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Research Review

Complexities of Climate Change: Impacts on Rice and Wheat Productivity in India and a Challenge to Global Food Security: A Review

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Abstract

Climate change, through its perils and risks generates vulnerable impacts that can surpass limits to adaptation and results in depletion and damages. The observed effects of past climate trends on global crop production and the increased susceptibility of plants enfeebled by the direct impacts of varying climatic conditions are evident in several regions of the world and are of special concern in agricultural dependent tropical regions with low or no levels of adaptation. Steady depletion of soil health and ecosystem services, sudden loss in food production from heat and drought are threatening food productivity thereby, compromising global food security worldwide. The present study is an overview of possible effects of the varying climate on rice and wheat production in India and it focuses on the impacts of the major climatic variables viz., CO_2, temperature and rainfall on yield and quality. The increase in these factors can lead to reduced yield of crops, increased incidence of pest and disease outbreak, stunt the growth or cause complete crop failure. Crop production and management is a huge challenge because it is always highly dependent on climate and environmental factors. Therefore, shifting weather patterns and other factors contributing to such challenges must be identified and rectified. There is a growing need to understand the ecological dynamics of climate change impacts, to identify hotspots of vulnerability and resilience and to identify management mediations. The mechanisms, potentials and limits of natural as well as technology-based solutions need to be explored and quantified.

Key words: Climate change, Crop response, Food security, Mitigation, Rice, Wheat

Carbon dioxide (CO_2) is the principal cause of climate change as it contributes highest in global warming. Climate change has irreversible impacts on natural and human systems and its extreme case scenario in the future is horrific. Many Green House Gases (GHG) are responsible for the rising levels of atmospheric temperatures which has led to concerns about future climatic condition and its effect on agriculture either directly or indirectly [1-2]. In recent times, the total gas emissions, including land-use change, reached a new height of 59.1 gigatons of carbon dioxide equivalent [3]. Agricultural activities, transportation based on fossil fuels and non-renewable energy generation contribute mainly to GHG emissions [4]. The major agricultural emissions include N_2O from fertilizers and CH_4 released from rice land and livestock production [5]. Climatic fluctuations are a global issue and agricultural activity is adversely affected by climate change as it is dependent on climate and other weather conditions. Climate change has both positive and negative impacts on agricultural systems at the global level and its effects are due to extreme variability in temperature, rainfall pattern, deprivation in soil water availability [6]. These variabilities are expected to have significant impacts on plants growth and development causing reduction in crop yield, fruits, vegetables and growing period [7]. Many crop species require optimally higher temperature during vegetative development than reproductive development. Due to extreme temperature during reproductive stage, pollen variability, fertilization and grain formation is also affected [8-9]. The impacts of climate change are most evident in agricultural productivity which results in direct, indirect and biophysical effect. Recently, with the advancement of the possible global climate change, world food security in general and its regional impacts in particular have come to the forefront of the scientific community [10].

Global food security and agricultural productivity

One of the most important challenges in the 21st century is global food security. Food security refers to the availability of safe and nutritious food to meet the dietary needs, physical and economic access, utilization and stability for leading an active and healthy life [11]. Due to continuous rise in GHG

