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# Climate change adaptation and mitigation in Indian agriculture

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## ABSTRACT

Climate change poses significant challenges to Indian agriculture, impacting crop yields, water availability, and overall food security. To address these challenges, a combination of adaptation and mitigation strategies is crucial. Adaptation measures involve adjusting agricultural practices to changing climate conditions, such as altering planting schedules, implementing water-saving techniques, and promoting resilient crop varieties. Mitigation strategies focus on reducing greenhouse gas emissions from agricultural activities, like adopting sustainable farming practices and enhancing carbon sequestration in soils. In India, the integration of adaptation and mitigation efforts is essential to enhance the resilience of farmers and agricultural systems to climate change impacts while contributing to global climate goals. By combining traditional knowledge with modern scientific approaches, Indian agriculture can navigate the complexities of climate change, ensuring sustainable food production and livelihood security for millions of farmers across the country. A concerted effort involving policymakers, researchers, extension workers, and farming communities is vital to bolster the resilience of Indian agriculture while contributing to global climate change mitigation efforts. Effective extension services are paramount for educating farmers and ensuring widespread adoption of these strategies. By prioritizing both adaptation and mitigation, Indian agriculture can navigate the challenges of climate change and ensure long-term food security.

***Keywords***: Climate policy, Sustainable Development Goals (SDGs), Food Security, Greenhouse gas emissions (GHGs), Adaptation, Mitigation, Renewable Energy

Climate change refers to long-term shifts in global or regional climate patterns, primarily caused by human activities that release greenhouse gases into the atmosphere. It is a significant and persistent change in the statistical distribution of weather patterns over an extended period, typically spanning decades or longer. Climate change is characterized by rising global air and ocean temperatures, shrinking snow and ice cover, and changes in atmospheric and ocean circulation patterns. The primary cause of modern climate change is human activity, particularly the burning of fossil fuels (coal, oil, and natural gas) and deforestation, which release large amounts of carbon dioxide ($CO_2$) and other greenhouse gases into the atmosphere. These gases trap heat from the sun, causing a gradual increase in global temperatures, known as the greenhouse effect. The main greenhouse gases contributing to climate change are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and various fluorinated gases. $CO_2$ is the most significant contributor, primarily resulting from the burning of fossil fuels and deforestation. One of the most significant consequences of climate change is global warming, which refers to the rising average surface temperature of the Earth due to the increased greenhouse effect. Global temperatures have risen by about 1.1°C (2°F) since the late 19th century, and this trend is expected to continue if greenhouse gas emissions are not substantially reduced.

The Intergovernmental Panel on Climate Change (IPCC) has determined that human-generated emissions of greenhouse gases have already warmed the global climate by nearly 2°F (1.1°C) since the late 19th century. Within the next few decades, the average global temperature is projected to reach or surpass 1.5°C (about 3°F) above pre-industrial levels, leading to widespread damaging impacts across the planet. The extent and rate of climate change, along with the associated risks, heavily depend on the mitigation and adaptation actions taken in the near future. Some

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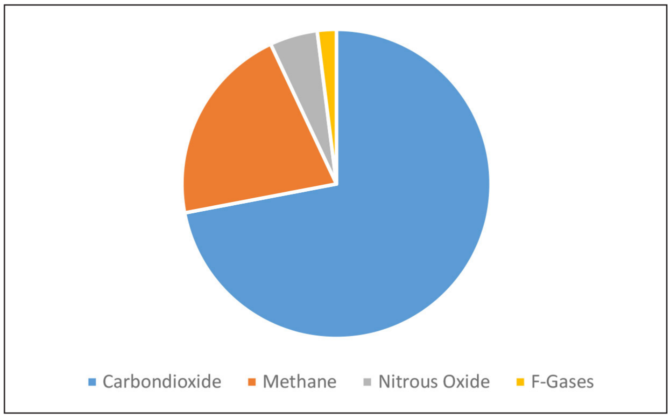

**Fig. 1:** Share of global GHG emissions in 2022 (Sources: Europa.EU)

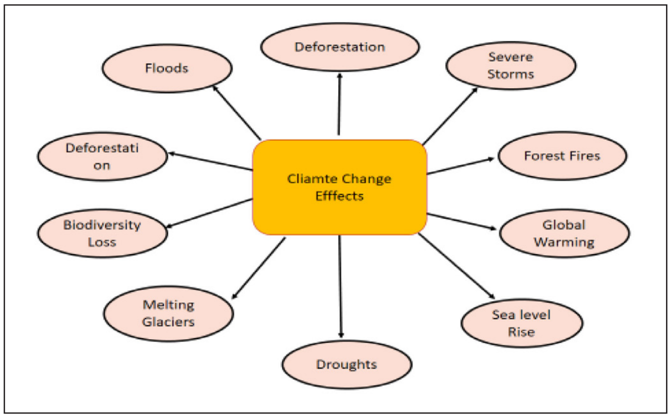

**Fig. 2:** Schematic diagram on effect of climate change

climate change effects, such as droughts, wildfires, and extreme precipitation events, are occurring faster than previously anticipated by scientists. Climate change poses a significant and urgent global challenge, primarily driven by human activities, with far-reaching impacts on the environment, human health, and social systems. Immediate and extensive action is required to reduce greenhouse gas emissions, enhance carbon dioxide removal, and adapt to the impacts of climate change.

## OVERVIEW OF AGRICULTURE'S VULNERABILITY TO CLIMATE CHANGE

Agriculture is one of the sectors most vulnerable to the impacts of climate change due to its direct dependence on climatic factors such as temperature, precipitation, and weather patterns. Here's an overview of agriculture's vulnerability to climate change:

***Temperature changes:*** Increasing temperatures can affect crop growth, development, and productivity. Some crops may experience reduced yields or become unsuitable for cultivation in certain regions as temperatures rise beyond their optimal range. Higher temperatures can also accelerate the depletion of soil moisture, leading to water stress and reduced crop yields.

