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A Review on Influence of Climate Change on Agronomic Practices and Crop Adaptation Strategies

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Climate change poses significant challenges to global agriculture, threatening food security, livelihoods, and ecosystem sustainability. This review explores the influence of climate change on agronomic practices and the strategies needed for crop adaptation. As rising temperatures, altered precipitation patterns, and increasing frequency of extreme weather events impact crop productivity, there is a growing need for climate-resilient agricultural practices. National and international policies, including climate-smart agriculture (CSA) initiatives and global climate agreements like the Paris Agreement, play a critical role in promoting sustainable agricultural frameworks. Agricultural extension services are crucial in disseminating knowledge and providing technical assistance to farmers, enabling them to adopt adaptive practices such as drought-resistant crop varieties, water conservation, and integrated pest management. Emerging technologies, particularly artificial intelligence (AI), machine learning (ML), and advanced breeding techniques, are driving innovation in agriculture, offering precise, data-driven solutions for improving climate resilience. AI and ML are being utilized to predict climate impacts, optimize resource use, and provide early warnings for pest and disease outbreaks. In parallel, advanced breeding techniques, including CRISPR-Cas9 and genomic selection, accelerate the development of climate-resilient crops by enabling faster and more precise breeding of traits such as drought and heat tolerance. Long-term monitoring of climate and agronomic changes through remote sensing technologies and climate models provides critical data for understanding climate impacts and refining adaptation strategies. Public-private partnerships are essential for scaling up climate-resilient agriculture by facilitating the mobilization of financial resources and promoting research and development (R&D) collaborations that lead to the development of innovative technologies and climate-smart practices. Additionally, enhancing global collaboration in agricultural research is vital for addressing the diverse impacts of climate change across regions. Overall, a combination of policy support, technological advancements, and coordinated research efforts is crucial for developing effective strategies to ensure the long-term sustainability and resilience of agricultural systems in the face of climate change.

Keywords: Climate-resilience; adaptation; drought-tolerance; ai-agriculture; sustainable-farming; precision-agriculture.

1. INTRODUCTION

1.1 Climate Change

Climate change refers to the long-term alteration of temperature and typical weather patterns in a place. The Earth's climate has undergone periodic changes over the millennia due to natural processes, including volcanic eruptions, ocean currents, and variations in solar radiation. However, in recent decades, the term "climate change" has increasingly come to be associated with human activities, especially the burning of fossil fuels, deforestation, and industrial activities, which are resulting in the buildup of greenhouse gases (GHGs) in the atmosphere. These GHGs, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), trap heat in the atmosphere, leading to the greenhouse effect, which causes the planet's surface to warm. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "any change in climate over time, whether due to natural variability or as a result of human activity" [1]. The rising concentration of GHGs is a driving force behind global warming, leading to unprecedented climatic shifts, including higher average global temperatures, erratic weather patterns, and an increase in the frequency of extreme events such as droughts, floods, and storms.

1.2 Climate Change in Agriculture

Agriculture is inherently dependent on climate and weather conditions. As the climate changes, so too does the viability of agricultural practices, which must adapt to cope with new environmental realities. Climate change affects agriculture in several ways, including altering the length and quality of the growing season, modifying water availability, influencing pest and disease pressures, and affecting soil fertility [2]. These changes can lead to reduced crop yields, compromised food quality, and increased costs for farmers as they invest in new technologies and strategies to mitigate the effects of a changing climate. The agricultural sector is particularly vulnerable because it relies on specific climate conditions for the successful cultivation of crops. Climate change has led to more extreme weather events, such as heatwaves, floods, and prolonged droughts, all of which can devastate crop yields. For example, studies have shown that global warming has already contributed to decreased yields for staple crops such as wheat, maize, and rice in certain regions. Its direct effects on crop productivity, climate change also influences the availability of water resources, which is critical for agricultural production. Changes in precipitation patterns, increased evapotranspiration due to higher temperatures, and the melting of glaciers can all contribute to water shortages in agricultural areas, particularly those dependent on irrigation. Moreover, the rising incidence of pest outbreaks and the spread of crop diseases, as influenced by changing weather conditions, can further strain agricultural systems [3]. The combined impact of these factors underscores the need for a comprehensive approach to climate change adaptation in agriculture, focusing on both agronomic practices and the development of climate-resilient crop varieties.

1.3 Purpose of the Review: Linking Climate Change to Agronomic Practices and Crop Adaptation

This review aims to explore the intricate relationship between climate change and agronomic practices, emphasizing the critical need for crop adaptation strategies to ensure food security in a rapidly changing environment. As climate change continues to alter the conditions under which crops are grown, agronomic practices must evolve to address the new challenges posed by more frequent extreme weather events, changes in temperature and precipitation patterns, and shifts in pest and disease dynamics. The review will examine how farmers can modify their traditional practices—such as adjusting planting dates, changing crop varieties, adopting sustainable water management techniques, and integrating modern technologies like precision agriculture—to cope with the impacts of climate change [4]. It will also explore crop adaptation strategies, including the development of drought-tolerant, heat-resistant, and climate-resilient crop varieties through both conventional breeding techniques and biotechnology. By linking climate change to agronomic practices, this review will highlight the importance of a multifaceted approach that involves research, innovation, policy intervention, and farmer engagement to mitigate the adverse effects of climate change on agriculture.