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emissions, plants are affected adversely and many important crop species are slowly declining. On a global scale, climate change could lead to the extensive loss of plants. Crop production depends on several important factors such as light, temperature, rainfall, humidity, carbon dioxide and moisture which varies according to geographical locations. Any change in these climatic factors leads to varying degrees of negative impacts in crop production and management, thereby compromising global food production. Due to interaction among climate change, crop production and food security, it is likely to have adverse climatic effects on agricultural productivity leading to food insufficiency [12]. Reduction in the agronomic crop productivity signifies the main threat to food security in this growing world's population. A higher level of global warming at 2°C or more enhances the risks of food security, thereby exposing people to problems of malnutrition, micro-nutrient deficiencies and acute food insecurity with profound impacts in Central and South America, Sub-Saharan Africa and South Asia [13]. An increase of 3°C, the regions exposed to climate-related hazards will considerably expand, showing regional discrepancy in food security risks. As a result of both climatic and non-climatic factors, half of the world's population face high risks of water deficit for at least some part of the year. Many human-induced climate change has brought detrimental effects, causing loss and damage to nature and mankind beyond natural climate variability. Over the years, though the agricultural productivity has its significant growth globally, it is climate change which has slowed this increase in the past 50 years, impacting positively in high latitude zones and negatively in low latitude zones. Both climate and crop productivity are inter-related with the global processes. Any threat of climate change looms over agriculture productivity and mainly the tropics, particularly the semi-arid regions of the developing world is more vulnerable to it.

Agriculture being the main occupation for nearly half of India's population plays an indispensable role in the overall economy. Though agriculture with other allied sectors contribute 15.4% of the Indian GDP [14], climate change has impacted both by loss of crop yield, reduced livestock productivity and fish production which has led to negative impacts on food security, nutritional security and rural livelihoods. In India, agricultural productivity is climate sensitive and the fluctuations like changes in temperature, precipitation and solar radiation can adversely affect the crop productivity, which may threaten food security. The alterations in climate changes the progressive stages of pathogens that affect the crop yield and growth, leading to an increase in pests and ultimately devastating the overall productivity. It has been estimated that the annual loss of US$ 9-10 billion was due to the adverse effects of climate change [15]. Water scarcity also pose a threat to food security of India. The Himalayan glaciers are slowly melting down because of elevated temperature, and if this continues, the fresh water stock for survival will be at a high risk in the near future [16]. In South Asian countries, 30% decrease in crop productivity is expected by mid-21st century. North India and Bangladesh are more prone to erratic changes in rainfall and temperature [17]. Projected scenario of climate change over the period 2010-2039 is decrease of crop yields by 4.5-9% but during 2070-2099 the impact is dramatic, reducing yields by 25% or even more which is a matter of concern [18].

Plant responses to varying environmental factors

Temperature plays a major role in the blooming and growth of plants. Different environmental stresses can induce crop responses like accelerated life cycle, reduced leaf area, inhibition of metabolism, damaged reproductive growth which cause serious threats to naturally available crops [19]. Throughout their lifetime, they might alter the initiation and developmental events in molecular, cellular and morphological level, thereby altering the final form of individual organs or whole plants. Such factors that affect these agricultural crops of importance include elevation of carbon dioxide and temperature, heat waves, variations in rainfall, modifications in pests or microbes, etc. While temperature fluctuations influence plant physiology [20], drought condition affects the morpho-physiology of plants negatively, water shortage decreases the metabolic competency, heat stress influences the productivity of grain and cold stress results in sterility [21-22]. The rise in atmospheric CO_2 concentration might affect future global agriculture production by changing the rate of transpiration and plant growth [23-24]. Higher temperature levels have shown reduction in photosynthesis and crop cycles and an increase in transpiration [25]. But the effects of climate change on crops quality and quantity may also be affected by the region, crop species and management [26].

Effects of elevated CO_2

CO_2 have significant impacts on crop growth, development and production. CO_2 as a plant resource is consumed in photosynthesis and extensive work on plant responses to elevated CO_2 both regional and global has urged researchers to consider disturbances and large-scale recovery. CO_2 is responsible for affecting plants directly via impacts on photosynthetic gas exchange and downstream developmental processes [27]. CO_2, being a potent greenhouse gas acts as a critical element of global environmental change and has indirect effects on plants thereby contributing to its associated changes in climate warming. As a result of elevated CO_2, plants synthesize more chloroplasts, mesophyll cells, longer stems, extended diameter, length and number of large roots, more lateral root production with changes in branching pattern [25].