***Precipitation changes:*** Climate change is altering precipitation patterns, leading to more frequent and intense droughts or floods in different regions. Droughts can severely impact crop production by reducing water availability for irrigation and causing water stress in plants. Conversely, excessive rainfall and flooding can damage crops, erode fertile topsoil, and disrupt agricultural activities.

***Extreme weather events:*** Climate change is increasing the frequency and intensity of extreme weather events, such as heat waves, storms, and hurricanes. These events can cause physical damage to crops, disrupt pollination, and lead to crop losses, affecting both yield and quality.

***Pest and disease dynamics:*** Changes in temperature and precipitation patterns can influence the distribution, prevalence, and severity of pests and plant diseases. Some pests and diseases may become more widespread or reach new areas, posing additional challenges for crop protection and management.

***Water availability:*** Agriculture is heavily dependent on reliable water sources for irrigation. Climate change can alter the availability and distribution of water resources, leading to water scarcity in some regions and impacting crop production.

***Soil health:*** Climate change can exacerbate soil degradation through processes like erosion, loss of organic matter, and salinization. These factors can reduce soil fertility and productivity, further contributing to yield losses.

***Livestock production:*** Climate change can impact livestock production through heat stress, changes in feed and water availability, and the spread of livestock diseases. These factors can affect animal health, productivity, and overall food supply from livestock sources.

***Socioeconomic impacts:*** The impacts of climate change on agriculture can have far-reaching socioeconomic consequences, particularly for small-scale and subsistence farmers who rely heavily on agricultural production for their livelihoods and food security.

Indian agriculture faces challenges like farming not being profitable, reliance on rain-fed systems (55% of agriculture), and the impacts of climate variability and change (Wani, 2023). Addressing agriculture's vulnerability to climate change requires a multifaceted approach, including developing climate-resilient crop varieties, adopting sustainable farming practices, improving water management strategies, enhancing early warning systems, and promoting diversification of agricultural systems. Collaboration among researchers, policymakers, and farmers is crucial to mitigate the impacts of climate change on agriculture and ensure food security for a growing global population.

## CLIMATE CHANGE IMPACTS

Climate change poses a significant challenge for the agricultural sector in India and globally. With rising temperatures, shifting rainfall patterns, and escalating extreme weather events, Indian farmers are directly experiencing the impacts of climate change on their crop yields and livelihoods. Combating these challenges requires the Indian government and stakeholders to prioritize developing and implementing effective adaptation and mitigation strategies. These strategies should focus on enhancing water use efficiency, promoting sustainable agricultural practices, and supporting farmers in adapting to the changing climate conditions. Climate change presents a significant challenge for

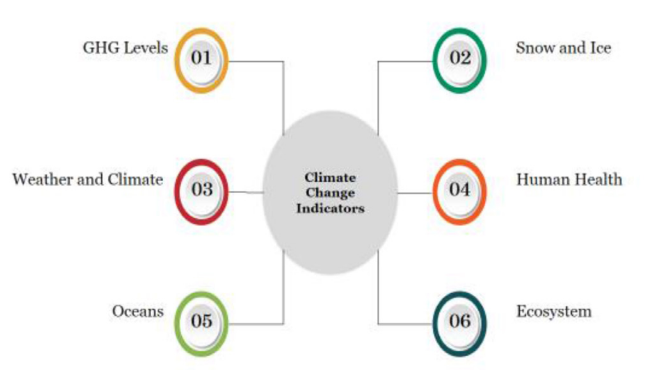

**Fig. 3**: Schematic diagram on climate change indicators

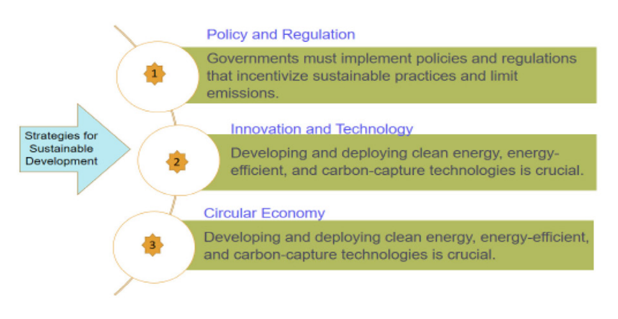

**Fig. 4:** Schematic diagram on strategies for sustainable development

the agricultural sector in India, necessitating the development and implementation of effective adaptation and mitigation strategies. These strategies should focus on improving water use efficiency, promoting sustainable agricultural practices, supporting farmers in adapting to the changing climate, and integrating water resource management. Additionally, the role of economists and researchers in understanding and addressing the impacts of climate change on agriculture cannot be overstated. A comprehensive approach encompassing vulnerability assessment, adaptation strategies, and mitigation efforts is key to addressing the far-reaching effects of climate change on the environment, economy, society, and human well-being in the context of Indian agriculture.

***Temperature rise:*** Global temperatures are escalating, resulting in heat waves, extreme heat events, and rising average temperatures worldwide. This has consequences for human health, agriculture, ecosystems, and infrastructure.

***Precipitation pattern shifts*****:** Climate change is altering precipitation patterns, leading to changes in rainfall intensity, frequency, and distribution. This can cause more frequent droughts, floods, and fluctuations in water availability, impacting water resources, agriculture, and freshwater ecosystems.

***Sea-level rise:*** Melting of ice caps, glaciers, and thermal expansion of seawater are causing sea levels to rise. This poses risks to coastal communities, infrastructure, and ecosystems, leading to coastal erosion, saltwater intrusion, and increased flooding during storms.

***Extreme weather events:*** Climate change is associated with an increase in the frequency and intensity of extreme weather events like hurricanes, cyclones, heatwaves, heavy rainfall, and wildfires. These events can cause widespread devastation, loss of life, population displacement, and damage to infrastructure and ecosystems.

***Agricultural impacts:*** Changes in temperature and precipitation patterns affect agricultural productivity, crop yields, and livestock health. Heat stress, water scarcity, pests, and diseases can reduce crop yields, disrupt food supply chains, and threaten food security, particularly in vulnerable regions.

***Biodiversity loss:*** Climate change is driving shifts in ecosystems, species distributions, and habitats, leading to biodiversity loss and disruption of ecological processes. Many species face extinction due to habitat loss, temperature regime changes, and disruptions to food webs and migration patterns.

