DEVELOPMENT AND IMPLEMENTATION OF ADAPTATION STRATEGIES TO MITIGATE THE IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

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Abstract:

Background: Climate change poses a significant threat to global food and nutritional security, driven by increasing greenhouse-gas emissions and rising temperatures due to the greenhouse effect.

Objective: This paper reviews the literature on climate change, focusing on its causes, projected impacts, and implications for agriculture, including physiological and metabolic plant activities, growth, productivity, pest infestation, and mitigation strategies.

Key Aspects:

1. **Causes of Climate Change:** Greenhouse-gas emissions, particularly CO2, contribute to the greenhouse effect, resulting in rising global temperatures.
2. **Projected Impacts:** The average global temperature is projected to increase by [insert degree] Celsius, leading to substantial economic losses worldwide. Climate change affects crop respiration rate, evapotranspiration, pest infestation, weed flora, and crop duration.
3. **Impact on Agriculture:** Climate change influences physiological and metabolic activities of plants, leading to changes in growth and productivity. It also exacerbates pest infestation, affecting crop yield and quality.
4. **Mitigation Strategies:** Various mitigation strategies are discussed, including measures to reduce greenhouse-gas emissions, improve soil health, enhance crop resilience, and implement sustainable agricultural practices.

Conclusion: Understanding the impacts of climate change on agriculture is crucial for developing effective mitigation and adaptation strategies. Addressing this challenge requires interdisciplinary efforts to promote sustainable agricultural practices and safeguard global food security.

Keywords: climate change; climate-smart agriculture; diseases; economics; pest; weeds

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Introduction

Climate change is one of the biggest challenges to the world in present times. It is defined as significant changes in the average values of meteorological elements, such as precipitation and temperature, for which averages have been computed over a long period. The past few decades indicate that significant changes in climate at a global level were the result of enhanced human activities that altered the composition of the worldwide atmosphere. The concentration of greenhouse gases such as methane (C.H.), carbon dioxide (C.O.), and nitrous oxide (NO) has increased by %, % and %, respectively, since. Carbon dioxide emissions, which account for the maximum proportion of greenhouse gases, rose. Billion metric tons in from. Billion metric tons in. The average global temperature has increased at an average rate of .–. ◦C per decade since, and is expected to increase by C by . Greenhouse gas (GHG) emissions, particularly C.O. from the combustion of fossil fuels and non-CO GHGs such as nitrous oxide, methane, and C.F.C.s add to global warming. The CO concentration in the atmosphere had increased too. Ppm in from. Ppm in, as shown in Figure. C.O. constitutes a significant proportion of greenhouse gases in the atmosphere: % from fossil fuels and industrial processes and % from forestry and other land use, followed by methane (%), nitrous oxide (%), and fluorinated gases (%). Before, CO emissions from fossil fuels were negligible, but they increased rapidly with industrialization. The Figure shows the increase in C.O. emissions over the years (–). The world has emitted around. Trillion metric tons of C.O. since. However, there are regional variations in the emission. Europe is the most significant contributor of C.O., having around billion metric tons of C.O. emissions, followed by Asia and the North

Literature Review

The American continent has recorded cumulative C.O. emissions of billion metric tons each. The U.S.A. is the most significant contributor to C.O. emissions (billion metric tons) and has contributed % of total historical emissions since, followed by China (billion metric tons). The European Union (E.U.-), a union of countries that sets collaborative targets, has contributed % of historical emissions of CO. Africa contributes only % of global cumulative C.O. emissions due to low per-capita emissions. However, countries like Brazil and India, whose historical emission is less, significantly add to the total emissions in the current context. With an increased level of C.O. in the atmosphere, the fertilization of crops is increased along with decreased energy requirements due to warming. These are specific positive impacts of climate change, whereas water resources are negatively impacted due to climate change. In the th century, the effects of climate change were mainly positive. Most countries benefitted until the trend remained the same for the developed world, while the Third-World countries were negatively impacted. Climate change will become a severe problem in the st century, and both rich and developing countries will face negative externalities (Hoegh-Guldberg, Jacob et al. 2019).