2. CLIMATE CHANGE AND ITS IMPACTS ON AGRICULTURE

2.1 Global Climate Patterns and Agriculture

Climate change is reshaping global climate patterns, which has direct consequences on agricultural systems worldwide (Table 1). Agriculture is highly sensitive to variations in temperature, rainfall, and extreme weather events. Climate models predict that changes in these global climate patterns will vary by region, and their impacts on agricultural productivity will depend on local environmental conditions as well as the capacity of farming systems to adapt [5]. The interaction between climatic variability and agriculture can result in disruptions to food supply chains, threaten food security, and alter land use patterns, making the need for adaptive agronomic practices more pressing.

Temperature variability: Temperature is a critical factor in determining the growth, development, and yield of crops. As global temperatures rise due to increased greenhouse gas concentrations, many regions are experiencing shifts in growing seasons, with longer periods of extreme heat. Higher temperatures can lead to heat stress in crops, reducing photosynthesis, impairing reproductive processes, and ultimately decreasing yields. For instance, it has been shown that wheat, maize, and rice yields decrease significantly when daily maximum temperatures exceed 30°C [6]. The effect of temperature on agriculture is not uniform across crops. For example, C_3 plants such as wheat, rice, and soybean are more sensitive to temperature increases than C_4 plants like maize, millet, and sorghum, which can tolerate higher temperatures. Nonetheless, continued warming is expected to challenge even heat-tolerant crops, especially if the rise in temperatures is accompanied by reduced water availability. Warming temperatures are expected to shift the geographical boundaries of where specific crops can be grown. Crops that are traditionally cultivated in cooler regions may need to be replaced by those adapted to warmer climates, affecting local agricultural economies and food security.

Table 1. Climate Change and Its Impacts on Agriculture Source: [11], [12], [13]

Impact Area	Climate Change Effects	Agricultural Consequences	Mitigation Strategies
Temperature Rise	Increased average global temperatures	Reduced crop yield, heat stress on plants and animals	Development of heat-resistant crop varieties, improved irrigation techniques
Altered Rainfall Patterns	Increased intensity of rainfall, shifting seasons	Crop failures due to droughts or floods, soil erosion	Adoption of water management practices, conservation tillage
Increased CO_2 Levels	Elevated atmospheric CO_2 levels	Enhanced photosynthesis in some crops but variable responses in others	Development of crop varieties that utilize higher CO_2 efficiently
Pest and Disease Proliferation	Changes in pest life cycles and geographic distribution	Increased pest outbreaks, loss of crops due to diseases	Integrated pest management (IPM), use of biopesticides
Sea Level Rise	Rising sea levels leading to coastal flooding	Loss of agricultural land in coastal areas, salinization of soils	Development of salt-tolerant crop varieties, construction of sea barriers
Extreme Weather Events	Increased frequency of storms, hurricanes, and droughts	Crop damage, infrastructure destruction, disrupted food supply chains	Early warning systems, resilient agricultural infrastructure
Soil Degradation	Higher rates of soil erosion and nutrient depletion	Reduced soil fertility, lower agricultural productivity	Sustainable land management practices, agroforestry
Shifts in Growing Seasons	Altered growing seasons, shorter or extended seasons	Mismatch between crop development stages and environmental conditions	Crop diversification, adjustment of planting and harvesting times

Rainfall distribution: Rainfall is another critical factor influencing agricultural productivity. Climate change is expected to alter rainfall patterns globally, with some regions experiencing increased precipitation and others facing severe droughts [7]. In many tropical and subtropical regions, erratic rainfall and extended periods of drought have become more frequent, significantly impacting rain-fed agricultural systems. Unpredictable rainfall disrupts the timing of planting and harvesting, often leading to reduced crop yields and increased risks of crop failure. Regions that experience increased rainfall may face different challenges. Excessive rainfall can cause waterlogging, leading to poor root development and lower oxygen availability in soils, both of which impair plant growth. Increased rainfall can also lead to nutrient leaching from the soil, reducing its fertility and negatively affecting crop productivity. On the other hand, regions that become drier due to reduced precipitation face severe water shortages, particularly in areas reliant on irrigation [8]. The reduction in freshwater availability is expected to limit the ability of farmers to maintain current levels of productivity, especially for water-intensive crops such as rice and sugarcane.

Extreme weather events: Extreme weather events, such as hurricanes, floods, and prolonged droughts, are becoming more frequent and intense due to climate change, presenting significant risks to agricultural systems. Extreme events can destroy crops, erode soils, and damage infrastructure critical to agriculture, such as irrigation systems, roads, and storage facilities. Droughts, in particular, are projected to become more common in many parts of the world, especially in semi-arid regions where agriculture is already vulnerable. Prolonged drought conditions not only reduce crop yields but also increase the risk of desertification, further limiting the land available for agriculture [9]. Flooding is another major risk, particularly in low-lying and coastal agricultural regions.

