A Comprehensive Review on Climate Change Adaptation Strategies in Agriculture: Challenges, and Future Pathways

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Abstract

This review examines the impact of climate change on Indian agriculture and adaptation strategies. Climate change, driven by human activities, poses challenges like rising temperatures and extreme weather events. Farmers use adaptation measures like altering planting dates and developing climate-resilient crops. Changing rainfall patterns, especially during the monsoon, affect foodgrain yield and the economy. Soil conservation, precision agriculture, and urban food production initiatives promote food security and resource recycling. Addressing water scarcity requires improved irrigation and efficient water management. Climate change affects agricultural pests, threatening global food security. Various adaptation strategies, including traditional practices, resource-conservation technologies, and socio-economic interventions, are being implemented. Climate-smart agriculture technologies like precision agriculture increase yields and resilience. Success depends on regional suitability, economic viability, and collective implementation. Agriculture operates within a complex socio-ecological system with uncertainties in policy, economics, and climate. Site-specific climate-smart agriculture practices are crucial for smallholders' resilience and food security. Publicly provided agricultural extension services can help adopt these technologies, but barriers like financial constraints and cultural factors must be considered. This review emphasizes the need for comprehensive, context-specific approaches to address vulnerabilities in Indian agriculture to climate change and ensure a sustainable future for food production and smallholder livelihoods.

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Introduction

One of the biggest environmental issues facing the modern world is climate change. Global climate change is caused by the emission of greenhouse gases (GHG), which include rising levels of gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Changes in rainfall patterns, a rise in sea level, and the migration of climatic areas as a result of rising temperatures are just a few of the swings that climate change will bring about. Due to shifting climatic trends, it is anticipated that the intensity of droughts, storms, and floods would

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increase. With an average temperature increase of 2.8° C, the global temperature will rise by 1.8° to 4° C (IPCC, 2007).

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Agriculture, a sector heavily dependent on weather conditions, is particularly susceptible to the impacts of climate change (Hasan *et al.*, 2016). Climate change poses a significant threat to the productivity of this sector, leading to economic and physical vulnerabilities. Climate-~~related~~dependent/influenced factors such as shifting rainfall patterns, rising temperatures, altered sowing and harvesting times, fluctuating water availability, and changing site suitability all exert a substantial influence on agricultural output (Shakoor *et al.*, 2011). These changes are expected to have far-reaching consequences, affecting food production, water resources, biodiversity, and livelihoods. In India, where a large portion of the population resides in rural areas and relies heavily on natural resources for their sustenance, sustainable resource management becomes imperative for long-term economic well-being. The timing of the monsoon plays a crucial role in Indian agriculture, influencing the agricultural market and essential commodities. Any deviations in rainfall patterns impact agriculture, thereby affecting the nation's economy and food security (Ahmad *et al.*, 2011). In India, agriculture contributes to approximately 52% of employment and contributes around 16% to the nation's GDP.

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The potential for worldwide climate change looms as a significant consequence of the anticipated doubling of atmospheric CO_2 levels and increased trace gas concentrations (Tangley, 1988). Current projections indicate a global temperature rise of 1.5° to 4.5° C, with winter experiencing more pronounced warming than summer, and greater warming occurring at higher latitudes. The precise magnitude, pace, and spatiotemporal characteristics of this climate response, however, remain uncertain. In the northern hemisphere, there are expectations of increased precipitation at high latitudes and reduced summer rainfall and soil moisture at moderate latitudes (Graham and Turner, 1990).

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The direct influence of weather and climate on agricultural production cannot be understated. Potential shifts in temperature, precipitation, and CO_2 concentration are poised to significantly impact crop development. Though effective adaptation strategies and adequate irrigation can mitigate some of the effects, the overall impact of climate change on global food production is still considered to be of low to moderate severity (IPCC, 1998). Given that climatic factors such as rainfall and temperature serve as critical inputs for the crop sector,

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any alterations or fluctuations in these variables are bound to exert substantial effects on crop yields (Barnwal andKotani, 2013).