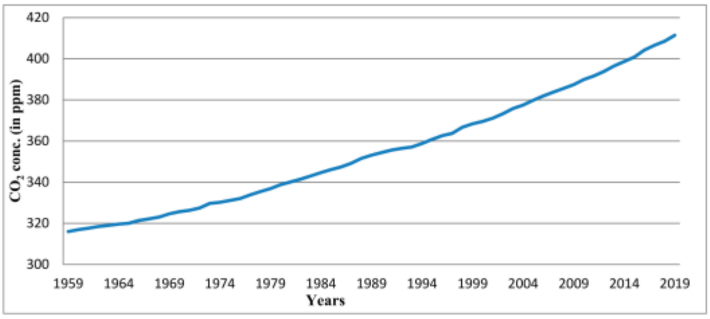
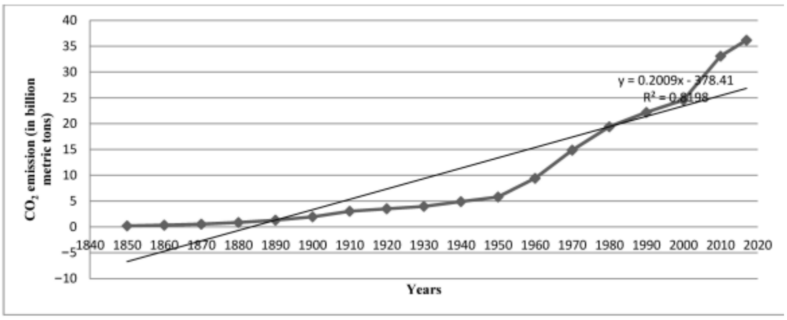
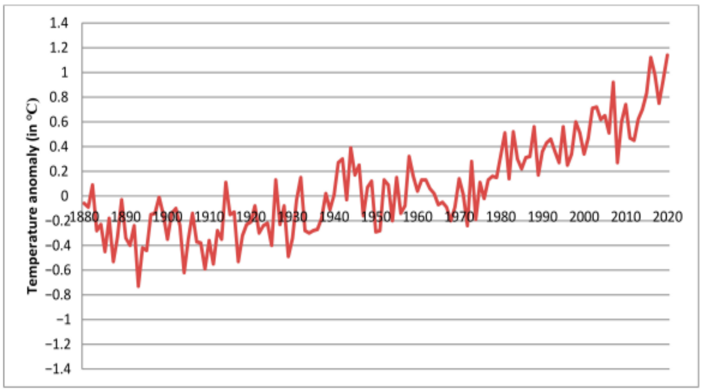


Figure 1. The increase in CO_2 concentration in the atmosphere (source: [8]).



The rise in greenhouse gases has implications for the rising temperature of the atmosphere. These infrared active gases, mainly carbon dioxide (C.O.), ozone (O), and water vapour (H.O.), absorb the thermal radiations emitted by the atmosphere and the surface of the Earth, which in turn warms the Earth. This phenomenon is known as the greenhouse effect. The average global temperature anomaly is shown in Figure and illustrates a significant increase in the global temperature compared to the average temperature of the base period (–). The global average temperature has increased in the range of –. ◦C since. Still, since the temperature changes in landmasses are much more prominent, the global land temperature has increased around twice that of the oceans. The temperature of land across the world has risen. ±. ◦C compared to the – average, while the increase was. ±. ◦C for the ocean surface temperature (excluding areas of sea ice).