Increased precipitation and rising sea levels can lead to salinization of soil, which diminishes soil fertility and hampers crop growth. For example, in South and Southeast Asia, rice-producing regions are increasingly vulnerable to flood events, which can destroy crops and result in significant economic losses for smallholder farmers. Hurricanes and typhoons, which are expected to increase in intensity, can devastate entire agricultural areas in a matter of hours, making it difficult for farmers to recover.

2.2 Regional Variations in Climate Change Effects on Agriculture

The impacts of climate change on agriculture are not uniform across regions [10]. Different regions will experience varying degrees of warming, changes in precipitation patterns, and exposure to extreme weather events, all of which influence the vulnerability and adaptive capacity of their agricultural systems.

Tropical and subtropical regions: Tropical and subtropical regions, where many developing countries are located, are expected to bear the brunt of climate change impacts on agriculture. These regions are highly sensitive to both temperature increases and changes in precipitation patterns. Tropical agriculture is often rain-fed, making it particularly vulnerable to changes in rainfall distribution. In many parts of sub-Saharan Africa and South Asia, climate change is expected to exacerbate existing challenges such as drought, soil degradation, and water scarcity, leading to declining crop productivity and food insecurity [11]. Crops like maize, which are staple foods in many tropical regions, are particularly vulnerable to heat stress and water shortages. Research has shown that yields of maize in Africa could decline by up to 30% by 2050 due to the combined effects of higher temperatures and reduced rainfall. In Southeast Asia, rice production faces similar risks from increased temperatures and shifting monsoon patterns. For smallholder farmers in these regions, the impacts of climate change on agriculture threaten not only their livelihoods but also their access to food.

Temperate regions: In contrast to the tropics, temperate regions may initially experience some benefits from climate change, particularly in the form of longer growing seasons and increased CO_2 fertilization, which can enhance crop growth. For example, in parts of North America, Europe, and Russia, rising temperatures could allow for the expansion of cropping areas further north, where colder temperatures have traditionally limited agricultural activity. However, these potential benefits are likely to be outweighed by the negative impacts of more frequent extreme weather events and the increased variability in climate conditions [12]. In temperate regions, crops such as wheat and barley may benefit from warmer temperatures and longer growing seasons in the short term, but as temperatures continue to rise, the negative effects of heat stress and water shortages will likely become more pronounced. In Europe, for example, research suggests that by the end of the century, crop yields could decline by 10–20% due to higher temperatures, reduced water availability, and increased occurrence of droughts. Moreover, the benefits of CO_2 fertilization are likely to be offset by other factors, such as nutrient limitations, pests, and diseases, which are expected to increase in prevalence due to climate change.

2.3 Long-term Impacts on Crop Yield and Agricultural Sustainability

The long-term impacts of climate change on crop yields and agricultural sustainability are profound. As temperatures continue to rise, rainfall becomes more unpredictable, and extreme weather events increase in frequency, agricultural systems will need to adapt to survive. Studies have shown that without significant adaptation measures, global crop yields could decline by up to 25% by the end of the century, with the most severe impacts being felt in tropical regions [13]. In addition to declining yields, climate change is expected to reduce the sustainability of agricultural systems. Soil degradation, water scarcity, and the loss of biodiversity will undermine the long-term productivity of farming systems, making it increasingly difficult to maintain current levels of food production. The need for climate-resilient agronomic practices is more urgent than ever, as the long-term viability of agriculture depends on the ability of farmers to adapt to changing environmental conditions while minimizing their environmental footprint.

3. INFLUENCE OF CLIMATE CHANGE ON AGRONOMIC PRACTICES

3.1 Changes in Cropping Patterns

The shift in climate patterns, driven by global warming and altered weather systems, has significantly influenced traditional cropping

Table 2. Influence of Climate Change on Agronomic Practices Sources: [23], [25],[26]

Agronomic Practice	Climate Change Influence	Adaptation Strategies	Expected Outcomes
Crop Selection	Shifts in temperature and precipitation patterns	Introduction of climate-resilient crop varieties	Improved resilience to temperature extremes and drought
Planting Dates	Altered growing seasons due to temperature changes	Adjustment of planting and harvesting schedules	Optimized crop growth, reduced risk of yield loss
Irrigation Management	Increased water scarcity, altered rainfall distribution	Adoption of precision irrigation techniques	Efficient water use, reduced water stress in crops
Fertilizer Application	Variability in nutrient uptake due to changing CO2 levels and temperature	Precision nutrient management, use of bio-fertilizers	Optimized nutrient use, reduced environmental impact
Tillage Practices	Increased soil erosion due to extreme weather events	Conservation tillage, zero tillage	Reduced soil erosion, improved soil health
Pest and Weed Management	Changes in pest and weed populations due to altered ecosystems	Integrated pest and weed management strategies	Reduced crop damage, minimized chemical inputs
Crop Rotation	Shifts in the suitability of traditional crop sequences	Diversification of crop rotations based on climate conditions	Enhanced soil fertility, pest control, and productivity
Soil Management	Soil degradation due to increased erosion and nutrient loss	Adoption of sustainable soil management practices (e.g., cover cropping, organic amendments)	Improved soil structure, moisture retention, and fertility
Harvesting Techniques	Unpredictable extreme weather events affecting harvest timing	Use of automated and climate-adaptive harvesting technologies	Minimized post-harvest losses, optimized labor use
Agroforestry	Vulnerability of monoculture systems to climate extremes	Integration of trees and shrubs with crops	Enhanced biodiversity, microclimate regulation, and soil protection

patterns worldwide (Table 2) [14]. These changes affect the timing of planting and harvesting, the geographical suitability of crops, and the adaptation of agricultural systems to new climatic realities.

