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Climate change adaptation strategies in farming systems

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Abstract

Agricultural systems worldwide face unprecedented challenges from climate change, including rising temperatures, altered precipitation patterns, extreme weather events, and shifting pest and disease dynamics that threaten global food security and farming community stability. This systematic literature review synthesizes approximately 80–100 peer-reviewed articles alongside institutional publications to evaluate climate change adaptation strategies across diverse agro-ecological and socioeconomic contexts. The study examines five strategic domains: climate-smart agriculture and integrated approaches, conservation agriculture and soil health, crop diversification, water management and irrigation, and digital agriculture and precision farming through thematic synthesis connecting biophysical adaptation mechanisms with socioeconomic enabling conditions. Key findings indicate that no single strategy sufficiently addresses the full spectrum of climate risks; rather, effective adaptation requires context-specific combinations of biophysical, technological, and institutional interventions. Conservation agriculture and crop diversification demonstrate strong resilience pathways through soil carbon sequestration and yield stability, yet face structural barriers from supply chain lock-in and market incentives favoring monoculture systems. Technologically intensive strategies offer substantial efficiency gains but exacerbate equity gaps, concentrating benefits among larger operations while leaving 500 million smallholder farms disproportionately exposed. The review concludes that transformative adaptation requiring fundamental system reconfiguration rather than incremental adjustments has become necessary, demanding integrated policy frameworks that secure land tenure, restructure market incentives, ensure equitable technology access, and embed indigenous knowledge within scientific innovation to sustain global food security under accelerating climate change.

Keywords: Precision farming; Climate adaptation; Agricultural resilience; Smallholder farmers; Food security

1. Introduction

The agricultural systems that exist throughout the world are facing their most challenging period because climate change brings about multiple environmental changes, including rising temperatures, new precipitation patterns, more frequent severe weather events, and alterations in pest and disease behavior (Altieri et al., 2015; Aryal et al., 2020). The impacts of these changes endanger global food security, the economic stability of farming communities, and the natural systems that support agricultural production. The Intergovernmental Panel on Climate Change (IPCC) forecasts that climate change will decrease crop yields by 2–6% every decade while global demand increases by 14% each decade until 2050 (Quandt et al., 2023).

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The concept of climate adaptation in agriculture has evolved significantly over the past decade. The initial methods for agricultural research involved making minor updates to existing farming methods through modifications of planting schedules and selection of different crop types (Hadarits et al., 2017). Modern research studies demonstrate the necessity of transformative adaptation because agricultural systems must undergo essential modifications to solve their fundamental problems and build capacity to withstand multiple threats (Wilson et al., 2020). The current shift demonstrates that scientists now understand climate change produces effects that exceed the capabilities of farmers to use small-scale changes for protecting their crops and sustaining their way of life (Panda, 2018; Vermeulen et al., 2018).

The urgent need for climate change adaptation affects smallholder farming systems which operate in developing countries through their management of 500 million farms that serve almost 2 billion people (Ariom et al., 2022; Obe et al., 2025). The systems experience a triple threat that combines climate exposure with resource limitations, economic restrictions, institutional weaknesses, and climate information access deficiencies (Petersen-Rockney et al., 2021; Williams et al., 2018). The vulnerability framework, which includes exposure, sensitivity and adaptive capacity has become essential for studying smallholder climate risk (Parker et al., 2019). The smallholder farmers who contribute only a small portion to global greenhouse gas emissions face severe climate impacts, which require them to develop both effective and fair adaptation methods (Abdul-Razak & Kruse, 2017; Bouroncle et al., 2017)

Current adaptation frameworks now focus on building organizational strength because they recognize farming systems as interconnected social and environmental systems that depend on physical, social, economic, and institutional elements (Sinclair et al. 2019; van Zonneveld et al. 2020). This literature-based analysis brings together scholarship on climate change adaptation strategies in farming systems. It reviews empirical studies on how climate-smart agriculture and integrated approaches affect resilience, productivity, and mitigation outcomes. It explores biophysical and institutional perspectives on conservation agriculture, crop diversification, water management, and digital agriculture, examining how these strategies reconfigure farming systems for climate adaptation. Lastly, it discusses how the convergence of these strategies informs models of agricultural adaptation and provides policy implications for sustainable food systems.