Effects of elevated temperature

Temperature is considered another important determinant of plant performance, their plant responses differ in the stages of plant development among crop species throughout their life cycle affecting insect behavior, distribution, development and reproduction [28]. Extreme temperature is responsible for influencing the reproductive phase of plant growth as it changes the time of reproductive events. These events may lower the plant's ability to gather the resources required for successful production of gametes [29]. The tropical land may become unsuitable for cultivation, while other temperate regions may produce more crops. Temperature instability will provide suitable environmental conditions for various insect pests of crops to boost their ability to survive in cold temperature. Exposure to high temperature reduces the chlorophyll content of the leaves since heat stress affects the functioning and changes the structural arrangement of the thylakoids [30-31]. Several other environmental factors such as light intensity, water availability and occurrence of strong winds are also associated with the effects of rise in temperature [32].

Effects of rainfall variability

Crop production is highly influenced by availability of water and in India, the summer monsoon accounts for 78% annual rainfall. Due to climate change, there will be alterations in patterns of rainfall, soil moisture storage and evaporation [33]. The total amount of seasonal rainfall patterns are highly important as it is estimated that over 80% of total global crop production is supplied mainly by rainfall [34]. Recently, it is predicted that, with increase in climate change, areas receiving high levels of rainfall will receive more, and those that are dry will become drier [35]. As a result of varying patterns in rainfall, farmers can no longer rely upon the seasonality of climatic variables. Shifting the weather patterns and planting seasons will likely affect the farmers to plan and manage crop production. Generally, crops are damaged physically by floods, heavy rainfall and hail storms. An exposure to extremely wet conditions in the field can delay planting and harvesting or even stunt the growth of field crops. Prolonged conditions of drought can cause complete crop failure and permanently damage plants [36]. Drought stress adversely affects the morphology, physiology and biology of plants. Frost causes sterility and abortion of formed grains and excessive heat causes reduction in grain number and grain filling period.

Effects of environmental factors on the two most important food crops of India

A growing concern is quite evident regarding crop responses to varying growth conditions, that affect their development and impacts food security and livelihoods amongst farmers, researchers and policy-makers. Several parameters are responsible for affecting climate change such as, temperature, precipitation patterns and atmospheric CO_2. High atmospheric CO_2 produces a stimulatory effect on the growth of C_3 crops like rice and wheat [37]. In the short term, an elevated temperature may affect different enzymatic reactions and gene expression whereas in the long term, carbon assimilation, growth rate and potential return may be affected [38]. Reports on global climate change suggested reduction in crop production by 10-40% between 2080 and 2100 under current agricultural management [39-40]. Over the last few decades, wheat and rice productivity has been declining and thus raising major concerns for food security world-wide [41]. In order to implement proper adaptation responses or measures, it is of utmost importance to learn and understand the changing scenario of rice and wheat production and how it affects further due to additional stresses resulting from varying climatic conditions.

Oryza sativa L. (Rice)