Climate change poses a grave threat to agriculture and the security of India's food supply, with particular emphasis on the critical role of water resources. In a country where 55% of cultivated lands lack irrigation facilities, water stands as the most vital agricultural resource (Kumar and Gautam, 2014). The demand for water has surged over time, propelled by urbanization, population growth, rapid industrialization, and other developmental pursuits. Moreover, changes in agricultural and land-use practices, excessive groundwater extraction, and alterations in irrigation and drainage have disrupted the hydrological cycle across various climate zones and river basins in India. As a result, water availability emerges as the linchpin of agricultural productivity. Throughout much of India, the quality and availability of water remain significant impediments to successful agriculture, underscoring the pressing need for comprehensive water resource management in the face of climate change.

Effects of Climate Change on Agricultural Productivity

The effect of Climate Change on Agriculture can be seen everywhere in the World (Yadav *et al.*, 2023). In India, the scientific community has employed a variety of techniques to assess the potential effects of climatic variability and change on agriculture. Historically, methods such as analogue analysis and statistical tools have been used to analyze historical data and understand the impacts of climatic variability. More recently, controlled environmental facilities like open-top chambers, free air carbon-dioxide enrichment facilities, phytotron setups, and greenhouses are being increasingly utilized to investigate how factors like temperature, humidity, and CO_2 levels affect crop growth and yield (Aggarwal, 2008). These controlled environments offer precise conditions for research, providing valuable insights into the potential impacts of changing climatic conditions on crop production and aiding in the development of adaptive strategies for agriculture in the face of climate change.

A defining issue of our time is climate change, primarily driven by human activities such as the combustion of fossil fuels and deforestation. This global challenge has far-reaching implications, and one of the sectors significantly impacted is agriculture, which plays a crucial role in ensuring food security, livelihoods, and economies worldwide. Climate change exerts a profound influence on agricultural productivity and sustainability, manifesting through shifts in temperature, altered precipitation patterns, extreme weather events, and rising sea levels. Temperature, in particular, emerges as a critical environmental factor influencing crop growth, development, and yields, affecting the pace at which crops progress through their phenophases. On one hand, crops require a minimum temperature threshold to complete specific life cycle stages, while exceptionally high or low temperatures, especially during crucial phases like anthesis, can detrimentally impact crop growth and production (Luo, 2011).

As global temperatures continue to rise, crop growth and productivity face direct consequences. The optimal temperature ranges for many crops are shifting, leading to adjustments in planting and harvesting times. Elevated temperatures can accelerate plant development, disrupt pollination, and enhance evaporation rates, placing plants under increased water stress. Moreover, any potential benefits arising from higher atmospheric CO_2 concentrations may be counteracted by rising air temperatures, further complicating the picture. Crop growing seasons may also shorten in response to these changes. Consequently, the interplay between temperature and CO_2 concentration presents a complex challenge in predicting their combined effects on plant growth and agricultural outcomes (Streck, 2005).

Drought, emblematic of the mounting trend in extreme weather events, is progressively on the rise (Mazdiyasni andAghaKouchak, 2015), resulting in diminishing agricultural yields (Lesk *et al.*, 2016). To combat the adverse impacts of drought, comprehensive monitoring and prediction systems have been established, providing essential data for early warning and mitigation strategies aimed at bolstering crop resilience and productivity (Hao andAghaKouchak, 2014). Concurrently, adaptation measures have been devised to mitigate these impacts and shape the extent to which climate change affects crop production, including adjustments in planting schedules, transitioning to more suitable crop varieties, developing novel strains, and altering cultivation practices (Leng and Huang, 2017). These adaptive strategies are pivotal in fortifying agricultural systems against the increasing challenges posed by a changing climate.

Climate change-related changes in precipitation patterns are having an increasing impact on crop growth, agricultural productivity, and food security. Rainfall and snowfall, both of which constitute precipitation, supply the vital water source required for plant growth and maintenance. By delivering water for the two main crop-growing seasons, Kharif (summer) and Rabi (winter), rainfall that occurs over India during the summer monsoon season (the major rainy season typically starts in June and ends in September) has a huge impact on the agricultural production of the nation. The entire foodgrain output in India and the nation's

Comment [R8]: Summer or rainy?

economy, which is heavily dependent on agriculture, are both impacted by variations in monsoon rainfall (~~Krishna~~ Kumar *et al*. 2004).Although a small 10% reduction in the long-term mean rainfall results in a considerable decline in rice production across India, rainfall is closely correlated with food productivity (Swaminathan, 1987). Precipitation patterns are changing as a result of climate change, including changes in rainfall frequency, intensity, and distribution. There are greater hazards of flooding and soil erosion in some areas due to more frequent and strong rainfall events. Others have protracted droughts that diminish agricultural productivity and cause a shortage of water.