***Health impacts:*** Climate change affects human health through various pathways, including heat-related illnesses, vector-borne diseases, air pollution, food insecurity, and mental health impacts. Vulnerable populations like children, the elderly, and marginalized communities are particularly at risk.

***Social and economic disruptions*****:** Climate change can exacerbate social inequalities, increase poverty, and disrupt livelihoods, particularly in developing countries and vulnerable communities. Extreme weather events, loss of agricultural productivity, and population displacement can lead to economic losses, social unrest, and migration.

***Water scarcity and quality*****:** Changes in precipitation patterns and increased evaporation rates can lead to water scarcity, affecting water availability for drinking, agriculture, industry, and ecosystems. Water quality may also be compromised due to pollution, salinization, and contamination from agricultural runoff and industrial activities.

***Ocean acidification*****:** Increased atmospheric $CO_2$ levels are absorbed by the oceans, leading to ocean acidification. This poses risks to marine ecosystems, including coral reefs, shellfish, and plankton, with implications for fisheries, coastal communities, and marine biodiversity.

These impacts highlight the urgent need for mitigation efforts to reduce greenhouse gas emissions and adaptation measures to build resilience and prepare for unavoidable climate change consequences. Addressing climate change requires coordinated action at local, national, and global levels to protect ecosystems, safeguard human health and well-being, and ensure a sustainable future. Challenges for sustainable agriculture include climate change, growing population, urbanization, low crop yields, water scarcity, land degradation, and poverty. Given the urgency and complexity of climate change, it is crucial for economists and researchers to examine vulnerability, adaptation, and mitigation in the context of agricultural economies such as India's. Addressing climate change in Indian agriculture requires a comprehensive approach that includes policies and investments in research, technology, and infrastructure.

### *Climate change impacts on food security and SDGs*

Climate change poses a significant threat to global food security and the achievement of Sustainable Development Goals (SDGs). The increasing competition for limited resources such as land, water, and energy, coupled with the overexploitation of fisheries, further compounds the challenges faced in food production. As climate change continues to impact ecosystems, water resources, and the overall environment, it directly affects agricultural productivity and food availability. This is particularly concerning in developing countries, where the combination of climate change and poverty exacerbates the effects on food security, leading to increased hunger and under nutrition. Although agriculture employs a large portion of India's population and contributes significantly to GDP (17-18%), challenges abound. Despite being a major food producer, India faces issues like profitability, rain dependence, and climate change. Sustainable agriculture is threatened by factors like water scarcity, land degradation, and population growth (Wani, 2023).

Furthermore, the impact of climate change on food production is not uniform across regions. Some areas are more vulnerable to the adverse effects of climate variability and change, which can exacerbate existing food insecurity. To address these challenges, it is essential to develop and implement integrated policies that consider both climate change mitigation and adaptation strategies. These policies should focus on sustainable land and water management, promoting climate-resilient agricultural practices, and improving access to reliable weather information and early warning systems that can help farmers adapt to changing climatic conditions in achieving food and nutritional security, climate change poses a major challenge due to its impact on natural resources, including the melting of glaciers, rising sea levels, changes in rainfall and temperature patterns, and alterations in water, land, and biodiversity patterns. These changes require a reevaluation of land-use patterns, agricultural enterprises, and crop varieties to ensure food and nutritional security in the face of climate change. Furthermore, it is crucial for governments to implement strategies at the household level and educate communities, particularly in rural areas, on how to adapt their farming practices to mitigate the impact of climate change on food production. In today's rapidly changing world, the significance of accurate weather forecasts cannot be overstated. Climate change impacts on food security and SDGs are closely intertwined, as food security is fundamental to achieving several SDGs related to poverty eradication, health, gender equality, and sustainable development. Addressing climate change's impact on food security is essential for achieving the SDGs and ensuring a sustainable future for all.

***Impact on food production and availability*:** Climate change affects food production and availability through various channels. Changes in temperature and precipitation patterns can lead to reduced crop yields, shifts in growing seasons, and alterations in crop suitability. This can result in food shortages, price volatility, and reduced access to nutritious food, undermining progress towards Zero Hunger.

***Vulnerability of smallholder farmers*:** Smallholder farmers, who often rely on rain-fed agriculture and have limited access to resources and technology, are particularly vulnerable to climate change impacts. Extreme weather events, droughts, floods, and changes in pest and disease dynamics can devastate crops and livestock, exacerbating food insecurity and poverty, hindering progress towards No Poverty.

***Nutritional impacts*:** Climate change can affect food's nutritional quality by altering crop composition, reducing nutrient content, and increasing foodborne disease risks. Poor nutrition undermines human health, contributes to malnutrition, stunting, and micronutrient deficiencies, hindering progress towards Good Health and Well-being.

***Gender dimensions*:** Women, central to food production, processing, and household food security, are disproportionately affected by climate change impacts. Climate-related shocks can increase women's workload, limit their access to resources and decision-making power, exacerbating gender disparities in food security and nutrition, undermining Gender Equality.

***Rural livelihoods and poverty*:** Climate change can disrupt rural livelihoods, reduce agricultural incomes, and force rural communities to migrate for alternative income and livelihoods. This can perpetuate poverty, exacerbate social inequalities, and undermine progress towards Decent Work and Economic Growth.

***Environmental sustainability*:** Climate change affects environmental sustainability by degrading land, water, and ecosystems, reducing agricultural productivity, and threatening biodiversity and ecosystem services. Unsustainable land use practices, deforestation, and soil degradation exacerbate climate change impacts, undermining progress towards Life on Land.