In India, rice is the staple food accounting for more than 60% of its population and ranks second in production in the world with an area covering approximately 45 million hectares. It prefers to thrive well in clayey and loamy soil between 22-32ºC with high humidity and rainfall around 150-300 cm. Rice productivity in India has increased considerably to 178 million tonnes in the recent years from 20.58 million tonnes in 1950 [42]. In Northern and Western regions of the world, one crop of rice is cultivated during May to November but in Southern and Eastern regions, due to favorable mean temperature, two or three crops of rice are cultivated per year. Rice is quite sensitive to low and high temperature stresses. An increase in temperature (>35°C) hampers pollination, shows poor anther dehiscence, causes spikelet sterility and negatively affects the growth of roots and shoots. Lowering temperature (<20°C) causes reduction in grain yield and panicle sterility, hampers flowering and tiller formation and delays rice germination [31]. Elevated temperature has a negative effect on rice production, but the impact of changes in rainfall is positive. Sometimes, water scarcity during meiotic phase of rice can cause reduction of 60% in harvest index and 35-75% in grain set [43]. Drought stress affects greatly in the process of fertilization and anthesis which occurs between 9 to 11 am [44]. An exposure to high temperature above 33ºC within 1-3 hours after anthesis can cause negative impacts on reproduction [45]. In India, it has been estimated that rice yield production will be reduced due to climate change under medium emission scenario (3 to 5%) and high emission scenario (3.5 to 10%). The former are assumed to be prevalent in the future, accounting rice production to be 104 million tonnes during mid-century (2021-2050) and 101 million tonnes during end century (2071- 2100) indicating a total reduction in rice yield by 2.5% and 5% respectively [46]. In India, changes in temperature and rainfall could lower average rice yield by 15-25% [47]. It has been reported that an increase in temperature by 1.5°C and decrease in the precipitation of 2 mm, reduces the rice yield by 3-15% [48] while an increase of 2ºC in average air temperature could reduce rice yield in high yield areas and low yield areas [49]. Each 1ºC rise in temperature, decreased the rice yield by 2.6%. Another study revealed that an increase in temperature by 2.5ºC during the vegetative and reproductive stages of the rice growth led to the decrease in grain yield by 23% and 27% respectively [50]. The impact of climate change on rice production in selected river basins of India indicated that there will be marginal reduction in rice production in the future [51]. Experiments conducted by maintaining temperature at 4ºC and a carbon dioxide enrichment level of 650 ppm, showed panicle initiation, flowering and maturity much earlier than those grown under existing normal condition. However, the experiments also recorded reduced leaf area index, lower yield of grain and straw, dry matter production and number of tillers. Sensitivity experiment of the CERES-rice model to CO_2 concentration indicated that an increase in CO_2 concentration leads to increased water use efficiency and yield because of its fertilization effect [52]. On the other hand, temperature sensitivity experiments have shown that there is a consecutive reduction in the yield for a change in temperature up to 5 °C. The projected results for duration 1980-2049 in Kerela concluded that a rise in temperature up to 50 °C can lead to a continuous decline in rice yield and every 1 °C rise of temperature will lead up to 6% decline in yield [53]. In India though rainfall boosts rice productivity in the short term, it has shown to have negative long-term impact as well [54].

Triticum aestivum L. (Wheat)

India is the second largest producer of wheat contributing about 13% of the wheat supply globally. Wheat flourishes well in fertile loamy and clayey soil, with rainfall around 75-100 cm and temperature between 10-15 °C during seed sowing and 21-26 °C during ripening and harvesting. It is grown chiefly in the Indo-Gangetic Plains, North-Western India encompassing a total area of 29.8 million hectares [55-56]. During 2021-22, the wheat productivity in India reached 105 million tonnes. Ideally, wheat requires average temperature of 20-25 °C for growth [57] and the period before flowering defines its productivity as the crop can be very sensitive to climate change during this period. Drought stress is another climatic factor which influences wheat during all stages of development, the most critical ones being grain formation and the reproductive stage [58]. Wheat crop is temperature sensitive, and an exposure to 34 °C results in low yields because of accelerated senescence [59-60]. Beyond the temperatures of 35 °C, wheat fails to survive as it reduces grain filling and hampers growth of storage organs. Heat stress affects yield of wheat and due to a 2 °C increase in seasonal temperature, the yield reduced to 20% in the Indo Gangetic regions of India [61]. In India, reports estimated that due to changing climate, decline in the wheat yield will range from 6-23% by 2050 and 15-25% by 2080 [62]. The time of sowing also impacts yield production and lately sown areas of wheat will probably be affected more in terms of variable impacts on yield than the timely sown ones.