Crop Adaptation Strategies

Climate change affects crop production through direct, indirect, and socioeconomic factors, with a noticeable rise in climate change-related events like droughts, floods, heat waves, and storms reported by the Food and Agriculture Organization (FAO). Farmers are adapting to these challenges, often through autonomous adaptation strategies, such as altering cropping patterns to include short-duration crops like pulses, vegetables, flowers, and fruits that can withstand warming and drying climates. Planned adaptation measures, like providing farmers with new drought-resistant seed varieties, are also crucial. Farmers are modifying crop types, planting times, and irrigation practices to cope. Information dissemination about innovative management techniques, like revised crop calendars, is vital, as are enhancements to water storage infrastructure like desilting farm ponds (Dhanya and Ramachandran, 2016).

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Farmers are increasingly cultivating short-duration, heat-tolerant crops such as pulses, maize, millets, and floriculture crops in response to climate variability. Phenological shifts in crops, including early blooming and fruiting, have been observed due to high temperatures and moisture stress, impacting both crop production and farmers' livelihoods (Brown, 2006).

Plant breeders face the challenge of developing crops that can thrive in changing conditions. They are using advanced breeding techniques like Rapid Generation Advance (RGA), Doubled Haploid (DH), Shuttle Breeding, Marker Assisted Back Crossing (MABC), Marker Assisted Recurrent Selection (MARS), Genomic Selection (GS), and Speed Breeding to accelerate genetic gains and create climate-resilient crop varieties (Begheyn*et al.,* 2016). Shuttle breeding, for instance, enables an additional generation by growing crops in different locations each year. Genomic Assisted Breeding Approaches are promising for developing climate-resilient crops, reducing generation times, and deciphering how different crop species respond to stress. However, plant breeders must now consider a broader range of environmental factors, including increased temperature, water supply variability, UV radiation, and salinity, when developing new crop varieties (Brettell, 2008).

Soil Management in a Changing Climate

Soil, a part of land, is most important factor for crop production. It is a diversified and complicated system (Pandey *et al*., 2023).Soils are indispensable for sustaining global food production, with no effective alternative available, as emphasized by Blanco-Canqui (2008). This vital resource plays a crucial role in strategies aimed at ensuring food security, particularly in developing nations that rely more heavily on land for their food production compared to wealthier nations, as highlighted by Lashgarara*et al.*,(2008). Sustainable intensification, a key approach, involves enhancing production efficiency in both on-farm inputs and off-farm resources while reducing environmental impacts, as proposed by Godfray *et al.*, (2010).

Precision agriculture (PA), also known as soil/site-specific technology, is a set of practices designed to maximize input utilization based on soil properties and landscape characteristics affecting agronomic production. PA leverages a combination of sensors, information technology, appropriate machinery, and other resource management practices to optimize agricultural operations, reducing the risk of non-point source pollution, a concern due to human activities contributing to the contamination of water resources (Cordell et al., 2011). Closing the human phosphorus (P) cycle, which has been disrupted since the 1950s, is vital to mitigating P pollution, and PA can contribute to this effort (Abelson, 1999).

PA encompasses various techniques, including directed traffic and precise tillage to minimize soil compaction, as well as permanent raised beds aimed at improving soil structure and yield (He *et al.*, 2012). Ensuring sustainable management of macro- and micronutrients is crucial for increasing production and enhancing human nutrition (Graham *et al.*, 2001). Integrated nutrient management (INM) plays a pivotal role in restoring soil fertility for smallholder farmers in Asia, incorporating practices like the use of animal dung, green manures, biological nitrogen fixation (BNF), and judicious application of chemical fertilizers (De Costa and Sangakkara, 2006).

Urbanization is a significant global trend, with varying levels of urban development across continents (Drescher, 2002). Urban areas face food insecurity and malnutrition challenges similar to rural regions, prompting the emergence of urban agriculture as a means of recycling biosolids and wastewater. Opportunities like rooftop gardens complement residential gardens and offer alternative approaches to urban food production (Whittinghill and Rowe, 2012).