***Resilience-building and adaptation*:** Building resilience and adapting to climate change are essential for achieving food security and advancing the SDGs. Climate-smart agriculture practices, sustainable land management, improved water management, and investments in resilient infrastructure and social protection systems can enhance resilience to climate change, support sustainable development, and contribute to multiple SDGs. Climate change impacts on food security intersect with several SDGs, highlighting the interconnectedness of environmental, social, and economic challenges. Addressing climate change and promoting sustainable food systems are essential for achieving the SDGs, ending hunger, reducing poverty, promoting health and well-being, and ensuring a sustainable future for all. By investing in agricultural research and innovation, developing countries like India have the potential to mitigate and adapt to climate change effects while simultaneously addressing poverty and food insecurity. Integrating water resource management and implementing appropriate policies can aid in reducing risks faced by farmers and minimizing adverse impacts on resources. Furthermore, farmers in developing nations like India are already taking steps to adapt to climate change and mitigate its impacts through various strategies such as crop management, water management, land management, and income diversification. However, these strategies face challenges related to input availability, high production costs, limited access to agricultural extension services, and the need for adequate adaptation knowledge and experience.

## CLIMATE CHANGE ADAPTATION STRATEGY IN INDIAN AGRICULTURE

It involves implementing management techniques that can effectively address future climate change scenarios. Below are some potential adaptation options relevant to Indian agriculture.

### *Smart agro-advisory*

Ensuring that farmers, particularly smallholder farmers, are well-informed about imminent climate abnormalities is crucial for successful adaptation. This can be achieved through:

***Swift dissemination of weather information***: India experiences various climatic extremes, making timely weather updates essential. Well-equipped weather stations and efficient extension services are needed to provide farmers with tailored advice on crop planting and input application. Developing advanced decision support systems (DSS) can further aid this process.

***Early warning systems***: Reliable and timely warnings about impending climatic risks can help identify areas and communities at risk of food insecurity due to climate change.

***Contingent crop planning***: Contingency plans should be developed for different regions, utilizing modern information and space technologies to monitor pest movements, as recommended by Srinivasarao *et al.,* (2010, 2020).

***Crop insurance***: Weather insurance, supported by standardized weather data, offers farmers an alternative to manage increased climatic risks.

***Community fodder and seed banks***: Events like droughts, dry spells, and floods can devastate crops and livestock. To cope, farmers, especially smallholder farmers in India, can establish community reserves of food, forage, and seeds. Support from the government and development partners is crucial, especially in the initial stages.

***Adoption of new-generation technologies***: Utilizing artificial intelligence, machine learning, and mobile app-based agro-advisory services can enhance farmers' decision-making abilities in the face of climate change.

### *Adoption of best management practices*

***Adoption of climate-smart varieties and climate-resilient crops:*** Millets are gaining importance as they are climate-resilient and can ensure nutritional security for smallholder farmers. Regarding varieties, the development of stress-tolerant crop varieties with higher yield potential and resistance to multiple abiotic (drought, heat, flood, salinity) and biotic (pests and diseases) stresses is essential to mitigate the adverse impacts of climate risks. For example, rice varieties like Sahbhagi Dhan, CR Dhan 209, and CR Dhan 210 are suitable for drought conditions, while Swarna sub1 is ideal for submergence. Similarly, wheat varieties such as HD 2987 are drought-tolerant, and DBW73 can withstand high temperatures (Pathak, 2023). These varieties can be grown in specific agroclimatic zones instead of conventional ones. Additionally, promoting new and unconventional crops like dragon fruit, quinoa, and chia, which are tolerant to various abiotic stresses, is crucial.

***Soil management***: Soil management is one of the most crucial measures for climate change adaptation, particularly in Indian rainfed agriculture (Srinivasarao *et al.,* 2015). Increasing climatic variability and extreme climate events such as heavy rainfall and strong winds can accelerate the process of soil erosion. To prevent wind-induced soil erosion, tree planting and hedgerow planting are used in semiarid areas, while vegetation cover, contour plowing, and contour hedgerows are common in humid and coastal areas. In mountainous regions, mini-irrigation facilities, water harvesting, and terrace gardening help control soil erosion. Changing tillage practices and shifting to zero tillage with residue retention help cropping systems adapt to water stress, excess water due to untimely rainfall, and high temperatures. Zero tillage and retention of crop residues increased soil organic carbon. These practices are also reported to increase water content in the soil. Therefore, such practices act as shields for farmers from the destructions caused by drought and minimize the risk of crop loss. Better soil management, especially in rainfed ecology, maintains soil health (Srinivasarao *et al.,* 2011a, Srinivasarao *et al.,* 2011b, Srinivasarao *et al.,* 2013) that eventually adds to sustainable agriculture.

***Crop diversification:*** Climate change poses a threat to agricultural sustainability by impacting both living organisms and non-living factors. Diversifying crops in terms of type and timing can be a cost-effective strategy to enhance the resilience of agricultural systems in the face of climate change (Srinivasarao *et al.,* 2012). The greater the diversity in production systems, the more resilient they become, contributing to food security and nutrition (Jat *et al.,* 2007; Gora *et al.,* 2022). Additionally, diverse production systems play a crucial role in providing essential ecosystem services such as nutrient cycling, carbon storage, erosion control, greenhouse gas reduction, and regulation of hydrological processes. Crop diversification helps build resilience to climate change by enabling the suppression of pest outbreaks and reducing the risk of pathogen transmission, which can occur due to increased climate variability, thereby buffering crop production against climatic stress. Transitioning to less water-intensive cropping systems, like the maize-wheat system, can improve the adaptation of production systems to water stress. Similarly, promoting neglected and underutilized species offers adaptation opportunities, especially in mountainous regions. Introducing short-duration crop varieties and planting early or late maturing varieties can mitigate the adverse impacts of climate change. Climate change also leads to increased soil salinity in coastal agricultural lands. In response, various stress-tolerant rice varieties and maize hybrids have been developed to address issues such as heat, cold, and frost. Altering cropping patterns, introducing new crops, or adjusting crop sequences are other strategies for climate change adaptation. In drought-prone areas, farmers often cultivate drought-adapted crops like sorghum and adjust production practices, such as staggered planting, to spread risk. Leguminous crops such as red grams, mung beans, and peanuts are used to supplement nitrogen lost due to soil erosion or flooding. In cool and humid climates, legumes are mixed with main crops to protect fallow land.