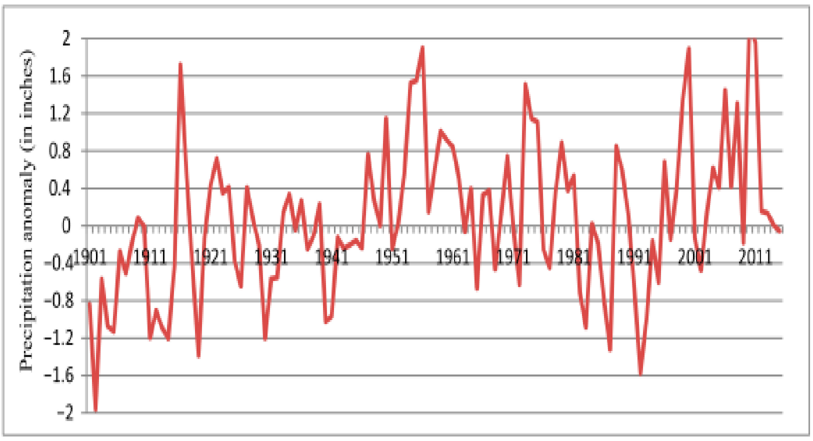
Moreover, since the Northern Hemisphere constitutes the more significant portion of landmasses, it has shown a higher average temperature than the Southern Hemisphere. The temperature of the Northern Hemisphere and the Southern Hemisphere has risen. ◦C and . ◦C, respectively, with a global average of. ◦C since. The extreme rise in temperature has been observed in the polar regions and has detrimental effects, like glacial melting. As the global temperature is rising, there is a need to reduce greenhouse-gas emissions to limit the temperature increase of ◦C relative to pre-industrialization. The developed countries contribute around a % to global temperature rise, sea-ice reduction, and upper-ocean warming, compared to –% for developing countries. The average global temperature is expected to rise by ◦C by and . ◦C by, as predicted by probabilistic computations of the IPCC's range of climate sensitivity. However, surpassing ◦C at the present radiative-force level does not seem likely to happen. But the risk is increasing, mainly due to the stabilizing radiative forces above ppm of C.O. Moreover, it is doubtful that the temperature will rise by ◦C if anthropogenic emissions were ceased tomorrow(Malhi, Kaur et al. 2021).



Climate change is projected to worsen in the upcoming future. In the Punjab province of Pakistan, there have been projections of increased minimum and maximum temperatures in the Kharif and rabbi seasons. In the Kharif season, the average maximum and minimum temperatures are predicted to rise. ◦C and – ◦C; in rabi, it is projected to increase by .–. ◦C and – ◦C, respectively, in simulations done for Sustainability, of the future mid-century (–). There have also been projections of variations in the regions' rainfall, more emphatically during the Kharif season (–%), while in the rabi season, the variations are minimal. The temperature minimums and maximums are also projected to rise in Punjab, India, by the middle and end of the century, as estimated by PRECIS (Providing Regional Climates for Impact Studies). Moreover, high temperatures (heat waves) from March to June and low temperatures during December and January (frost) are also predicted. The extremes in weather parameters, mainly minimum temperature, maximum temperature, and precipitation, are also projected to be observed more frequently, with higher intensity in China, with additional warming. ◦C. Moreover, if global warming is kept below • C, the weather extremes will be lowered. The global precipitation anomalies over the base period (–) are shown in Figure, which shows that the precipitation change is showing a positive trend, but these vary according to the region. There was a fundamental change—inches in precipitation worldwide from to. However, temperature and precipitation extremes are more likely to be witnessed shortly due to global warming. Extreme precipitation phenomena, heavy rainfall or drought, depending on a region's geography. An increased average river flows due to prolonged heavy rain is more likely to be observed in South and East Asia, while the drought in southern Africa and South America will be less severe. The rainfall pattern of the Indus river basin is projected to show uneven variations spatially and seasonally. Precipitation is predicted to rise in the upper Indus basin, while the same has been launched to decrease in the lower basin. Moreover, the upper basin is also projected to face increased warming than the lower basin. There is a probability of more warm extremes, lesser cold extremes, and more strengthened precipitation extremes in the future period in the northeastern United States. Higher emissions will intensify these changes. The increased intensity and frequency of precipitation also impact soil erosion and will have more adverse consequences in northeast China if greenhouse-gas emissions increase(Holland, Kirschvink et al. 2008).

Analysis on climate

Precipitation anomalies have detrimental effects on agriculture, mainly in developing nations. Apart from affecting crop yields, it significantly influences cropland areas. Evidence suggests that the approximately % rate of cropland expansion in the developing world over the last two decades is due to dry anomalies as farmers expand the area to compensate for yield losses. If limited, global warming will severely threaten the world's food security. ◦C, the % of developing countries' vulnerability will be reduced compared with the same regions at ◦C. Ensuring food for the world's population in the face of climate change is difficult, owing to its massive impact on agriculture production. There must be an annual increase in the world's agricultural output by % from/to, comprising a rise of % in developing and % in developed countries, to fulfil the food and nutritional requirements of the population. Climate change is known to harm agricultural production and is projected to reduce the global cereal production of maize and wheat by .% and .%, respectively. Because of climatic factors, plants face several abiotic stresses such as salinity, drought, heat stress, cold stress, etc. . Shortage of water availability, soil fertility loss, and pest infestations in crops are the significant undesirable impacts of climate change. This review attempts to consolidate the studies related to the effects of climate change on crop yields, associated weed infestations, and economic consequences for –. Moreover, mitigation and adaptation strategies to combat climate change are also discussed to understand their possible significance(Malhi, Kaur et al. 2021).