Water Management and Irrigation

Water is an essential element for all living organisms, including humans, animals, and plants, making it fundamental to life itself. Its importance extends to various critical aspects, such as food security, livestock husbandry, industrial processes, biodiversity preservation, and environmental conservation. Freshwater is the only source of water that can be used across a spectrum of essential needs, including drinking, industrial applications, agriculture, and more. However, the accessibility and availability of clean drinking water remain challenges for millions of people in India and around the world, and this issue is exacerbated by various factors.

In many regions, particularly in areas with limited water resources, water demand has reached a critical juncture. Irrigation should aim to restore soil water in the root zone to a level at which crop can fully meet its evapotranspiration requirement (Kumar *et al*., 2023). Despite the Earth's abundance of water, factors like overexploitation of water resources, inadequate water supply infrastructure, and the impact of climate change contribute to water scarcity (Mancosu, 2015). The 21st century confronts us with a profound global problem: the lack of access to water, driven by causes including overpopulation, agricultural demands, water pollution, and ineffective governance (Chakkaravarthy and Balakrishnan, 2019).

Climate change compounds the challenges to freshwater resources, affecting both their quantity and quality. India, in particular, faces heightened demand for water due to urbanization, industrialization, the agricultural sector's need for increased water, and a rapidly growing population (Amarasinghe *et al.*, 2007). In response, efforts have been made to promote water efficiency, guided by the principle that "more can be achieved with less water" through improved management practices (Allan, 1999).

Comment [R10]: More crop per drop is a more recent slogan

Enhancing allocative and irrigation water efficiency constitutes better water management. The approach varies based on irrigation technology, environmental conditions, land characteristics, and the timing of water application, often tied to appropriate water pricing for agricultural use (Omezzine and Zaibet, 1998). Irrigation scheduling, a critical component, influences water use efficiency (WUE) by determining the timing and quantity of irrigation, with plant water status assessments, soil moisture monitoring, and crop evapotranspiration estimations serving as methods for achieving this. However, soil-based assessments have limitations, as they provide point-based data subject to spatial and temporal variability (Gillies, 2005).

Addressing water scarcity is a paramount global challenge (Jury and Vaux, 2005). To alleviate water shortages, accurate monitoring of water use, including improved estimation of return flows and evapotranspiration, is essential. The adoption of more efficient irrigation practices may result in reduced water deliveries, potentially affecting downstream water rights holders who rely on return flows, emphasizing the need for careful management to balance competing water demands (Ward and Pulido-Velazquez, 2008).

Comment [R11]:

Pest and Disease Dynamics in a Warming Climate

Global climate change exerts a substantial impact on agriculture, directly and indirectly affecting agricultural insects and pests. Indirect effects encompass changes in the interactions between pests, their environment, and other insect species, including natural enemies, competitors, vectors, and mutualists (Prakash *et al.*, 2014). Direct impacts on pests encompass alterations in reproduction, development, survival, and dispersal. As noted by Yamamura and Kiritani (1998), even a modest 2°C temperature increase can lead to insects experiencing one to five additional life cycles in a single season. Elevated carbon dioxide (CO_2) concentrations can affect insect feeding rates and host chemical defenses, as suggested by Arora and Dhawan (2013), thereby influencing population densities, growth rates, fecundity, and consumption rates of insect pests (Fuhrer, 2003).

The impact of rising CO_2 levels on insect pests is closely tied to the specific plant hosts they rely on. C3 crops such as wheat, rice, and cotton are more vulnerable to the effects of elevated CO_2 compared to C4 crops like corn and sorghum. This differential response to elevated atmospheric CO_2 may lead to asymmetric impacts on herbivory, with insects that feed on C3 plants potentially experiencing different effects than those that feed on C4 plants (Lincoln *et al.*, 1984).

Climate change-induced factors like flooding, extreme weather events, and the creation of new ecological niches can lead to shifts in the population dynamics of soil-dwelling insects. These changes provide opportunities for insect pests to establish, multiply, and migrate across different geographic regions, potentially resulting in new and severe pest challenges for farmers in the years ahead. Cross-border movement of crop pests poses a threat to food security, with global implications (FAO, 2020).

Temperature plays a pivotal role in influencing pest population dynamics, impacting metabolism, metamorphosis, mobility, and host availability (Shrestha, 2019). Rising temperatures may lead to increased herbivory, based on the distribution and behavior of modern insects (DeLucia*et al.*, 2008). Soil-dwelling species are less affected by temperature fluctuations than aboveground insects due to the thermal buffering capacity of soil (Bale et al., 2002). For instance, aphids may emit fewer alarm pheromones at higher temperatures, potentially increasing their susceptibility to predation by parasitoids and insect predators (Awmack *et al.*, 1997).