***Water management***: Water harvesting, an ancient practice in India, offers a potential solution to manage irrigation water scarcity throughout the year. Significant water savings have been observed through this method. Similarly, adopting micro-irrigation systems such as sprinklers and drip irrigation can save significant water use. Laser land levelling (LLL) significantly improves water and nutrient use efficiency, making agriculture more resilient to water stress. Zero tillage in wheat production systems provides economic and environmental benefits. Under agroforestry systems, leaf litter decomposition enhances soil fertility, reduces water runoff, and controls erosion, thereby increasing resilience to climate variability.

The most comprehensive climate-smart water management, as outlined by Sikka *et al.,* (2018), includes several key components:

***Community tanks*****:** Desilting traditional community tanks has helped increase surface water storage and groundwater recharge.

***Farm ponds*****:** Supplemental irrigation from farm ponds is a recognized adaptation strategy to rainfall variability. Widely adopted in NICRA villages, farm ponds have led to increased irrigated area, crop productivity, and groundwater levels.

***Check dams*****:** Ex situ storage of water in seasonal streams helps store runoff water in different rainfall zones, providing resilience for direct use or groundwater improvement.

***In situ soil moisture conservation*****:** Rainwater management techniques like ridge and furrow systems conserve rainwater at the farm level while draining excess water, helping cope with moisture stress and prevent waterlogging.

***Soil and crop management practices*****:** Resource-conserving technologies like zero/minimum tillage, bed planting, and direct-seeded rice improve irrigation efficiency and reduce energy for groundwater pumping. Solar-powered drip systems offer water and energy savings.

***Watershed management*****:** Participatory integrated watershed management approaches ensure resilience to climate variability and change through biophysical and socio-economic interventions that conserve resources, increase food production, improve livelihoods, protect the environment, generate employment, address gender and equity issues, and conserve biodiversity. Agroforestry interventions on marginal soils help increase soil carbon and mitigate climate change effects. A watershed approach, integrating top-down and bottom-up management within a river basin perspective, enables sustainable water resource management by considering all watersheds upstream and downstream. This holistic framework combining biophysical and social approaches could serve as a model for climate change adaptation.

### *Energy-smart technologies*

Modern agriculture heavily relies on energy inputs, necessitating the adoption of renewable energy sources and efficient energy management to mitigate risks associated with climate change. Water management systems should be designed to minimize energy usage and carbon footprint. Various soil and crop management practices, such as mixed cropping, intercropping, organic farming, conservation tillage, residue management, mulching, and integrated farming systems, have shown promise in protecting agro-ecosystems while providing food, fuel, and timber. Diversified agricultural production systems are more resilient to climate change compared to monocropping. Integrated crop and soil management systems increase soil carbon sequestration, aiding in climate change mitigation. Incorporating energy-producing plants into integrated farming systems can enhance energy security in changing climates. Energy-smart technologies like zero tillage and minimum tillage, along with resource conservation technologies, have the potential to increase crop productivity with less water and energy use. For example, minimum tillage practices have shown yield gains and reduced emissions of $CO_2$ and $N_2O$, improving soil water content, organic matter, and crop yields, particularly in rainfed conditions. Intercropping systems with minimum tillage also contribute to soil carbon sequestration. Several green energy options can be effectively implemented in the Indian context. Firstly, perennial crops offer advantages over energy-producing annual crops, requiring fewer inputs such as fertilizer, leading to reduced greenhouse gas emissions and higher energy savings. Secondly, integrating bioenergy, biodiesel, and biomaterial production into the cropping calendar can contribute significantly to achieving energy security.

Additionally, the deployment of windmills and solar collectors, as well as the installation of photovoltaic panels, can effectively harness renewable energy sources. Biogas production units and power generators offer further opportunities for sustainable energy production. Moreover, equipment for bio-oil purification, fermentation and distillation facilities, and efficient water distribution equipment are essential components of a comprehensive green energy strategy. By implementing these options, India can make significant strides towards a more sustainable and energy-efficient future in agriculture, mitigating the impacts of climate change while promoting energy security and environmental sustainability.

### *Responsible nutrient management*

Efficient nutrient management is a crucial strategy for mitigating the adverse impacts of climate change, such as drought (Srinivasarao *et al.,* 2003). For instance, if rice planting faces delays due to late monsoon onset, increasing nitrogen (N) application can compensate for yield reductions. Optimized nutrient management enhances the resilience of production systems to extreme weather events like floods and droughts. Smart nutrient practices encompass various approaches, including utilizing nutrient-efficient crop varieties, adopting soil test-based fertilizer application, employing tailored fertilizers, and integrating improved N fertilizers. These practices play a pivotal role in Climate-Smart Agriculture (CSA), promoting higher production, system resilience, and greenhouse gas (GHG) mitigation. For instance, real-time nitrogen management not only enhances crop yield and nitrogen use efficiency (NUE) but also minimizes nitrate losses, thereby mitigating groundwater pollution and $N_2O$ emissions simultaneously. Key smart nutrient practices encompass green manuring, brown manuring, site-specific nutrient management (SSNM), leaf color chart (LCC)-based nitrogen application, and soil health card-based nutrient management. Real-time, site-specific integrated nutrient management involves supplying nutrients tailored to crop needs across space and time, considering factors like product, place, rate, and timing.

Incorporating legumes into cereal-cropping systems enriches nitrogen supply and soil quality. Adoption of "soil health card"-based nutrient management improves upon traditional "soil test-based nutrient management" but necessitates robust institutional support for accurate testing and reporting.

### *Conservation agriculture*

Conservation agriculture (CA) represents an ecosystem-centered approach to sustainable farming and land stewardship, emphasizing three fundamental principles:

(1) maintaining minimal soil disturbance through practices like no-till or reduced tillage during crop establishment,

(2) ensuring permanent soil cover through the use of crop residues and cover crops, and

(3) diversifying cropping systems with rotations tailored to economic, environmental, and social considerations, incorporating legumes and cover crops, alongside other sound agronomic practices.