It is estimated that a rise of 0.5 °C rise in winter temperature could decrease the wheat production by 0.45 ton per hectare and 1 °C increase yield reduced by 10% [63]. A study revealed that due to the impact of changes in temperature and rainfall, there will be considerable reduction in wheat yield by 25% by 2080 in India [62]. As wheat is a high irrigation crop, a drastic decline in wheat production is seen due to deficit in irrigation [64]. Apart from global warming, a lot of constraints on irrigation in India is affecting indirectly and limiting the potential for yield gains. Proper irrigation is important to increase productivity but reduced irrigation causes loss of yield between 4-36%. The influence of rainfall is not significant because more than 85% of the wheat land area is irrigated. Elevated CO_2 levels has a positive impact on wheat production due to the CO_2 fertilization effect, thereby enhances grain and straw yield due to an increase in leaf area duration, number of ears per m^2 and kernel weight [65-66]. In developing countries, approximately 81% of wheat consumed is produced and utilized within the country and it contributes to nearly 21% of the world's total food grains [67]. Due to the rise in temperature, the grain filling phase decreases which is the major problem of crop productivity in changing climatic conditions [68]. Therefore, producing stress-tolerant crop plants and sustaining crop yield is an important task in current agriculture [69].

Every plant species responds variously to the elements of global change and a prediction to the effects of climate change is a challenging task. Increasing global warming by 1.5 °C would cause serious climate hazards and myriad risks to both humans and ecosystems. Recently, GHG emissions has been stimulated to a soaring height with the economic expansion and increased population growth which may threaten food security and alter global food production patterns. Measures of mitigation to the growing pace of climate change are sought otherwise it might pose grave consequences for the economy and food security globally.

In India, rice and wheat are the two major staple food crops and their reduction in yield due to climate change is a matter of concern. Crop productivity varies from region to region and is influenced by factors like type of the soil and fertility, water availability, water logging, temperature, rainfall pattern, flood and other climatic conditions. Hence, region specific appropriate and affordable adaptation strategies like improved varieties, altered agronomy need to be identified and adopted for the assessment by the farmers in order to curtail the risk in yield of rice and wheat. The cost of transaction stands as a hindrance to farmers while adopting a particular technology. Low-cost technologies can lower the negative impacts of climate change. High yielding heat tolerant varieties may be useful for areas with high end season temperatures and water scarcity.

CONCLUSION

The present study has addressed global food security and highlighted the responses of plant to varying environmental factors like CO_2, temperature and rainfall. Considering the importance of these food crops to India's food security, some of the potential impacts of climate change on productivity of rice and wheat has been emphasized. A through assessment of the effects of global climatic variations on agriculture is imperative to understand the multi-dimensional magnitudes of climate change impacts on both the crops. Regions which are vulnerable may need more specific, intensive and innovative research, therefore, more rigorous study needs to be done at regional scale. There is an urgent need to develop better crop and grazing land management practices under different environmental conditions. Different steps to achieve this goal is to understand the underlying processes involved in interactions of the crop in relation to its environment and the possible factors responsible for impacting crop growth. Popularization of technologies like system of rice cultivation, aerobic rice cultivation for water saving and mitigation of GHG emissions is essential to ensure yield sustainability, to reduce the impacts of climate variables and to build a resilient system in accordance to changing climate. Mitigation of GHG emissions in agriculture can be possible through improved land management practices, agro-forestry, restoration of degraded lands and organic soils, improved water management, livestock and manure management. Integrated research on the combined effects of increased CO_2 levels, temperature and rainfall on rice and wheat yield, quality and its nutritional value are significantly essential for investigation for understanding mechanisms behind the responses and to developing research strategies to overcome negative impacts on both quality and quantity. Through selection and breeding techniques, varieties of rice and wheat which can grow under adverse climatic conditions should be identified for their tolerance to extreme conditions such as submergence, drought, heat and salinity. It is necessary to understand how productivity of rice and wheat changes in varying climatic conditions and management practices in order to address the issue of food security. Climate change is likely to impose significant costs on the India's economy, therefore researchers working with modern technology need to recognize and adapt to increasing temperature.

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