Comment [R12]: Repetition of same fact

Precipitation patterns, including changes in quantity, intensity, and frequency, are significant indicators of climate change. Altered rainfall patterns, such as droughts and floods, can directly impact insects that overwinter in the soil, affecting their survival and diapause patterns. Flooding and heavy rains can also wash away insect eggs and larvae (Pathania et al., 2020). Staley et al. (2007) investigated the effects of drought and increased summer rainfall on wireworms, soil-dwelling pests that pose a substantial threat to crops like potatoes, corn, and sugar beets. Their findings suggest that increasing summer rainfall events can lead to a rapid rise in wireworm populations in the upper soil layers (Gregory *et al.*, 2009). These observations underscore the complex and multifaceted relationship between climate change and agricultural pest dynamics.

Mitigation and Adaptation Strategies

Adaptation is a critical policy option in response to the effects of climate change, particularly in sectors highly sensitive to climatic conditions like agriculture (Fankhauser, 1996). Agriculture's intrinsic sensitivity to climate makes it one of the most vulnerable industries to the risks and impacts of climate change (Parry and Carter, 1989; Reilly, 1995). Studies have consistently shown that, without adaptation, climate change poses significant challenges to agricultural production, economies, and communities. However, with effective adaptation strategies, vulnerability can be reduced, and opportunities for resilience and sustainable development can be harnessed (Nordhaus, 1991).

A wide range of agricultural adaptation strategies have been proposed to mitigate the anticipated negative effects of climate change. In arid and semi-arid regions, farmers have developed traditional management strategies over generations to enhance soil water retention, reduce sensitivity to drought, and combat soil erosion (Hulme, 1999). One such strategy involves raised beds with tied ridges, which helps retain rainwater, reduce runoff, and enhance water infiltration (Altieri and Nicholls, 2017).

Adaptive agricultural practices encompass a combination of conventional and agroecological management systems, including practices such as biodiversification, improved soil management, and water harvesting (Altieri and Nicholls, 2017). These practices lead to resilient soils and cropping systems, ensuring food security in the face of climate change while also promoting soil health, quality, and carbon sequestration. Key adaptation strategies can be categorized as resource-conservation technologies, cropping-system technologies, and socioeconomic or policy interventions (Venkateswarlu and Shanker, 2009).

In sub-Saharan Africa, adapting to climate change involves implementing sequential cropping systems and adjusting sowing dates according to climate conditions, minimizing crop yield losses (Verchot*et al.,* 2007). Agroforestry practices in Kenya offer opportunities to reduce greenhouse gas accumulation in the atmosphere, benefiting both adaptation and mitigation efforts (Malhi *et al.,* 2021). Additional straightforward adaptation measures include changing planting dates and crop cultivars (Aggarwal, 2008).

Conservation agriculture, characterized by minimal soil disturbance, crop rotation, and soil cover, holds promise for reversing soil degradation caused by conventional tillage and sequestering carbon. However, it should be noted that the carbon sequestration potential of no-till cultivation is limited (Powlson*et al.,* 2014).

Aerobic rice cultivation, aided by micro-irrigation technologies, offers a sustainable approach to rice production, conserving irrigation water and reducing methane emissions (Parthasarathi *et al.,* 2012). Precision farming, which involves more efficient fertilizer management, has the potential to improve nitrogen use efficiency and reduce greenhouse gas emissions (Ladha *et al.,* 2007; Bhatia *et al.,* 2012).

Implementing climate-smart agriculture techniques can boost crop yields and farmer incomes, with laser land leveling cited as an example that reduced expenses and limited losses from climatic fluctuations (Pal *et al.,* 2020). However, the success of these adaptation and mitigation techniques depends on factors like their applicability to specific regions, public acceptance, economic viability, and technical complexity. These strategies are most effective when multiple interventions are employed in synergy to support one another.

Challenges

According to Darnhofer (2010), agriculture is a complex, dynamic socio-ecological system that is subject to policy, economic, and climatic uncertainty. Site-specific climate-smart agriculture (CSA) practices will play a critical role in boosting the income of the most vulnerable populations, minimizing the impact of climate change on food security, and improving smallholders' resilience (FAO 2018, 2017).