Shift in growing seasons: Climate change is causing shifts in the growing seasons for many crops due to changes in temperature and precipitation patterns. Warmer temperatures are leading to an earlier onset of the growing season in many temperate regions, particularly in the northern hemisphere, where spring is arriving earlier each year. This shift can have both positive and negative effects. In some cases, longer growing seasons may increase the productivity of certain crops, but they also expose crops to heat stress, reduced water availability, and increased pest pressure later in the season [15]. Crops that require specific temperature ranges or photoperiods may no longer thrive in their traditional regions. For example, maize, which has a specific temperature threshold for growth, may suffer from yield losses if exposed to extreme heat during its reproductive phase. Additionally, earlier planting dates may not align with traditional rainfall patterns, leading to challenges in water availability and seedling establishment.

Altered crop suitability in different zones: As temperatures rise and precipitation patterns shift, the geographical zones where certain crops can be grown are also changing. Warmer temperatures are pushing crop production zones poleward, where previously unsuitable areas are becoming viable for crops that require warmer conditions. For instance, crops like maize and soybean, traditionally grown in temperate regions, are now being cultivated at higher latitudes [16]. This shift is not without its challenges. In tropical and subtropical regions, crops that have adapted to specific climatic conditions may become less viable due to heat stress and changing rainfall patterns. For example, rice, a staple crop in Asia, is highly sensitive to temperature increases, and yields could decline significantly as temperatures continue to rise. Farmers in these regions may need to adopt new crop varieties or switch to alternative crops that are better suited to the changing climate.

3.2 Soil Health and Fertility Management under Changing Climate

Soil health and fertility are crucial for sustaining crop productivity, but they are highly susceptible to the effects of climate change [17]. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events are all contributing to soil degradation and nutrient imbalances.

Soil erosion and degradation: Climate change is exacerbating soil erosion and degradation, particularly in areas that experience more intense rainfall and flooding. Increased rainfall intensity can wash away topsoil, the most fertile layer of soil, leading to reduced soil quality and productivity. Additionally, prolonged droughts can reduce vegetation cover, leaving soils exposed to wind and water erosion. Soil degradation not only affects crop yields but also reduces the soil's ability to retain moisture and nutrients, further compromising agricultural productivity. In some regions, desertification is becoming a significant concern. As temperatures rise and precipitation decreases, particularly in semi-arid areas, soils are becoming more prone to desertification, reducing the land available for agricultural use [18]. This poses a major threat to food security, particularly in regions that are already vulnerable to climate change.

Nutrient management in response to climate stress: Climate change also affects the nutrient dynamics of soils, making it more challenging to maintain soil fertility. Higher temperatures and altered rainfall patterns can accelerate the breakdown of organic matter in soils, leading to faster nutrient depletion. Additionally, increased rainfall intensity can cause nutrient leaching, particularly of nitrogen and phosphorus, which are essential for crop growth. To cope with these challenges, farmers are adopting more efficient nutrient management practices, such as precision fertilization and the use of organic amendments to improve soil structure and nutrient retention [19]. These practices aim to optimize nutrient availability for crops while minimizing nutrient losses due to erosion and leaching.

3.3 Irrigation and Water Management Practices

Water availability is a critical factor in agricultural production, and climate change is significantly altering the distribution and availability of water resources. As precipitation patterns become more erratic and water demand increases, efficient water management practices are becoming essential for sustaining agricultural productivity.

Changing water availability: In many regions, climate change is leading to increased water scarcity, particularly in areas that rely on irrigation. Warmer temperatures increase evapotranspiration rates, reducing the amount of water available for crops. Additionally, changes in precipitation patterns are leading to more frequent and severe droughts, particularly in arid and semi-arid regions [20]. This changing water availability is forcing farmers to adopt new water management strategies, such as switching to drought-tolerant crops or reducing the area under cultivation. In some regions, farmers are also investing in rainwater harvesting and water conservation technologies to ensure a reliable water supply for crops.

Efficient irrigation techniques for climate adaptation: As water becomes scarcer, efficient irrigation techniques are becoming increasingly important for maintaining crop productivity. Traditional irrigation methods, such as flood irrigation, are highly inefficient, leading to significant water losses due to evaporation and runoff [21]. In contrast, modern irrigation techniques, such as drip irrigation and sprinkler systems, deliver water directly to the roots of plants, reducing water use and improving water-use efficiency. Precision irrigation, which uses sensors and data analytics to optimize water delivery based on the needs of the crops and the soil's moisture content, is also gaining popularity as a climate adaptation strategy. These technologies allow farmers to reduce water waste and ensure that crops receive the optimal amount of water, even in the face of changing climatic conditions.

3.4 Pest and Disease Management

Climate change is also affecting pest and disease dynamics, leading to increased pest pressure and the emergence of new disease patterns. Warmer temperatures and changes in rainfall patterns are creating more favorable conditions for pests and pathogens, threatening crop productivity.