The preservation of permanent soil cover is essential for shielding the surface from the adverse impacts of rainfall and sunlight exposure, while also ensuring a consistent food supply for soil microbes and plant roots. This fosters enhancements in soil biodiversity, microbial activity, soil aggregation, and carbon sequestration (Pathak *et al.,* 2021). Diverse crop rotations provide a varied "diet" for soil microorganisms and facilitate the recycling of soil nutrients from deeper layers through the cultivation of different crops. Integrating legume crops into crop sequences and rotations aids in biological nitrogen fixation, pest management, and bolstering soil biodiversity.

Beyond crop-centric practices, CA encompasses broader natural resource management strategies aimed at enhancing synergies between crop production and ecosystem conservation. These include diversified farm practices such as agroforestry, watershed management, livestock and fodder management, improved fallows, and community-managed protected areas. CA also addresses climate-related challenges and contributes significantly to climate change mitigation efforts by reducing greenhouse gas emissions, conserving biodiversity, and preserving ecosystem services. CA facilitates the sequestration of atmospheric carbon dioxide into soil carbon, albeit at a gradual pace, especially through the incorporation of crop residues and perennial woody biomass like fruit trees and living fences. Practices such as reduced or no-tillage, coupled with retaining at least 30% of residues on soil surfaces, can enhance carbon sequestration while simultaneously improving soil properties.

### *Low carbon technology*

Several carbon-negative technologies are imperative, including:

***Integrated Nutrient Management***: This approach optimizes nutrient supply by incorporating organic sources like compost and green manure, fostering soil organic carbon accumulation. By reducing reliance on synthetic nitrogen fertilizers, it also mitigates nitrous oxide emissions. Moreover, practices such as intercropping, mixed cropping, crop rotation, and the integration of leguminous nitrogen-fixing crops enhance nutrient and water utilization efficiency.

***Biochar Application***: Applying biochar enhances soil biological activity, improves nutrient utilization efficiency, and boosts carbon sequestration. Combining biochar with nitrogen fertilizer can regulate organic nitrogen mineralization. Additionally, biochar alters carbon pool ratios, reducing greenhouse gas emissions.

***Conservation Agriculture (CA):*** CA practices like minimum tillage, residue management, and crop diversification safeguard soil from erosion, reduce evaporation, and conserve nutrients. CA also curtails carbon dioxide emissions from mechanization by lowering energy demands. It fosters water and nutrient conservation, elevating crop productivity and efficiency while enhancing soil ecosystem resilience and organic carbon sequestration.

***Organic farming***: These systems prioritize crop rotation, mulch, composts, and green manures over inorganic fertilizers or pesticides, facilitating soil carbon replenishment.

***Integrated farming system (IFS)***: IFS integrates compatible crops and animals, combining crop, livestock, aquaculture, and agro-industry synergistically. Resource recycling within IFS bolsters soil organic carbon stocks, minimizes system risks, enhances productivity, reduces external input dependency, and recycles bio-resources and crop residues. IFS aims to ensure stable income, maintain agro-ecological balance, decrease fertilizer and pesticide usage, optimize organic resource utilization, and conserve farm resources comprehensively.

### *Harnessing renewable energy sources*

Agrivoltaics presents a promising solution for rural electrification, water conservation, yield enhancement, sustainable income generation, and reduction in pesticide and fertilizer usage (Mahto *et al.,* 2021). This approach not only has the potential to alleviate financial distress among farmers, especially in regions with high suicide rates but also holds opportunities for local solar panel manufacturing, thereby reducing costs. The localized manufacturing of solar panels could also stimulate job creation and fortify India's economic infrastructure. Consequently, agrivoltaics offers a pathway to address multiple socio-economic challenges, and its initial success is anticipated to raise social awareness and drive widespread adoption throughout the nation.

### *Embracing regenerative agriculture*

Regenerative agriculture represents a holistic approach to farming that prioritizes the restoration and enhancement of ecosystem health, moving beyond mere sustainability. It seeks to improve soil health, enhance biodiversity, bolster water retention, and mitigate greenhouse gas emissions.

Key principles of regenerative agriculture, as outlined by Mishra *et al.,* (2022), include:

***Minimal soil disturbance***: Employing practices like no-till or reduced tillage to preserve soil structure and minimize erosion.

***Cover crops and crop rotation***: Utilizing cover crops to safeguard soil, suppress weeds, and enhance fertility, alongside crop rotation to diversify plant species and replenish soil nutrients.

***Diverse agroecosystems***: Integrating various crops, trees, and livestock to boost biodiversity and enhance ecosystem resilience.

***Livestock integration***: Managing grazing patterns to mimic natural processes, enhance soil fertility, and regenerate pastures.

***Soil health management***: Enhancing soil organic matter through composting, mulching, and organic matter integration to improve structure, water retention, and nutrient availability.

***Water management***: Implementing techniques like contour plowing, terracing, and water-harvesting systems to enhance infiltration, reduce runoff, and improve water efficiency.

***Agroforestry***: Introducing trees into farming systems for additional benefits such as carbon sequestration, shade, windbreaks, and wildlife habitat.

Regenerative agriculture strives to cultivate agri-food systems that are productive, profitable, environmentally sustainable, and resilient to climate change. It emphasizes collaboration with nature to leave the land healthier and more productive for future generations.

## MITIGATION OF GHGS

Mitigation strategies for reducing greenhouse gas (GHG) emissions in agriculture typically revolve around three core principles:

(ι) diminishing the production of greenhouse gases within the soil,

(ιι) impeding the transformation and subsequent emissions of these gases from soil to the atmosphere, and

(ιιι) augmenting the uptake of greenhouse gases by soil-plant systems.

The net greenhouse gas exchanges are contingent upon striking a balance between production and consumption. Thus, comprehending the underlying mechanisms and drivers governing these processes is imperative for devising and implementing effective mitigation technologies across diverse production systems and agro-ecological regions. The IPCC's 5th assessment reports have delineated mitigation options for greenhouse gas emissions in agriculture into two pathways: supply-side and demand-side mitigation options. Supply-side measures encompass land-use modifications in crop and livestock systems, along with carbon sequestration in soil-plant systems. Strategies such as judicious fertilizer and manure utilization, including the deep placement of nitrogenous fertilizers like urea super granules, and balanced application of phosphorus and potassium through sulfate-containing fertilizers, along with compost featuring a low C:N ratio, are advocated for mitigating methane emissions. Coordinating irrigation scheduling with nitrogen fertilization has demonstrated efficacy in curtailing $N_2O$ emissions across various crops. Drip and sprinkler irrigation systems, particularly in orchards, are identified as viable mitigation options for $N_2O$ and $CO_2$ emissions. Moreover, augmenting the frequency of split irrigation events and foliar nitrogen spray in wetland crops proves effective in mitigating both $N_2O$ and $CH_4$ emissions in such ecosystems.