Materials and Methods A systematic review of the literature was done through PRISMA (Preferred Reporting Items for Systematic Meta-Analysis), as shown in Figure. The studies related to the research goals were searched on Google Scholar using the following keywords: climate and agriculture; mitigation and climate change; climate change and economics; comfort and economics. Moreover, the search was performed for the years –. A total of documents were screened, out of which papers were found relevant. Research papers published in journals having an impact factor were finally selected, and their results are reported here(O'Dea, Lagisz et al. 2021).

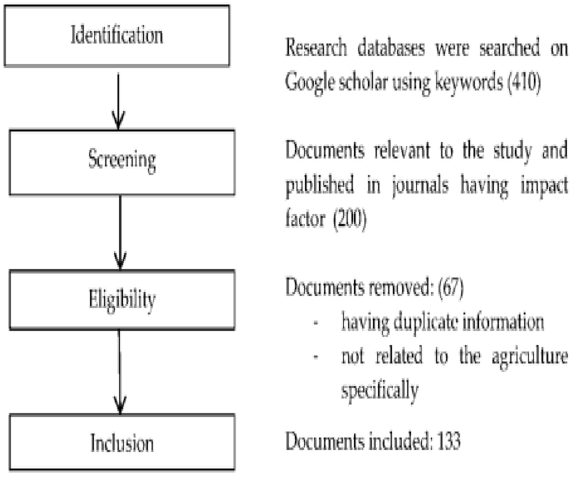


Figure 5. Method for selection of research papers for review and analysis.

Causes of Climate Change

Temperature changes are caused by natural phenomena and anthropogenic activities on Earth, which ultimately initiate the concentration of GHGs. Anthropogenic activities lead to the emission of greenhouse gases such as C.O., methane, nitrous oxide, and other substances that lead to ozone depletion in the atmosphere. The increased C.O. concentration in the atmosphere can affect microbial activities in the soil, along with implications on water content, and therefore increased atmospheric C.O. (– ppm) can stimulate nitrous oxide and methane emission from upland soil and wetlands, respectively, which nullifies the .% mitigation effect of climate change as predicted by increasing terrestrial carbon sink. The agriculture sector contributes % of total emissions, primarily methane and nitrous oxide. The global emission of non-agricultural greenhouse gases is predicted to rise if dietary preferences and food energy consumption remain constant. However, with changing preferences toward high-value foods such as milk and meat, emissions are expected to grow at an even higher rate. The emission can be reduced with technological mitigation, meat consumption, or both. The livestock sector is the main contributor to greenhouse-gas emissions. According to the IPCC, it generates around –.% of emissions; however, it can contribute up to % of GHG emissions based on lifecycle analysis (Trenberth 2018).

Other parameters, such as humidity, wind speed, temperature and rainfall, also impact crop yields. Without these parameters, there has been a chance of over-prediction of the cost of climate change. Moreover, it was found that climate change is likely to reduce the yields of wheat, corn, and rice in China. Extreme weather events have become more frequent since the s in the Netherlands and have significantly affected the wheat yield in the Dutch region. The week in which an extreme weather event occurred determined the extent of yield reduction in wheat. There has been a projection of higher droughts soon due to climate change in most regions of the world and an increase in drought-affected areas. To .% is projected by. Africa is cited as the most vulnerable area. The yield of major crops in drought areas is expected to be reduced. The loss of crop yields can increase food prices and have an absurd effect on agriculture welfare globally, with a .% annual loss of future G.D.P... However, climate change has limited influence on the world food supply, but developing countries will face severe negative consequences. In India, the temperature is predicted to rise. ◦C and . ◦C, along with a doubling of C.O. concentration and longevity of heat waves, which could have a detrimental effect on the agriculture sector. In the arid region of Rawalpindi, Pakistan, an annual loss of INR /acre is to be borne by farmers with a ◦C increase in temperature. In contrast, the net revenue can be increased by INR . and INR . with an increase in rainfall, respectively. The yield losses in three cereal grains (rice, maize, and wheat) are projected to worsen globally with a ◦C increase in mean surface temperature. In sub-Saharan Africa, the average crop yield is projected to be reduced by –% due to climate change. The total fish demand in Solomon Island is also projected to exceed the production, which will have severe implications for food security, as per-capita consumption will be reduced(Malhi, Kaur et al. 2021).