2. Methodology

This study employed a systematic literature review methodology to evaluate climate change adaptation strategies employed by farmers across diverse agro-ecological regions and socioeconomic contexts. A total of roughly 80–100 peer-reviewed articles were retained for detailed analysis after the systematic search and screening process. The search strategy utilized multiple academic databases including Scopus, Web of Science, Google Scholar, and ScienceDirect to ensure comprehensive coverage of relevant scholarship. Search terms combined controlled vocabulary and free-text keywords related to climate change adaptation, agricultural systems, and specific strategies, including combinations of climate-smart agriculture, conservation agriculture, crop diversification, water management, digital agriculture, precision farming, climate adaptation, agricultural resilience, smallholder farmers, and food security. Boolean operators were applied to refine searches and capture the intersection of climate adaptation with agricultural practice and policy.

The selection of sources followed three criteria: relevance to climate adaptation in agricultural systems, credibility of publication venues and author expertise, and recency with emphasis on publications from 2015 onward to capture contemporary developments in adaptation science. The sample prioritized empirical evidence from developing countries and developed countries, alongside global comparative research studies and institutional publications from organizations such as the FAO, USDA, and World Bank. Government reports and international organization documents supplemented peer-reviewed literature to capture policy-relevant perspectives and operational frameworks.

The analytical approach employed thematic synthesis to integrate findings across multiple studies, examining how technological adoption, biophysical mechanisms, socioeconomic barriers, and policy interventions collectively shape agricultural climate resilience. The research constructed a conceptual framework connecting biophysical adaptation methods with socioeconomic enabling conditions through the integration of agroecology, climate science, and institutional theory. This framework guided the organization of findings across five strategic domains: climate-smart agriculture and integrated approaches, conservation agriculture and soil health, crop diversification strategies, water management and irrigation, and digital agriculture and precision farming.

3. Literature review

3.1. CSA and Integrated Approaches

The primary framework that solves challenges of food security and climate adaptation and climate mitigation has become Climate-Smart Agriculture (Chandra et al. 2018; Rosenstock et al. 2016). FAO (2013) defines CSA as an approach for transforming and reorienting agricultural production systems and food value chains so that they support sustainable development and can ensure food security under climate change with three pillars: increasing productivity, building incomes, and reducing emissions. The current framework has developed into integrated solutions that aim to achieve multiple objectives according to USDA (2024) and recent research (Wakweya, 2023; Ariom et al., 2022). The CSA framework serves as an effective unifying framework, but its implementation needs to consider local conditions and existing obstacles because it should not be treated as a standard solution.

It is operationalized through climate policy, which directs funding toward incentivizing climate-smart agricultural practices via conservation and risk management programs. The use of cover crops together with reduced tillage systems establishes two benefits because they boost carbon sequestration and enhance soil moisture retention while they stop erosion (USDA, 2024). Research confirms that CSA practices help farmers build resilience while they maintain their current crop production levels (Jamil et al., 2021). The research of Rosenstock et al. (2016) discovered proof deficiencies that related to "triple-win" results whereas Chandra et al. (2018) revealed that initial research focused more on adaptation than on mitigation although recent studies now strive to create comprehensive solutions (FAO, 2023; Panda, 2018). The existing CSA policies show advancements yet the society faces difficulties when trying to achieve equal results in productivity, resilience, and mitigation which needs more scientific investigations together with flexible operational approaches.

Alternative frameworks address similar goals through different entry points. Sustainable Intensification targets yield optimization with reduced environmental footprints yet omits explicit climate adaptation mechanisms (Pretty et al., 2018). Agroecology prioritizes ecological processes and farmer-led innovation over external input dependency, contrasting with CSA's market-oriented and policy-driven orientation (Altieri & Nicholls, 2017). Conservation Agriculture confines its scope to soil management practices minimal tillage, residue retention, and crop diversification without extending to economic resilience or emissions accounting (Kassam et al., 2019). Climate-Resilient Agriculture centers on shock absorption and risk management, deliberately excluding mitigation obligations that CSA incorporates. Meanwhile, Regenerative Agriculture pursues soil carbon restoration as its primary metric, lacking the food security and productivity benchmarks embedded in CSA (LaCanne & Lundgren, 2018). No single approach subsumes the others; CSA's broad umbrella accommodates diverse practices but risks incoherence without the ecological specificity of agroecology or the yield accountability of sustainable intensification (Newell & Taylor, 2018).

The promise of CSA implementation faces obstacles because resource-constrained environments create ongoing execution difficulties. Wakweya (2023) discovered that technical difficulty and required resources together with inadequate understanding of local situations made it hard to implement the solution. Okoronkwo et al. (2024) demonstrated that traditional practices in sub-Saharan Africa offer effective and culturally suitable solutions which top-down programming fails to recognize thus requiring hybrid solutions. The research conducted by Ariom et al. (2022) established that three structural obstacles which include land tenure insecurity and limited market access together with inadequate climate information access need to be resolved. The research results show that CSA requires context-specific solutions instead of universal technical solutions (Masud et al., 2017; Lamichhane et al., 2022). The implementation of CSA requires future projects to focus on participatory methods which combine indigenous knowledge systems with scientific progress to eliminate systemic barriers and produce fair sustainable results.

