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CLIMATE CHANGE MITIGATION AND ADAPTATION MEASURES IN AGRICULTURE: A MINI-REVIEW

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ABSTRACT

Climate change represents one of the main threats to agriculture as a result of alterations in temperature and precipitation patterns, the increased frequency of extreme events, and the growing pressure from pests and diseases, which compromise crop productivity and global food security. Furthermore, the agricultural sector's contribution to greenhouse gas emissions and the high vulnerability of production systems have highlighted the need for the integrated implementation of mitigation and adaptation strategies. A literature review was conducted to synthesize scientific evidence on the impacts of climate change on agriculture, as well as mitigation and adaptation measures. The reviewed literature shows that climate impacts on crop productivity are closely linked to the effectiveness of management practices. The studies analyzed indicate that practices such as conservation agriculture, efficient nitrogen management, agroforestry, crop diversification, and improved water management reduce greenhouse gas emissions, increase carbon sequestration, and strengthen the resilience of production systems to adverse climatic conditions. Furthermore, the evidence indicates that integrating mitigation and adaptation measures can generate synergiesthat optimize environmental sustainability, agricultural productivity, and the stability of rural livelihoods.

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INTRODUCTION

Climate change represents one of the main threats to agriculture globally by altering temperature and precipitation patterns, increasing the frequency of extreme events, and directly affecting crop productivity, especially in vulnerable regions (Lobell *et al*., 2011; Hansen *et al*., 2013; Challinor *et al*., 2014). These alterations have led to significant reductions in the yields of staple crops such as wheat, maize, and rice, compromising food security and the stability of agri-food systems (Lesk *et al*., 2016; Zhao *et al*., 2017). Given this scenario, mitigation and adaptation in agricultural systems have become crucial strategies for reducing greenhouse gas emissions and strengthening productive resilience. Practices such as conservation agriculture, efficient nitrogen management, agroforestry, and the use of climate-stress-tolerant cultivars have demonstrated their potential to reduce agricultural vulnerability and contribute to environmental sustainability (Lal, 2004; Howden *et al*., 2007; Smith et al., 2008; Jose, 2009; Paustian *et al*., 2016). The objective of this review was to analyze the impact of climate change on agriculture, as well as mitigation and adaptation strategies that can contribute to the development of more sustainable and resilient production systems in the face of changing climate scenarios.

Climate Change and its Impact on Agriculture: Climate change refers to persistent alterations in average climate patterns that directly affect agroecosystems caused primarily by the anthropogenic increase in greenhouse gases such as CO_2, CH_4, and N_2O, which intensify the natural greenhouse effect and modify the planet's energy balance (Hansen *et al*., 2013; Stocker *et al*., 2013). Since the pre-industrial era, CO_2 concentrations have steadily increased, leading to a rise in average global temperature, accompanied by changes in precipitation, a greater frequency of extreme events, and regional climate variability (Bindoff *et al*., 2013). Observational evidence and climate models agree that human influence is the dominant cause of the warming recorded since the mid-20th century (Hansen *et al*., 2013; Stocker *et al*., 2013). This warming is not spatially homogeneous but rather exhibits regional contrasts that affect atmospheric and oceanic circulation, with repercussions for continental hydrological systems (Bindoff *et al*., 2013). These changes directly influence ecosystems and the provision of essential environmental services, especially in agriculture, which depends on climate stability and is highly sensitive to thermal and water variability (Rockström *et al*., 2009; Challinor *et al*., 2014). As a result, agricultural productivity is highly exposed to variations in temperature, precipitation, and the frequency of extreme climatic events. Therefore, climate change represents a central challenge to the sustainability of production systems, making it necessary to integrate mitigation and adaptation strategies based on sound scientific evidence (Smith *et al*., 2008; Howden *et al*., 2007). Impacts of climate change on agriculture. Climate change is one of the main drivers of transformation in contemporary agricultural systems, as it simultaneously alters the thermal, water, and biogeochemical conditions that regulate plant productivity. Empirical evidence consistently shows that the sustained increase in global average temperature affects crop physiology by modifying photosynthesis, respiration, and the duration of phenological cycles, resulting in significant yield reductions, particularly in staple cereals such as wheat, maize, and rice (Challinor *et al*., 2014; Zhao *et al*., 2017). Agroclimatic models indicate that each 1°C increase in global temperature could reduce global wheat yields by approximately 6%, rice yields by 3.2%, and maize yields by 7.4%, even without considering the increased frequency of extreme events (Zhao *et al*., 2017). These effects are not spatially homogeneous, as tropical and subtropical regions, characterized by temperature ranges close to the physiological threshold for crops, are more vulnerable to additional warming (Lobell *et al*., 2011; Challinor *et al*., 2014). In addition to warming, changes in precipitation patterns are altering water availability and seasonality, affecting both rainfed and irrigated systems. Simulation studies indicate that increased interannual rainfall variability raises the likelihood of crop losses, water erosion, and soil degradation, compromising the productive sustainability of key agricultural regions (Lesk *et al*., 2016). The intensification of prolonged droughts and torrential rains generates water stress, nutrient leaching, and soil compaction, factors that reduce productive efficiency and increase uncertainty in food systems (Martínez *et al*., 2025). Climate change also influences the distribution and severity of pests, diseases, and weeds. Rising temperatures expand the geographic range of insect vectors and pathogens, increasing biotic pressure on crops and generating higher production costs for chemical or biological control (Deutsch *et al*., 2018). From a socioeconomic perspective, these impacts translate into greater vulnerability of rural livelihoods, especially in regions where agriculture is the main source of income and subsistence. Lobell *et al*. (2011) demonstrated that climate change has already significantly reduced agricultural productivity growth in several regions of the world, exacerbating existing inequalities and compromising global food security. Thus, climate change not only represents an environmental challenge for agriculture but also a systemic constraint on development, equity, and socioeconomic stability in rural regions.