Furthermore, the utilization of nitrification inhibitors and slow-release nitrogenous fertilizers emerges as a recognized mitigation approach for $N_2O$ emissions. Coated urea briquettes incorporating fly ash can further bolster nitrogen use efficiency and curtail $N_2O$ emissions in submerged rice-paddy systems. Implementing prudent real-time nitrogen management, entailing the synchronization of nitrogen supply from the soil with the crop's demand, is pivotal. Diverse approaches, including fertilizing at critical growth stages, leveraging leaf color charts and SPAD meters for nitrogen assessment, and deploying sensor-based technology for identifying nutrient deficiencies to optimize fertilizer application, are aimed at enhancing fertilizer utilization efficiency, particularly nitrogen use efficiency.

Demand-side mitigation options for reducing greenhouse gas emissions encompass:

***Dietary adjustments*:** Non-vegetarian diets typically contribute more to emissions compared to vegetarian counterparts, especially ruminant meat like beef and lamb. Studies advocate for adopting flexitarian, healthy, and vegetarian diets to substantially cut emissions, particularly those associated with ruminant meat consumption.

***Food loss and waste management*:** Developing nations often grapple with significant food loss due to storage issues and inadequate infrastructure, while waste is prevalent in developed countries. Preventing food loss and waste serves both as a climate adaptation measure, reducing yield losses from climate variability, and as a mitigation strategy by decreasing emissions linked to excessive agricultural production.

***Supply chain governance*:** Promoting local production and consumption tailored to environmental suitability is pivotal. Localized production minimizes transportation losses, bolsters food security, and lowers emissions associated with food loss. However, the environmental impact of the entire supply chain must be considered. While utilizing local livestock products may reduce emissions by shortening the supply chain, importing from highly productive systems with lower emissions footprints may sometimes be advantageous. Therefore, supply chain regulation should hinge on a comprehensive life cycle analysis of greenhouse gas emissions for the entire system, rather than isolated components.

Mitigating climate change involves reducing greenhouse gas emissions into the atmosphere and increasing carbon dioxide removal. To limit global warming to below 1.5°C, global greenhouse gas emissions must reach net-zero by 2050, or by 2070 for a 2°C target. Achieving this requires unprecedented, far-reaching, and systemic transformations across energy, land use, urban planning, transportation, buildings, and industrial sectors. Climate change also exacerbates humanitarian crises caused by heat waves, wildfires, floods, tropical storms, and hurricanes, leading to displacement, loss of life, and property damage. It disproportionately affects marginalized communities with limited access to resources, including indigenous peoples, women, and low-income populations. Climate-induced migration, driven by sea-level rise, extreme weather events, and conflicts over natural resources, is expected to increase, potentially leading to statelessness for some individuals.

### *Climate change mitigation strategy in Indian context*

***Mitigation options for reducing $CH_4$ emissions from Indian agriculture:*** Best management practices can be adapted for low methane emission agri-food system (Bhattacharyya *et al.,* 2020)

- Provide drainage for 2–3 days after transplanting rice-paddy between maximum tillering and panicle initiation stages.
- Use intermittent irrigation for irrigated medium and lowland rice, and alternate wetting-drying cycles for rainfed rice.
- Maintain sulfate in reduced zones of acid sulfate soil to lower $CH_4$ emissions.
- Replace conventional puddled rice cultivation with direct-seeded rice (DSR) along with effective weed and water management, integrating new generation selective herbicides and farm machinery for sustainable yield with reduced $CH_4$ emission.
- Implement dry-direct seeded rice instead of wet-direct seeded rice in medium to upland ecologies.
- Opt for transplanting relatively older rice seedlings (21–30 days) instead of very young seedlings (8–10 days).
- Introduce low $CH_4$ emitting rice cultivars in suitable ecologies.
- Promote aerobic decomposition of rice straw during winter/summer to reduce $CH_4$ emissions in subsequent wet seasons.
- Implement in situ green manuring as paired row cropping (rice-rice-Sesbania) with proper timing of incorporation (25–30 days after sowing) instead of traditional green manuring methods.
- Optimize planting time to reduce $CH_4$ emissions, considering diurnal temperature variations.

***Mitigation options for reducing $N_2O$ emissions from Indian agriculture:*** Best management practices for low $N_2O$ emission agri-food system (Bhattacharyya *et al*., 2020)

- Application of coated ammonium citrate can significantly reduce $N_20$ emission in arable soils.
- Application of bio char reduces $N_20$ emissions.
- Zero and Minimum tillage reduce $N_20$ Emission compared to conventional tillage in rice wheat system.
- Nitrification inhibitors like (1) 2-chloro-6-(trichloromethyl) pyridine (nitrapyrin), (2) dicyandiamide (DCD), and (3) 3, 4-dimethylepyrazole phosphate (DMPP), neem cake, neem oil etc.
- Deep placement of urea in the reduced zone of paddy fields reduce $N_20$ emissions.
- Site specific nutrient management considers both nutrient supply capacity and yield targets.
- Split application of nitrogenous fertilizers either based on critical physiological stages of the crop or using tools like Leaf color chart and SPAD meters.