However, if the temperature is increased beyond that equivalent to doubled C.O., this can cause substantial economic losses. The detrimental impact of climate change will be enormous in developing countries' tropical regions, but it will largely depend on the region's climate scenario. The drier part of Sri Lanka (north and east) will experience huge losses in agriculture compared to the cooler central highland area, the output of which is expected to remain the same or even increase with rising temperatures. The pace of climate change determines its impact, thereby determining the cost of adjustment, so environmental policies must be dynamic and implemented with adaptation and flexibility(Savi, Petruzzellis et al. 2018).

The increased C.O. concentration can potentially offset the losses in crop yields due to rising temperatures and reduced soil moisture. The raised C.O. concentration considerably reduces the global yield losses by mainly decreasing agricultural consumptive water use (–%). Moreover, the crop yields' regional differences are primarily due to different growing environments. The concentration of nutrients (N, Fe, Zn, and S) mainly found in proteins is reduced in non-leguminous C crops with an elevated level of C.O. At the increased level of C.O., enhanced vegetative and reproductive growth, and enhanced seed yield is observed in rice crops at an ambient air temperature of ◦C; however, with increased temperature, the seed set was decreased. At an elevated level of C.O., the zinc and iron content of C grain crops and legumes are dropping, which has detrimental effects on human health. C plants and legumes' protein concentration is also observed to be lowered, while C plants are unaffected by a raised C.O. level. Climate changes also impact the microbial population present in the soil and their enzymatic activities. When assessed from a temperature gradient tunnel with a – ◦C higher temperature, the microbial population was significantly higher than in field conditions. The people of nitrogen-fixing and P-solubilizers bacteria and fungus, as well as enzymatic activities, were significantly higher under a wide range of temperatures. Still, the highest parameters were found on or near the optimum temperature. In contrast, the growth of endophytic fungus and plant-growth-promoting bacteria has a positive, negative, or neutral impact, depending on the temperature range. The effects of climate change on various crops' productivity, as estimated through different models, are shown in Table 1(Saddique, Cai et al. 2019)

Projected changes in climate are most likely to affect the development and survival of pathogens. An area's temperature or weather pattern transition is predicted to increase a crop's susceptibility to various pests, diseases, and weeds. Increased yields are projected in countries of high and mid-latitudes, while products are projected to decrease at lower latitudes. However, there are projections of a –% increase in losses due to insect pest infestation with an increased temperature of one degree. Climate change can potentially increase the pest population and its migration, adversely impacting agricultural yields and even viability, as the pest population depends mainly on abiotic factors such as humidity and temperature. In Brazil, the infestation of coffee nematodes and leaf miners is expected to increase due to an increase in the number of generations in a month compared to the climatic conditions of –. Pest infestation thereby has led to substantial pesticide costs for pest management. There is statistical evidence that increased rainfall and temperatures increased the prices of pesticides for crops such as corn, potatoes, and soybean, in contrast to a reduction in wheat in the U.S.A. The ratio of arable land affected by the European corn borer and the Colorado potato beetle is expected to increase by and % for the second generations in the HadCM-high scenario. The unoccupied areas of high altitudes are also found vulnerable to these pests in the system of increasing temperatures in Central Europe. In the current global-warming scenario, an expansion of the suitable areas for wheat aphids (Schizaphis graminum) has been predicted to upper latitudes in the northern hemisphere.