3.2. Conservation agriculture and soil health

Conservation Agriculture (CA) combines three practices which include minimal soil disturbance, permanent vegetation cover and crop rotation to create a fundamental method which protects climate change adaptation. The FAO (2013) recognizes CA as a key component of climate-smart agriculture, while the USDA (2024) similarly dedicates resources to expanding climate-adaptive practices. The practice of CA increases soil moisture retention while stopping erosion, which creates dual advantages that support various ecosystem service objectives (Jat et al., 2023; Sadiq et al., 2025). The presence of international organizational backing together with strong scientific proof makes CA a confirmed method that helps with climate adaptation, but its successful use in different situations requires knowledge of its physical processes.

The biophysical mechanisms that enable CA to resist climate change have been thoroughly researched by scientists from various countries. The study by Cárceles Rodríguez et al. (2022) showed that CA systems sequester carbon at 0.1 to 1.0 Mg C per hectare per year which results in water use efficiency improvements between 20 to 40 percent and erosion control through 50 to 98 percent reduction. The experimental evidence provided by Teng et al. (2024) demonstrated that CA systems sustain crops under 1.5°C warming while conventional systems experienced a 15 to 20 percent yield decline because soil microbiome alterations raised fungal biodiversity. Al-Kaisi & Lal (2017) and Reicosky (2020) confirm these findings because they demonstrate how CA improves soil biological, chemical, and physical functions through climate changes. The application of CA provides scientific evidence for multiple climate resilience pathways which operate through different biophysical systems, making it especially useful for future warming scenarios.

Implementation challenges must be solved before biophysical advantages can lead to successful climate adaptation in smallholder agricultural systems which exist throughout developing nations. Jat et al. (2023) found that when South Asia implemented CA correctly it improved both mitigation and adaptation results although the practice had to be partially adopted which restricted its full advantages. Sadiq et al. (2025) recommended that CA should become more integrated with agroforestry and precision nutrient management while researchers needed to study its socio-economic effects. Research by Hailu & Teka (2024) in Ethiopia and Mondal et al. (2024) in South Asia shows that different regions face unique obstacles which include problems with residue management and limitations in labor resources and machinery availability. To achieve CA's complete capacity all three fundamental principles must be implemented together with all associated methods and environmental support which addresses the particular needs of smallholder farmers who work in various agricultural practices and economic environments.

3.3. Crop diversification strategies

The basic climate risk management method which includes intercropping, rotations and variety mixtures, and underutilized species has received scientific attention since it serves as a core climate risk management technique (van Zonneveld et al. 2020 Labeyrie et al. 2021). The USDA (2024) recognizes diversification as key for adaptation, noting "shifts in production systems under climate change" require adaptive decision-making. Additionally, van Zonneveld et al. (2020) developed a framework which shows that successful diversification needs market opportunities, labor availability, knowledge access, and land tenure security to succeed. The sustainable crop production intensification guidelines established by FAO (2013) match this systems perspective. The process of diversification establishes a systems-level approach that builds resilience through the need to manage various conditions that extend beyond farm boundaries. The ecological benefits of diversification remain established according to research, yet the actual results depend on how well diversifiers execute their work. Vernooy (2022) discovered that functional diversity which combines species with different drought tolerances and phenological patterns delivers better resilience than increasing species numbers. Labeyrie et al. (2021) discovered that farms with higher crop diversity experienced 20–30% smaller yield losses during droughts than monoculture farms. Mustafa et al. (2019) underline that underutilized crops provide essential advantages for climate change food security diversification strategies. The research results show that organizations that implement targeted functional diversification methods achieve measurable benefits in extreme weather conditions.

Single-crop production systems dominate global agriculture due to historical specialization in mechanization and bulk commodity markets. These systems maximize immediate output per hectare when weather patterns remain predictable, yet they concentrate biological and financial exposure into one species (Gaudin et al., 2015). Diversified arrangements distribute this exposure across multiple harvests, creating buffer capacity when individual crops fail. Research indicates that uniform plantings accelerate pest cycles and accelerate nutrient depletion, while mixed plantings disrupt disease transmission pathways and improve below-ground resource partitioning (Ratnadass et al., 2012). Financially, specialized operations lock producers into volatile global price swings for one commodity, whereas multi-crop operations access broader market niches and local consumption networks (Di Falco & Chavas, 2009). The infrastructure supporting monoculture from combine harvester design to grain elevator logistics to futures market contracts was built iteratively over decades and now resists reconfiguration toward multi-species management (MacDonald et al., 2013). Consequently, the persistence of single-crop agriculture reflects embedded capital investments and institutional inertia rather than superior performance under shifting climate regimes. Transition pathways must therefore address equipment retooling costs, fragmented supply chains for minor crops, and recalibration of actuarial models that currently penalize heterogeneous fields (Bowman & Zilberman, 2013).