Mitigation Measures in Agricultural Systems: Mitigation in agriculture plays a critical role in climate change strategies because the sector is both a contributor to greenhouse gas emissions and a potential carbon sink. Mitigation in agricultural systems is primarily focused on reducing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as increasing carbon sequestration in soils and biomass. Agriculture and land use contribute substantially to the global emissions balance, making their transformation a key component of effective climate mitigation strategies (Smith *et al*., 2008; Paustian *et al*., 2016). One of the most studied strategies is conservation agriculture, which includes practices such as reduced or no-till farming, the use ofcover crops, and diversified crop rotation.These practices promote the accumulation of organic carbon in the soil, improve soil structure, and reduce erosion, thereby contributing simultaneously to climate mitigation and long-term productive sustainability (Lal, 2004; Paustian *et al*., 2016). Lal (2004) demonstrated that agricultural soils have a high carbon sequestration potential, which can offset a significant fraction of agricultural emissions if appropriate management practices are implemented. Agroforestry represents another well-documented mitigation strategy. Integrating trees into agricultural landscapes increases carbon storage in aboveground and belowground biomass, while improving functional biodiversity and the stability of the production system (Jose, 2009; Griscom *et al*., 2017). Griscom *et al*. (2017) estimated that nature-based solutions, including agroforestry practices, could contribute up to 37% of the mitigation needed to meet the global climate goals established in the Paris Agreement. Furthermore, the efficient management of nitrogen fertilizers is a fundamental strategy for reducing N_2O emissions, one of the gases with the highest global warming potential. The use of controlled-release fertilizers, nitrification inhibitors, and precision application strategies has been shown to significantly reduce nitrogen losses to the environment without compromising agricultural yields (Robertson *et al*., 2000; Smith *et al*., 2008). These practices also contribute to improved nutrient use efficiency, generating additional economic benefits for producers. In livestock systems, mitigation strategies include improving forage quality, modifying diets to reduce enteric CH4 emissions, and proper manure management to minimize emissions during storage and field application (Gerber *et al*., 2013). These interventions reduce the climate footprint of livestock production while increasing productive efficiency and system resilience. However, the literature also highlights that the implementation of mitigation measures faces structural barriers, such as financial limitations, a lack of political incentives, and risks perceived by producers in the face of technological changes (Smith *et al*., 2008; Paustian *et al*., 2016). Therefore, effective mitigation in agriculture requires comprehensive approaches that combine technological innovation, coherent public policies, and knowledge transfer mechanisms adapted to local contexts, while also supporting long-term system resilience.

Adaptation Measures in Agricultural Production: Adaptation measures are essential for maintaining agricultural productivity and food security under increasing climate variability and uncertainty. Climate change adaptation in agriculture seeks to reduce the vulnerability of production systems and strengthen their capacity to respond to current and future climate disturbances. Unlike mitigation, which addresses the causes of climate change, adaptation focuses on managing and reducing its unavoidable impacts for food production and rural livelihoods (Smit and Skinner, 2002; Howden *et al*., 2007). One of the most well-documented adaptive strategies is crop and variety diversification, which reduces the risk of total crop losses from extreme events and improves long-term yield stability. By spreading production risks, diversification enhances system stability under extreme climatic events. The use of cultivars tolerant to drought, heat, or salinity allows for maintaining productivity in contexts of increasing climate stress (Howden *et al*., 2007; Challinor *et al*., 2014). Furthermore, functional diversification improves the ecological resilience of agricultural systems by reducing dependence on monocultures that are highly vulnerable to environmental disturbances. Efficient water management is another key element of agricultural adaptation; these practices contribute directly to enhancing the resilience of agricultural systems under conditions of increasing water scarcity. Technologies such as drip irrigation, rainwater harvesting, and climate-data-driven irrigation scheduling allow for the optimization of water use in scenarios of increasing scarcity (Howden *et al*., 2007; Rockström *et al*., 2010). Rockström *et al*. (2010) demonstrated that sustainable intensification strategies based on water efficiency can significantly increase water productivity in agricultural systems in arid and semi-arid regions.