Increased pest pressure due to temperature rise: Warmer temperatures are extending the geographical range of many pests, allowing them to thrive in regions where they were previously unable to survive [22]. For example, the fall armyworm, a major pest of maize, is now spreading into regions of Africa and Asia where it was not previously found, causing significant crop losses. In addition to expanding their range, pests are also experiencing faster reproductive cycles and increased population growth under warmer conditions, leading to more frequent and severe pest outbreaks. Farmers are adapting to this increased pest pressure by adopting integrated pest management (IPM) strategies, which combine biological control methods with the judicious use of chemical pesticides [23]. These strategies aim to minimize the impact of pests while reducing the environmental and health risks associated with pesticide use.

New disease patterns emerging due to climate factors: Climate change is also contributing to the emergence of new disease patterns in agricultural systems. Warmer temperatures and increased humidity create more favorable conditions for the spread of fungal and bacterial diseases. For example, rust diseases, which affect wheat and other cereals, are becoming more prevalent as temperatures rise and rainfall patterns change. Farmers are responding to these new disease patterns by adopting disease-resistant crop varieties and using fungicides and other chemical treatments to manage disease outbreaks. However, the increasing use of chemicals in agriculture raises concerns about the development of resistance in pathogens, highlighting the need for more sustainable disease management practices [24].

3.5 Use of Precision Agriculture Tools in the Face of Climate Change

The growing challenges posed by climate change have spurred the adoption of precision agriculture tools, which use data and technology to optimize agronomic practices and improve climate resilience.

Technological interventions for climate-resilient agronomy: Technological innovations, such as remote sensing, drones, and climate-smart machinery, are helping farmers monitor their crops more effectively and make data-driven decisions about planting, irrigation, and pest management. These technologies allow farmers to respond quickly to changing climatic conditions and optimize their use of resources, such as water and fertilizers, to improve crop productivity and resilience. Precision agriculture also enables the use of climate models and weather forecasts to inform agronomic decisions, such as the timing of planting and harvesting. For example, weather forecasting tools can help farmers anticipate droughts or heavy rainfall and adjust their irrigation schedules accordingly [25].

Role of remote sensing and forecasting: Remote sensing technologies, such as satellite imagery and drones, play a key role in monitoring crop health and assessing the impacts of climate change on agricultural systems. These tools provide real-time data on soil moisture, vegetation health, and crop growth, allowing farmers to detect early signs of stress and take corrective action. Forecasting models, which use climate data to predict future weather patterns and their potential impacts on agriculture, are also helping farmers plan for climate variability [26]. These models can inform decisions about crop selection, irrigation, and pest management, enabling farmers to reduce risks and improve resilience in the face of climate change.

4. CROP ADAPTATION STRATEGIES TO CLIMATE CHANGE

The impacts of climate change on agriculture, including increased temperatures, altered precipitation patterns, and extreme weather events, have necessitated the development of effective crop adaptation strategies. These strategies aim to ensure food security and agricultural sustainability by enhancing the resilience of crops to climate stressors. Crop adaptation strategies involve the development of climate-resilient crop varieties, the adoption of agroecological and sustainable farming practices, the application of biotechnological innovations, and the implementation of risk diversification strategies for farmers [27].

4.1 Breeding Climate-resilient Varieties

One of the most crucial strategies for adapting to climate change is the development of crop varieties that can withstand climate-induced stresses, such as drought, heat, and shortened growing periods. Breeding efforts have focused on improving the genetic resilience of crops to cope with the challenges posed by climate change.

Drought-resistant varieties: Drought is one of the most significant challenges posed by climate change, especially in arid and semi-arid regions. Drought-resistant varieties of crops are being developed through both traditional breeding and modern biotechnology to enhance the ability of crops to survive with limited water [28]. These varieties often exhibit traits such as deep root systems, efficient water use, and the ability to maintain physiological processes under water stress. For example, drought-resistant varieties of maize and wheat have been successfully developed and introduced in regions like sub-Saharan Africa, where water scarcity threatens crop yields. These varieties have significantly reduced yield losses during periods of drought, helping to ensure food security in water-limited environments. The use of molecular markers and genomic selection has further accelerated the development of drought-tolerant crops, allowing breeders to select for drought resilience traits with greater precision [29].

Heat-tolerant crops: Heat stress is another major challenge posed by climate change, particularly in tropical and subtropical regions where temperatures are expected to rise significantly. Heat-tolerant crop varieties have been developed to maintain productivity under high temperatures, which can negatively affect photosynthesis, reproductive development, and grain filling. Heat-tolerant varieties of rice have been bred to withstand high temperatures during critical growth stages such as flowering and grain filling, which are particularly sensitive to heat stress [30]. Similarly, heat-tolerant wheat varieties have been developed for cultivation in regions where rising temperatures threaten traditional wheat-growing areas. These varieties are essential for ensuring stable crop yields in a warming climate.

