are required to integrate different improvements to develop optimized crop production technology packages.

India is agro-ecologically highly diverse. Different regions in the country have variable climate, topography and pest (diseases, insect-pests and weeds) scenario and agri-systems. There are temperate and tropical climate zones as well as desert and high rainfall regions. Thus, there cannot be one-size-fits-all solution, and right-sized technology package will have to be developed for different agro-ecologies. This implies that crop research will expand exponentially. To harvest the potential benefits, improved technologies and management practices should be put into widespread use in crop production on farmers' fields. To accomplish that, farmers need to be encouraged, educated and equipped to learn the latest scientific and management practices in crop cultivation, and complement the same by personal experimentation and local knowledge. In case of technologies and practices that target resource conservation (micro-irrigation and fertigation schedules, integrated non-chemical and chemical solutions) rather than enhanced productivity, provision of need-based financial incentive initially may be considered to prompt farmers to adopt the same.

To achieve these goals, emphasis has to be on strengthening human resources and institutional infrastructure, expanding and linking basic and applied researches, fortifying inter-disciplinary/inter-institutional/ministerial collaboration and policy support. Further, enhanced investment is needed in R&D to enable the scientific community to develop, improve, integrate and promote new climate-smart innovations, technologies and practices, and their diffusion. However, limited financial resources are a critical constraint affecting the efforts on mitigation, adaptation and climate-resilient development. Though, global funding support has increased since AR5 (IPCC, 2014), yet, the current support is insufficient (even for mitigation) and hindering the progress especially in developing countries. The financial support needs to increase many-fold. Enhancement of financial support and rapid technology innovation both essentially require global collaboration. Furthermore, public finance is an important enabler in this endeavour and will also leverage private finance.

In India agriculture is important, economically as well as socially because of dependence of large section of the society on it. All-out efforts must be made for transitioning the agriculture to be more sustainable so that agriculture becomes a contributor to the climate-resilient development aimed at securing a liveable and sustainable future for all.

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