Sustainable soil management also plays a crucial role in adaptation. Practices such as maintaining plant cover, incorporating organic residues, and reducing tillage improve soil structure, increase its moisture retention capacity, and reduce its vulnerability to erosion and compaction (Lal, 2004; Paustian *et al*., 2016). These physical and chemical improvements to the soil increase crop resilience to droughts, floods, and temperature fluctuations. From an institutional and socioeconomic perspective, adaptation requires not only technical changes but also the strengthening of local capacities, access to reliable climate information, and effective agricultural extension systems (Smit and Skinner, 2002; Howden *et al*., 2007). The literature highlights that the successful adoption of adaptive strategies depends on factors such as land tenure security, access to credit, and the integration of traditional knowledge with modern science. Taken together, adaptation measures enhance the capacity of agricultural systems to cope with climate variability, stabilize food production, and support the resilience of rural livelihoods under progressive climate change.

Synergies between mitigation and adaptation: Integrating mitigation and adaptation has become a central principle in climate-smart agriculture due to the interconnected nature of climate risks and management responses.In recent years, the literature has highlighted the importance of designing agricultural strategies that simultaneously integrate mitigation and adaptation objectives, recognizing that many practices can generate dual benefits if properly implemented (Smith and Olesen, 2010; Paustian *et al*., 2016). These synergies are fundamental to maximizing the efficiency of climate interventions in the context of limited resources and competing agricultural and environmental demands. Agroforestry is one of the clearest examples of these synergies. Incorporating trees into agricultural systems increases carbon sequestration in biomass and soils, contributing to mitigation, while also improving microclimate regulation, reducing evaporation, and increasing resilience to droughts and extreme temperatures (Jose, 2009; Griscom *et al*., 2017). Empirical studies show that agroforestry systems can stabilize yields under variable climate scenarios, while strengthening functional biodiversity and the provision of ecosystem services. This dual functionality illustrates how a single practice can simultaneously address mitigation and adaptation objectives. Soil management practices, such as no-till farming and the use of cover crops, also offer dual benefits. These practices increase organic carbon storage, reducing atmospheric CO_2 concentrations, while improving the soil's capacity to retain water and nutrients, thus strengthening crop tolerance to droughts and floods. In this way, climate vulnerability and the environmental footprint of agricultural production are simultaneously reduced (Lal, 2004; Paustian *et al*., 2016). Furthermore, efficient nitrogen management contributes to both mitigations, by reducing N_2O emissions, and adaptation, by improving production efficiency and reducing dependence on external inputs, which is particularly relevant in contexts of climate uncertainty and economic volatility (Robertson et al., 2000; Smith et al., 2008). These synergies allow for the optimization of resource use and strengthen the economic and environmental sustainability of agricultural systems. Despite these synergies, the literature cautions that not all measures automatically generate dual benefits and that trade-offs between mitigation and adaptation may exist. For example, certain carbon sequestration strategies through intensive afforestation can compete with food production if not properly designed, which could compromise local food security (Smith and Olesen, 2010; Paustian *et al*., 2016). Therefore, it is necessary to carefully evaluate biophysical and socioeconomic contexts to maximize synergies and minimize conflicts between climate and production objectives. In summary, integrating mitigation and adaptation into agriculture offers a strategic path to address climate change efficiently and sustainably, provided it is based on systemic approaches, robust scientific evidence, and coherent public policies.

CONCLUSIONS

This review highlights that addressing climate change in agriculture requires integrated management approaches. Practices such as conservation agriculture, agroforestry, efficient nitrogen management, crop diversification, and sustainable water management represent effective strategies for reducing greenhouse gas emissions and strengthening the resilience of agricultural systems to climate change. These outcomes are achieved through mechanisms such as carbon sequestration, improved resource use efficiency, and enhanced adaptive capacity to adverse environmental conditions, thereby reinforcing the importance of mitigation and adaptation as complementary and synergistic approaches for the development of sustainable and resilient agricultural production systems.

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