Varieties with shorter growing periods: As climate change alters growing seasons, crop varieties with shorter growing periods are becoming increasingly important. These varieties can be harvested before the onset of extreme weather events, such as heatwaves, droughts, or heavy rains, which often occur later in the growing season [31]. Short-duration varieties of crops such as rice, maize, and sorghum are being developed to allow farmers to adjust planting schedules and avoid the most extreme climate events. In regions with increasingly erratic rainfall, short-duration varieties enable farmers to make the most of shorter rainy seasons or to plant multiple crops within a single growing season. The development of these varieties is particularly critical in regions where climate variability is disrupting traditional cropping cycles.

4.2 Agroecological and Sustainable Farming Practices

In addition to breeding climate-resilient varieties, agroecological and sustainable farming practices play a vital role in building resilience to climate change [32]. These practices enhance the sustainability of agricultural systems by promoting biodiversity, improving soil health, and optimizing resource use.

Agroforestry systems for adaptation: Agroforestry, the practice of integrating trees into agricultural systems, offers a valuable adaptation strategy for mitigating the impacts of climate change. Trees provide multiple benefits, including shade, windbreaks, and improved soil fertility through the addition of organic matter and nitrogen fixation. Agroforestry systems can also help buffer crops against extreme weather events, such as storms and droughts, by reducing wind and water erosion and improving water retention in soils [33]. In tropical regions, agroforestry has been successfully implemented to increase the resilience of smallholder farmers to climate change. For example, in East Africa, agroforestry systems incorporating nitrogen-fixing trees, such as *Faidherbia albida*, have improved crop yields and soil health while reducing the need for chemical fertilizers. These systems also contribute to carbon sequestration, making them an important component of climate mitigation efforts.

Conservation agriculture and no-till farming: Conservation agriculture, which includes practices such as minimal soil disturbance (no-till farming), crop rotation, and the maintenance of soil cover, is another key strategy for enhancing resilience to climate change. These practices improve soil structure, increase water infiltration, and reduce soil erosion, making agricultural systems more resilient to drought and extreme rainfall [34]. No-till farming, in particular, has gained attention for its ability to reduce soil erosion and improve soil moisture retention in dry climates. By minimizing soil disturbance, no-till farming helps preserve soil organic matter and microbial diversity, which are critical for maintaining soil health and fertility under changing climate conditions.

Integrated farming systems for enhanced resilience: Integrated farming systems, which combine crop production with livestock and/or aquaculture, offer a holistic approach to building climate resilience. These systems enhance resource use efficiency by recycling nutrients and organic matter between different components of the farm [35]. Integrated farming systems are particularly valuable in smallholder farming contexts, where they can reduce farmers' reliance on external inputs and improve the overall sustainability of the agricultural system. For example, in Southeast Asia, integrated rice-fish farming systems have been shown to improve crop yields and reduce the impact of climate variability by enhancing nutrient cycling and water management. These systems also provide additional sources of income and food security, making them a valuable adaptation strategy for vulnerable farming communities.

4.3 Role of Biotechnology in Crop Adaptation

Biotechnology offers powerful tools for developing climate-resilient crops through genetic modification and advanced breeding techniques [36]. These innovations are essential for addressing the challenges posed by climate change, such as drought, heat stress, and disease outbreaks.

Genetically modified crops for climate resilience: Genetically modified (GM) crops have been developed to enhance resilience to environmental stressors, including drought, heat, and pests. For example, drought-tolerant maize varieties, developed through genetic modification, have been introduced in several African countries, where they have improved crop yields under water-limited conditions. Similarly, GM crops with enhanced resistance to pests and diseases, such as Bt cotton and Bt maize, have reduced the need for chemical pesticides, thereby lowering production costs and environmental impacts [37]. While GM crops offer significant potential for climate adaptation, their adoption has been met with regulatory and public resistance in some regions. However, ongoing research continues to explore new genetic modifications to enhance the resilience of key staple crops to climate-induced stresses.

Marker-assisted selection for climate-tolerant traits: Marker-assisted selection (MAS) is an advanced breeding technique that uses molecular markers to identify and select for specific traits, such as drought tolerance or heat resistance, in crop breeding programs. MAS accelerates the breeding process by allowing breeders to target specific genes associated with climate resilience, reducing the time required to develop new crop varieties [38]. For example, MAS has been used to develop drought-tolerant rice varieties, such as *Sahbhagi Dhan* in India, which has improved yields in drought-prone regions. The use of MAS in crop breeding programs is expanding rapidly, offering a promising tool for developing climate-resilient crops.

4.4 Risk Diversification Strategies for Farmers

In addition to crop and farming system adaptations, risk diversification strategies are essential for protecting farmers from the economic impacts of climate change [39]. These strategies help farmers manage the risks associated with crop failure, market fluctuations, and extreme weather events.

Crop insurance and financial safety nets: Crop insurance is an important tool for mitigating the financial risks associated with climate variability. Insurance schemes compensate farmers for losses due to extreme weather events, such as droughts, floods, or storms, providing a financial safety net that helps them recover and continue farming. In many developing countries, crop insurance schemes have been introduced as part of broader efforts to enhance resilience to climate change. For example, in India, the Pradhan Mantri Fasal Bima Yojana (PMFBY) provides crop insurance to millions of farmers, protecting them against yield losses caused by extreme weather events [40]. Similarly, index-based insurance schemes, which use weather indices to trigger payouts, have been implemented in Africa and Asia to provide timely compensation to farmers affected by climate shocks.