***Addressing $CO_2$ emissions in Indian agriculture***

Indian agriculture is often regarded as either carbon-neutral or a significant carbon sink due to its ability to absorb $CO_2$ through photosynthesis. However, both plants and soil respire, releasing $CO_2$ back into the atmosphere. To maintain a favorable ecological $CO_2$ balance and mitigate emissions from soil to the atmosphere, various strategies can be adopted. Firstly, implementing minimum tillage or zero tillage practices in rice-wheat cropping systems can reduce $CO_2$ emissions compared to conventional tillage methods. This is achieved by promoting soil compaction and reducing heterotroph activity. Moreover, soil aggregation under reduced tillage helps retain trapped carbon, further minimizing $CO_2$ emissions. Despite promoting $CH_4$ production, continuous submergence in rice-paddy systems actually diminishes $CO_2$ emissions from the system. Introducing legumes into rice-based cropping systems has also demonstrated efficacy in lowering $CO_2$ emissions compared to monoculture maize cultivation. Additionally, incorporating biochar and mulch in agricultural and horticultural systems can mitigate $CO_2$ emissions and bolster carbon sequestration. This is facilitated by introducing stable carbon pools into the soil and regulating labile carbon fractions and soil respiration.

## POLICY AND PROGRAMS

With more than 50% of its people working in agriculture, India is one of the world's top producers of agricultural goods. However, the effects of climate change such as variable rainfall, temperature increase, and extreme weather are posing a growing danger to the productivity of agriculture. In response, the Indian government has created and put into action a number of policies and initiatives targeted at improving agricultural sector to adapt and mitigate climate change.

***National Action Plan on Climate Change (NAPCC):*** The NAPCC describes India's approach to mitigating climate change in a number of industries, including agriculture. The NAPCC stresses the need for adaptation strategies while acknowledging that agriculture is particularly vulnerable to climate change. It encompasses missions with specific goals pertaining to climate-resilient agriculture and water management, such as the 'National Water Mission' and the 'National Mission for Sustainable Agriculture (NMSA)' (Government of India, 2008).

***Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):*** PMKSY uses a variety of techniques, including micro-irrigation, watershed development, and rainwater gathering, to increase water use efficiency. PMKSY helps agriculture adapt to climate change by developing effective water management techniques, especially in water-stressed areas PKVY (Ministry of Jal Shakti, 2015).

***Paramparagat Krishi Vikas Yojana (PKVY):*** Because organic farming methods are recognized to enhance soil health and biodiversity, PKVY supports them. Furthermore, by reducing the usage of chemical inputs like pesticides and fertilizers, organic farming contributes to attempts to mitigate the effects of climate change. Farmers who switch to organic agricultural practices are given financial incentives and training under PKVY (Ministry of Agriculture & Farmers' Welfare, 2016).

***Soil Health Card Scheme:*** This program, which went into effect in 2015, aims to assess soil health and give farmers' customized advice on how to increase soil fertility. This program is essential for adaptation because healthy soils are more resilient to climate change-induced pressures like droughts and floods (Ministry of Agriculture & Farmers' Welfare, 2015).

***National Mission on Sustainable Agriculture (NMSA):*** The NMSA places a strong emphasis on promoting crop diversification, integrated farming systems, and agroforestry as examples of climate-resilient agricultural practices. Farmers may lessen their exposure to the effects of climate change by embracing climate-smart technologies and diversifying their crop kinds (Ministry of Agriculture & Farmers' Welfare, 2014).

***Crop Insurance Program based on Weather (WBCIS):*** Farmers are provided with financial insurance by WBCIS against crop losses caused by unfavorable weather conditions. Through the reduction of the financial risks linked to climate variability, this program encourages farmers to implement risk-reduction strategies and climate-resilient practices (Ministry of Agriculture & Farmers' Welfare, 2016).

***Pradhan Mantri Fasal Bima Yojana (PMFBY):*** Launched in 2016, PMFBY aims to provide affordable crop insurance to farmers. This scheme not only facilitates recovery from crop losses but also fosters the adoption of recommended climate-resilient practices, as insurance coverage is contingent on the implementation of such practices (Ministry of Agriculture & Farmers' Welfare, 2016).

## CONCLUSIONS

The discussion around climate change adaptation and mitigation in Indian agriculture highlights the pressing need and intricacy of tackling climate-related issues within the agricultural sector. The effects of the climate change present serious risks to food security, agricultural production, and the achievement of the Sustainable Development Goals (SDGs). The effects are extensive, ranging from unpredictable weather patterns upsetting conventional farming methods to water scarcity and soil degradation. Furthermore, the interplay between the climate change and food security highlights the need for proactive measures to safeguard vulnerable populations and ensure access to nutritious food. Despite these challenges, embracing climate change adaptation strategies including crop diversification, water-efficient practices, and resilient crop varieties, the agricultural sector can enhance its resilience to climate shocks. Simultaneously, the mitigation efforts aimed at reducing GHG emissions from agriculture through practices like organic farming, agroforestry, and improved livestock management are imperative. In addition, an effective implementation of policy frameworks and programs are crucial towards climate change adaptation and mitigation in Indian agriculture.

## WAY FORWARD

- In order to effectively adapt and mitigate the effects of climate change in Indian agriculture, a comprehensive and multidimensional strategy is required.
- Building resilience against changing climatic patterns will require integrating climate-smart agriculture strategies, such as crop diversification and water management.
- Using technology innovations like data analytics and remote sensing gives farmers access to real-time information they need to make smart decisions.
- Promoting the use of cutting-edge farming methods, such as agroforestry and precision agriculture, increases production and helps sequester carbon.
- Expanded crop insurance and simple loan access are two examples of strengthened financial institutions that will give farmers a safety net against climate-related hazards.
- The development of public-private partnerships is necessary to pool resources and knowledge and enable the expansion of sustainable practices.
- Prioritizing education and awareness initiatives will enable farmers to better understand the effects of climate change and how to adapt to them.
- Furthermore, a unified and well-coordinated strategy to a resilient and low-carbon agriculture sector will be ensured by policy alignment with climate goals and Sustainable Development Targets.
- With the strong synergy of technology-program-policy, Indian agriculture has a strong potential towards sustainable agriculture critically required for food and nutritional security besides SDGs.
- Indian agriculture sector has a major role in SDG targets along with contributing to Paris Agreement and Net Zero Carbon Commitments of Government. The proactive policy and programs will certainly contribute to global collective actions of climate change adaptation while reducing GHGs.

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