In contrast, the area is forecast to contract in the northern hemisphere. The insect outbreak of pest species is also expected to rise. It will likely affect new places with the increasing temperature in Sweden and its forestry sector. The future projection of the potato tuber moth (Phthorimaea operculella), when done through G.I.S. modelling, reported an estimated increase in the pest's damage potential in tropical and subtropical warmer regions, where the problem already prevails. It is also predicted to expand in temperate and mountainous areas, with a slightly increased damage potential—the life cycle of pathogens such as Puccinia striiformis f.sp. Practice is projected to be limited by increasing temperature, while an increase in the concentration of atmospheric C.O. is estimated to provide advantageous conditions for Fusarium pseudograminearum. Climate change impacts populations' geographical distribution and growth rate, along with increasing the number of generations. Climate change can extend the development season of the pests and change the synchronization of crops and pests (Grace, Achick et al. 2019). Moreover, the increased C.O. level and the rising temperature are increasing the threat of late blight of potato, blast, and sheath blight of rice, which could seriously threaten the world's food security. Weed infestation of crops is also affected by climate change. C weeds respond more strongly to increased C.O. concentration, with increased leaf area and biomass. C weeds are a significant problem in C plants, while C weeds in C plants become less competitive. Weeds compete with crops for water and nutrients, as they have higher nutrient requirements than crop plants. Climate change also influences the dynamics of the crop–weed competition. Besides weed growth, climate change also significantly influences herbicide efficacy, affecting the herbicidal mode of action. Climate change is projected to have a favourable influence on wheat crop weeds, which are vital to world food security. In the wake of climate change, new geographical horizons are being opened for weeds. Their management can only be possible if new management practices are being planned while considering climate change. Pest infestations of various crops are predicted to worsen with climate change, as warmer and humid conditions favour pest proliferation. However, it will vary from region to region and according to the pests' adaptability to climate change. . Mitigation and Adaptation to Climate Change Farmers' perceptions of climate change's threat and severity have the most important motivational factor in voluntary mitigation. However, the adaptation depends on the availability of related information. Moreover, there will be a reduction in the number of people exposed to water stress with mitigation strategies. Still, the remaining people will need adaptation strategies due to their exposure to increased pressure (Srinivasa Rao, Mani et al. 2022).

Traditional agroecological management systems, biodiversification, soil management, and water harvesting can help farmers adopt climate-resilient technologies. These management practices ensure increased carbon sequestration, improved soil health, quality, and reduced soil erosion, leading to resilient soils and cropping systems, ultimately ensuring food security during climate change. These educational interventions, which focus on local, tangible, and actionable aspects, and could be monitored by individual behaviour, are the most successful in providing climate-change education for ecological development. The farmers were basically in support of adaptations. Still, GHG reduction is endorsed by only a few, which shows the need to focus on interventions having both the features of adaptation and mitigation. The main adaptation methods of comfort can be broadly classified into resource-conservation technologies, cropping-system technologies, and socio-economic or policy interventions. Small and marginal farmers cannot cope with climate change due to less awareness, making them more susceptible to losses. The farmers of African countries are also very vulnerable to climate change due to financial implications and a lack of management strategies. There have been ways to curb climate change's impact through agronomic practices, such as a shift in sowing dates. The optimum sowing dates for wheat have been identified as October – in the northeastern part, October – in the central region, and October – in the southwestern region of Punjab, India. The yield loss of the crops is lowest when the farmers have adopted sequential cropping systems in sub-Saharan Africa and adjusted the sowing dates according to climate. The agroforestry sector can mitigate GHG accumulation in the atmosphere and thus help small farmers of Kenya adapt to climate change. Some specific simple approaches to decreasing GHG emissions include alternate drying in rice, mid-season drainage, improved livestock diet, increasing N-use efficiency, and soil carbon. Simple adaptation strategies like changing planting dates and varieties can potentially decrease the impact of climate change. Technology diffusion is critical in shaping farmers' response to climate change. The main priority areas are market integration and support of public research and capacity-building (Likassa, Bekele et al. 2021).