Diversification of crops and livelihood sources: Diversifying crops and livelihood sources is another key strategy for reducing the risks associated with climate change. By growing a variety of crops, farmers can spread their risks and reduce their vulnerability to specific climate events, such as droughts or pest outbreaks. Crop diversification also enhances biodiversity and improves soil health, making agricultural systems more resilient to environmental stressors. In crop diversification, many farmers are diversifying their income sources by engaging in off-farm activities, such as small-scale businesses or wage labor [41]. This livelihood diversification provides an additional safety net, reducing farmers' reliance on agricultural income and improving their ability to cope with climate-related shocks.

5. POLICY AND INSTITUTIONAL SUPPORT FOR CLIMATE ADAPTATION IN AGRICULTURE

Climate change poses significant challenges to agriculture, requiring a comprehensive framework of policies and institutions to support adaptation. National and international policies, agricultural extension services, and public-private partnerships play key roles in fostering climate-resilient agriculture by providing necessary guidance, financial resources, and capacity-building for farmers to adopt adaptive practices [42]. Governments and international bodies have established policies to promote sustainabl agricultural practices and provide financial and technical support for climate adaptation. Climate-smart agriculture (CSA) integrates productivity, adaptation, and mitigation, aiming to improve resource efficiency and reduce vulnerability. Countries like Kenya have adopted CSA frameworks, and the African Union's CAADP promotes CSA for food security and climate resilience [43]. Agreements like the Paris Agreement emphasize climate adaptation in agriculture. Nationally Determined Contributions (NDCs) include agricultural adaptation measures such as drought-resistant crops and soil health improvements. The Koronivia Joint Work on Agriculture under the UNFCCC further integrates agriculture into global climate discussions [44]. Agricultural extension services provide vital knowledge and technical support to farmers, promoting the adoption of climate-resilient practices. Extension services raise awareness about climate risks and adaptation strategies. Programs like India's NICRA and Africa's ACSAA educate farmers on sustainable practices, including water conservation and pest management. Training programs and participatory approaches like Farmer Field Schools (FFS) equip farmers with the skills to implement resilient practices such as conservation agriculture and crop rotation [45].

Public and private sector collaboration for climate-resilient agriculture: Collaborations between public and private sectors provide funding and technological innovations necessary for climate adaptation. Organizations like the Global Environment Facility (GEF) and the Green Climate Fund (GCF) provide financial support for climate adaptation projects. Private companies invest in climate-resilient technologies like drought-tolerant seeds and precision agriculture tools. Public-private R&D partnerships have advanced climate-resilient technologies. Initiatives like the CGIAR's CCAFS program focus on developing drought-tolerant crops and sustainable farming practices [46].

6. CHALLENGES AND LIMITATIONS IN ADAPTING AGRONOMIC PRACTICES TO CLIMATE CHANGE

Adapting agronomic practices to the realities of climate change is essential for ensuring agricultural resilience and food security. However, there are numerous challenges and limitations that hinder the widespread adoption of climate-resilient practices. These barriers can be economic, technological, knowledge-based, or socio-cultural in nature. Understanding these challenges is crucial for developing targeted solutions that enhance the adaptive capacity of farmers, especially in developing countries that are most vulnerable to climate change impacts.

Economic barriers to adoption of climate-resilient practices: One of the primary challenges to adapting agronomic practices to climate change is the economic barrier faced by farmers, particularly smallholders in developing countries. Climate-resilient practices often require significant financial investments in new technologies, inputs, and infrastructure, which can be prohibitively expensive for resource-constrained farmers [47]. For instance, transitioning to sustainable irrigation systems such as drip irrigation or the adoption of precision agriculture tools necessitates upfront capital costs that many farmers cannot afford. The lack of access to affordable credit and insurance further exacerbates this economic barrier. In many developing regions, rural financial institutions are either underdeveloped or inaccessible, leaving farmers with few options to finance the adoption of climate-resilient technologies. Even when credit is available, high interest rates and stringent collateral requirements often deter smallholders from borrowing for climate adaptation investments [48]. Without sufficient economic support, farmers may continue to rely on traditional practices, which are increasingly unsustainable in the face of climate change.

Technological limitations in developing countries: The technological gap between developed and developing countries poses a significant limitation to the widespread adoption of climate-resilient agronomic practices. In many developing regions, the availability of modern agricultural technologies, such as advanced irrigation systems, drought-resistant seeds, and precision agriculture tools, is limited due to a lack of infrastructure, research, and investment [49]. This technological limitation leaves farmers in these areas vulnerable to the impacts of climate change, as they lack the tools necessary to adapt their practices effectively. For example, precision agriculture technologies, which allow for efficient use of water, fertilizers, and pesticides through real-time monitoring of soil and crop conditions, are rarely available to smallholder farmers in developing countries due to high costs and the lack of technical expertise. Additionally, the development and dissemination of climate-resilient crop varieties, such as drought-tolerant or heat-resistant crops, are often delayed in developing countries due to underfunded agricultural research institutions and inadequate seed distribution networks [50]. In many developing countries, the technological limitations are compounded by poor infrastructure, including unreliable electricity, inadequate transportation networks, and limited access to modern communication technologies. These infrastructural deficiencies hinder farmers' ability to adopt and effectively use climate-smart technologies. For instance, farmers in remote areas may struggle to access weather forecasts or market information, which are essential for making informed decisions about planting and harvesting in a changing climate. The lack of digital infrastructure also prevents farmers from taking advantage of mobile-based applications and platforms that provide climate advisories and extension services.