The adoption of technologies like CSA is likely to be supported by publicly offered agricultural extension services (Aker 2011). These services distribute vital information to farmers (Lamontagne-Godwin *et al.*, 2018). However, several obstacles hinder the adoption of climate-smart practices, including financial limitations, labor shortages, land and water scarcity, insufficient transportation resources, and low farmer organization membership (*Deressa et al.*, 2008).

While farmers may be generally open to adopting new techniques, they might find specific practices insufficient, superfluous, or challenging to integrate into their current management systems (Smithers and Smit 1989). Barriers to adoption also encompass institutional, socioeconomic, and cultural factors. These include the need for financial capital (Burbi et al. 2016), lack of knowledge, unsatisfactory land tenure, market failures, and inadequate infrastructure (Altieri and Nicholls 2012). Additional considerations involve the suitability of innovations for end-users, labor requirements, access to external inputs, and the use of crop residues for animal feeding (Giller *et al.*, 2009).

Another significant hurdle is the adoption process itself, particularly with regard to its social dimensions, such as age, gender, and diversity. For example, women and men farmers may not have equal access to, use of, or benefits from certain practices (Archer 2003). Similar disparities may occur among farmers with varying income levels, education, family size, land tenure, religious affiliations, places of origin, or connections to institutions and influential individuals. When assessing the suitability of CSA practices and the obstacles to their implementation, these aspects must be considered.

Furthermore, the level of institutional support within a region can influence the speed at which CSA practices are adopted, especially those requiring higher initial startup costs or technical expertise. Investments in infrastructure, extension services, and healthcare within agricultural communities can significantly impact farmers' willingness to take risks and, consequently, their adoption of new practices (Below *et al.*, 2010).

Conclusion

The Indian scientific community employs various methods, including historical data analysis and controlled environmental facilities, to assess climate variability's impact on agriculture. Human-driven climate change significantly affects agriculture through temperature shifts, extreme weather events, and changing precipitation patterns. Rising temperatures can accelerate plant growth but may also cause water stress, while extreme weather events like drought reduce crop production. Adaptation measures, such as altering planting dates and developing new crop varieties, help mitigate these impacts. Changing precipitation patterns during the Indian monsoon season significantly influence foodgrain yield and the country's economy. Climate change leads to shifts in rainfall patterns, affecting food productivity and increasing flooding and drought risks. It directly and indirectly impacts crop production with increased extreme events. Farmers adapt by shifting to short-duration crops, while Genomic Assisted Breeding aims to develop climate-resilient varieties. Soil is crucial for global food production, especially in developing countries. Sustainable intensification, using precision agriculture and nutrient management, enhances productivity while reducing environmental impact. Urban food production, including rooftop gardens, addresses food insecurity and promotes resource recycling. Water scarcity is a growing global challenge due to mismanagement, pollution, climate change, and population growth. Improved irrigation techniques, better management, and efficient water use are essential for addressing this issue. Accurate measurement of water use, including return flows and evapotranspiration, is crucial to mitigate water scarcity challenges and their impacts. Climate change significantly impacts agricultural pests by altering their life cycles, behavior, and interactions with the environment. Rising temperatures accelerate pest reproduction, while increased CO2 affects feeding rates and host plant dynamics. Different plant responses to elevated CO2 influence herbivory patterns. Climate-induced ecological shifts create new pest challenges, posing threats to global food security. Adaptation is crucial, with strategies including traditional and agroecological practices, resource-conservation technologies, cropping-system technologies, and socio-economic interventions. These approaches enhance soil health, increase carbon sequestration, improve crop yields, and reduce greenhouse gas emissions. Water-saving techniques like drip irrigation and precision agriculture are valuable. The adoption of climate-smart agriculture technologies, such as laser land leveling, can increase resilience, depending on regional suitability, economic viability, and collective implementation. Agriculture operates within a complex socio-ecological system filled with uncertainties. Site-specific climate-smart agriculture (CSA) practices are essential for mitigating climate change's impact, but barriers include financial constraints, labor shortages, and infrastructural deficits. Institutional, socio-economic, and cultural factors play crucial roles, and adoption challenges depend on factors like age, gender, income, and institutional support. Publicly provided agricultural extension services can facilitate CSA technology adoption.

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