Conservation agriculture has the potential to reverse the degradation caused by conventional tillage over the years, as it leads to minimizing soil disturbance, crop diversity, and maintenance of soil cover. Moreover, conservation agriculture leads to lower GHG emissions, reduced fertilizer use, and higher terrestrial carbon sequestration. Minimum soil disturbance, crop rotation, and soil cover are the underlying principles of conservation agriculture that pave sustainable agriculture methods. In South Asia, farmers are adopting zero tillage for wheat cultivation primarily because of a –% reduction in cultivation cost. Moreover, zero tillage leads to higher yields with lesser variability in wheat and maize. No-till practices were also claimed as an alternative to conventional tillage, which mitigates the impact of climate change through carbon sequestration; however, its effects in mitigating climate change are exaggerated, as the additional organic Carbon in no-till cultivation is minimal. There have been various factors responsible for the adoption of conservation agriculture (C.A.), namely perception of individual benefits, functional market exchange techniques to supply the mandatory resources for C.A. implementation, economic motivation for farmers, development of farmer organizations to encourage local adaptation, and the creation of a suitable environment by alliances of farmer organizations and institutions. The means to adapt to climate change are mainly modified farm practices. They are significantly influenced by the policy decisions suiting the climatic variability and climate extremes, along with social, political, and economic conditions. The conventional intensification of agriculture causes enormous financial losses, out of which almost % are caused by the mismanagement of nutrients, which makes nutrient management a critical aspect. Carbon sequestration, or an increase in soil organic carbon (S.O.C.), can be encouraged by no-till farming, cover crops, manuring, nutrient management, agroforestry, and soil restoration.

Moreover, carbon sequestration can reduce –% of fossil-fuel emissions globally. Direct-seeded rice (D.S.R.) causes fewer GHG emissions compared to transplanted rice. Dry D.S.R. and wet D.S.R. have .% and .% lower potential for global warming, respectively, in comparison to transplanted rice. Moreover, wet D.S.R. also produced a .% higher yield than transplanted rice(Polidoro, de Freitas et al. 2021).

Aerobic rice also has massive potential in mitigating future climate change, as it saves the % of irrigation water used in land preparation and % of the water used in crop growth. The cultivation of aerobic rice by using micro-irrigation technologies is a suitable method for sustainable rice production. It also helps in reducing methane emissions from rice fields. There could be a shortage of fresh water available for irrigation in the western U.S., China, and south, west and central Asia, which could lead to the conversion of – million ha of irrigation area to rainfed area and cause a loss of – pal in food production. However, the incremental cost of mitigation in sprinkler irrigation is reported to be highest, i.e., USD t, due to water-pressure requirements, which could add to GHG emissions. Agricultural practices based on site-specific information can help reduce N application without lowering profitability. Precision agriculture is therefore considered more profitable than the management of the whole field. In northwestern India, inefficient fertilizer management by farmers has led to lower nitrogen use efficiency. A leaf colour chart (L.C.C.) was found very suitable for improving the time and fertilizer rate. After applying fertilizers, when the L.C.C. showed less than shade, the rice yield was on par with the recommended blanket dose of Kg N/ha. Application of fertilizers in rice at L.C.C. ≤ decreased methane and nitrous oxide emissions by % and %, respectively, over conventional N fertilizer application in divided doses. In wheat, it led to % lower nitrous oxide emissions than traditional N fertilizer application. The adoption of laser land levelling (L.L.L.) has increased crop yields and farmer income(Surendran, Raja et al. 2021).

Laser land levelling (L.L.L.), weather-advisory services, and crop insurance are the most-preferred C.S.A. technologies of the eastern indo-Gangetic plains (I.G.P.). At the same time, the farmers of the western I.G.P. mainly prefer direct seeding, L.L.L., zero tillage, crop insurance, and irrigation scheduling. These mitigation strategies have massive mitigation and adaptation potentials. However, they depend upon the suitability of technology to the region, people's perception, economic viability, and technical complexity. Moreover, these strategies work well when some interventions are used together in solidarity with each other. . Economic Impact of Climate Change and Climate-Smart Agriculture Technologies Climate change has initially had specific positive impacts. Still, the environment's unavoidable warming is a negative externality. A rise in temperature beyond ◦C has net negative results, and more than ◦C can cause total welfare loss. The world's social cost of carbon emission is expected to be USD /tC (tonnes of Carbon) and to rise % per year. The net economic gains in the fishery sector of Solomon Island will be considerable if mitigation strategies for climate change are adopted. Climate change also will severely affect agricultural markets, causing a reduction of .% in global G.D.P. There would be a projected annual loss of .–% in household welfare if the climate predicted for the s occurred today. Both market and non-market damages increase in quadratic progression and are expected to cost .% of G.D.P. with a ◦C increase in mean global temperature. If future mitigation strategies follow the adaptation of the system used in the past, global income is projected to show a % decrease and a broader gap in income inequality. Global economic growth is projected to be reduced by .% per year. The economic benefits of various climate-smart agriculture technologies can be seen in Table 2 (Taneja, Pal et al. 2019).