Knowledge gaps and uncertainty in climate forecasts: Another major challenge in adapting agronomic practices to climate change is the presence of significant knowledge gaps and uncertainties in climate science and forecasting. While climate models provide valuable insights into long-term trends, there remains considerable uncertainty about the specific impacts of climate change on regional weather patterns and agricultural systems [51]. This uncertainty makes it difficult for farmers and policymakers to plan effectively for future climate conditions, as the timing, intensity, and geographic distribution of climate impacts can vary widely. For example, while global climate models may predict increasing temperatures and changing precipitation patterns, they often lack the precision needed to make accurate forecasts at the local level, where agricultural decisions are made. In many developing countries, the availability of localized climate data is limited, and weather monitoring infrastructure is often inadequate, leading to poor forecasting accuracy and limited early warning systems for extreme weather events. This lack of reliable data hampers the ability of farmers to adopt timely and effective adaptation measures, such as adjusting planting dates or switching to more resilient crop varieties [52].

Social and cultural factors influencing adaptation: Social and cultural factors also play a critical role in shaping farmers' willingness and ability to adopt climate-resilient agronomic practices. Cultural beliefs, social norms, and community dynamics can either facilitate or hinder the adoption of new technologies and practices, depending on how they align with existing traditions and values. In many rural communities, traditional farming practices are deeply rooted in cultural identities and social structures, and changing these practices can be met with resistance. For example, farmers may be reluctant to adopt new crop varieties or conservation techniques if they perceive them as a threat to their cultural heritage or if they are unfamiliar with the long-term benefits [53]. Additionally, the social status of farmers who are seen as innovators or early adopters may influence others in the community, either encouraging or discouraging the broader uptake of climate-resilient practices. Gender dynamics also play a significant role in the adoption of climate-resilient practices. In many developing countries, women are responsible for a large portion of agricultural labor, yet they often have limited access to land, credit, and extension services. These gender-based inequalities can limit women's ability to adopt adaptive practices and technologies, reducing the overall resilience of agricultural systems. Efforts to promote climate adaptation must therefore take into account the social and cultural contexts in which farming takes place and ensure that adaptation strategies are inclusive and equitable [54].

7. FUTURE AND RESEARCH NEEDS

As climate change continues to impact global agricultural systems, there is an urgent need for innovations and research to enhance farming resilience. The future of climate-resilient agriculture relies on emerging technologies, long-term climate monitoring, and increased global research collaboration. These efforts are vital for adapting agronomic practices, improving food security, and ensuring sustainable agricultural productivity amidst growing climate uncertainties.

Emerging technologies for climate-resilient agriculture: Technological advancements are transforming agriculture, offering solutions to climate change challenges. AI and machine learning (ML) are powerful tools that improve productivity, optimize resource use, and enhance resilience. AI-driven systems analyze soil, weather, and crop performance data to predict climate impacts and provide early warnings of pest outbreaks. ML improves climate forecasting, enabling proactive farming decisions. Advanced breeding techniques, like CRISPR-Cas9, are revolutionizing plant breeding by developing drought- and heat-resistant crops quickly [55]. Genomic selection further accelerates the breeding of climate-resilient crops by selecting the best plants based on genetic markers.

Long-term monitoring of climate and agronomic changes: Long-term data collection is crucial for understanding climate impacts on agriculture. Remote sensing technologies like satellites and drones monitor crop health and soil conditions in real time. These technologies provide insights into how regions are responding to climate changes, helping to refine adaptation strategies. Sophisticated climate models integrating historical and current data will guide future agricultural policies and investments [56].

Enhancing global collaboration for climate change research in agriculture: Global collaboration is essential for addressing climate change's diverse impacts on agriculture. Organizations like CGIAR and its CCAFS program foster international cooperation on climate adaptation, enabling shared research and best practices. Multilateral agreements, such as the Paris Agreement, emphasize international collaboration on research and technology development for agricultural resilience. Platforms like the Climate-Smart Agriculture portal allow knowledge sharing among farmers, researchers, and policymakers, promoting climate-resilient practices globally [57].

8. CONCLUSION

Climate change presents significant challenges to global agriculture, demanding a multifaceted approach to adaptation. Through national and international policies, climate-smart agriculture initiatives, and the guidance of global agreements like the Paris Accord, governments are working to integrate resilience into farming systems. Agricultural extension services play a pivotal role in raising awareness and building capacity among farmers, ensuring they are equipped to adopt climate-resilient practices. Public-private partnerships provide the funding and technological support necessary for the development and implementation of innovative adaptation strategies, while research collaborations drive the creation of climate-resilient crops and sustainable farming practices. Moving forward, enhancing global collaboration, leveraging emerging technologies, and ensuring equitable access to resources are essential for strengthening agriculture's ability to withstand the growing impacts of climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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