Conclusions and Prospects

An increasing population has put a lot of pressure on agriculture to ensure the food and nutritional security of the world, which is further worsening with climate change. Even though there are uncertainties regarding the future climate scenario and its possible impacts, various studies report that climate change will decrease agricultural productivity in the coming years. The critical climate factors, temperature, precipitation, and greenhouse gases, significantly hampered pest infestation, soil fertility, irrigation resources, physiology, and plants' metabolic activities. Some mitigation and adaptation strategies have been developed to offset the harmful impact of climate change on agricultural Sustainability. These technologies include water-smart practices (laser land levelling, rainwater harvesting, micro-irrigation, crop diversification, raised-bed planting, direct-seeded rice), nutrient-smart practices (precision nutrient application, leaf colour charts, crop residue management), weather-smart activities (stress-tolerant varieties, ICT-based agrometeorological services), carbon-smart activities (zero tillage, legumes, crop residue management) and knowledge-smart activities (agricultural extensions to enhance capacity-building). These technologies significantly reduce the effects of climate change on crops and make them more suited to the climate by minimizing unfavourable impacts. Climate change is predicted to cause substantial economic losses at the micro and macro levels that can be mitigated through these interventions(Gueuning, Frey et al. 2020). But these interventions must be organized at the regional or local level to improve their efficacy. Mitigation and adaptation strategies are expected to increase farmers' income without compromising agricultural production sustainability. The future of climate change and its associated impacts is highly unpredictable, making planning for mitigation and adaptation a bit complex. This necessitates formulating climate-resilient technologies involving an interdisciplinary approach according to the region. Suitable varieties must be developed to adapt to climatic variations and planned agronomic management and crop pest control. Farmers need to be educated regarding various climate-smart technologies and be provided training to simplify their use at the field level(Fan, Si et al. 2020).

Conclusion

Climate change presents a multifaceted challenge to global food security, with far-reaching implications for agricultural productivity, ecological balance, and socio-economic well-being. The evidence synthesized in this review underscores the urgency of addressing climate change through coordinated international efforts and innovative strategies.

Firstly, recognizing the interconnected nature of climate change impacts on agriculture is paramount. Changes in temperature, precipitation patterns, and extreme weather events disrupt crop growth cycles, soil fertility, and water availability, posing significant challenges to food production. Furthermore, shifts in pest and disease dynamics exacerbate yield losses and threaten food supply chains, particularly in vulnerable regions.

Secondly, mitigating climate change requires a comprehensive approach that addresses both its root causes and associated impacts. Reducing greenhouse-gas emissions through energy transition, afforestation, and sustainable land management practices is crucial for curbing global warming and limiting adverse effects on agriculture. Additionally, enhancing adaptive capacity and resilience within agricultural systems is essential for coping with climate-induced stresses and shocks.

Thirdly, adaptation strategies must be context-specific, integrating traditional knowledge with cutting-edge technologies to build climate-resilient food systems. Investing in climate-smart agricultural practices, such as conservation agriculture, agroforestry, and precision farming, can enhance productivity while minimizing environmental degradation. Moreover, promoting crop diversification, water-saving irrigation techniques, and genetic resilience in crops can buffer against climate variability and ensure food security for vulnerable communities.

Furthermore, fostering international collaboration and knowledge exchange is critical for scaling up successful adaptation and mitigation initiatives. By leveraging collective expertise and resources, countries can enhance their capacity to address climate change impacts on agriculture effectively. Moreover, supporting smallholder farmers and marginalized communities, who are disproportionately affected by climate change, is essential for fostering inclusive and sustainable development.

In conclusion, confronting the complex challenges posed by climate change requires bold and coordinated action at the global, regional, and local levels. By prioritizing climate resilience, innovation, and equity, we can build a more sustainable and resilient food future for all. The urgency of the climate crisis demands transformative changes in agricultural policies, practices, and investments to ensure the well-being of present and future generations. Together, we can harness the power of agriculture to mitigate climate change, protect biodiversity, and secure food and nutrition for a thriving planet.

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