Industrialized systems face ongoing obstacles that prevent their ability to implement diverse solutions. Roesch-McNally et al. (2018) discovered that the US Corn Belt faces adoption limitations because its structural elements which include specialized equipment and restricted markets and crop insurance programs that support monoculture farming. The USDA (2024) studies Environmental Benefits Index updates to enhance climate ranking factor assessment through increased weight. Menesch et al. (2023) discovered that Ethiopian farmers used crop diversification to achieve better yield stability but their progress faced limitations because of insufficient seed availability and agricultural training that emphasized single-crop systems. Ponce (2020) discovered that market entry rights together with property ownership security create the foundation for sustainable development. The research shows that to achieve successful diversification efforts structural challenges must be resolved through coordinated policy actions (Zenda & Rudolph, 2024). Systematic policy changes which connect market systems with educational resources and risk control methods must take place to unlock the climate adaptation benefits of diversification.

3.4. Water management and irrigation

Water scarcity is one of the biggest challenges farmers face today, and climate change is making it worse by shifting rainfall patterns, increasing evaporation rates, and reducing snowpack that feeds rivers (Cai et al., 2015). Researchers have identified four practical strategies that farmers can use together to manage water more effectively: using water more efficiently, timing irrigation precisely, applying just enough water to keep crops healthy without waste, and improving the soil's ability to hold moisture (Chartzoulakis & Bertaki, 2015). When farmers combine these approaches, they can cut their water use by 20 to 40 percent while still maintaining the same crop yields (Chartzoulakis & Bertaki, 2015; Rosa, 2022). The key is to see these methods as one connected system rather than separate fixes this helps farms adapt to both climate stress and increasing competition for limited water resources.

Expanding irrigation can protect crops from drought and keep production stable, but only if it is planned carefully. Rosa (2022) warns that poorly planned irrigation growth can backfire by draining rivers dry and depleting groundwater reserves, which hurts everyone in the long run. A better approach is managing water at the watershed level, looking at how farms, communities, and ecosystems all share the same water source. The World Bank (2024) highlights Rwanda's Land Husbandry project as a success story by combining rainwater harvesting with efficient irrigation and soil conservation, farmers' controlled erosion, boosted yields, and becoming more resilient to droughts. The FAO (2013) adds that farmers should also choose drought-resistant crop varieties and use simple water-saving techniques alongside modern tools, always keeping the bigger picture of sustainable resource use in mind.

New technologies like drip irrigation, sprinklers, and digital water monitoring can help farmers use every drop wisely, but getting these tools to all farmers remains a challenge. Gabr et al. (2024) recommend that farmers match their crop choices to the water efficiency of their irrigation system. Drip systems work best for certain crops, while sprinklers suit others, especially in water-scarce regions. Cai et al. (2015) emphasize that farmers need reliable weather forecasting and flexible crop planning to respond to changing water availability. Digital agriculture offers precise water distribution systems that deliver exactly where and when crops need it (Balasundram et al., 2023), but these innovations only work if they reach smallholder farmers and not just large commercial operations. Ultimately, successful water management for climate adaptation requires combining technology with strong local institutions and fair policies, so that productivity gains do not come at the expense of the environment or neighboring communities.

3.5. Digital agriculture and precision farming

Digital agriculture, combining precision farming, satellite imagery, artificial intelligence, and connected devices has become a powerful tool for helping farmers adapt to climate change (Bolfe et al., 2020). The World Bank (2023) defines it simply as "the use of information and communication technologies across the agriculture and food system," which allows farmers to cut costs, make better decisions, and access new markets. Research by Balasundram et al. (2023) highlights four key areas where farmers benefit: applying fertilizers and nutrients only where needed, adjusting irrigation based on soil conditions, using data to predict crop problems before they arise, and relying on improved weather forecasting. These technologies enable farmers to reduce their spending on seeds, water, and chemicals by 15 to 30 percent without sacrificing their harvest. The USDA (2024) is actively using these tools to meet its climate adaptation goals, helping farms prepare for extreme weather events. Ultimately, digital agriculture strengthens farmers' ability to manage their resources wisely and build resilience against climate threats through better data and smarter decision-making.

The USDA (2024) is putting digital tools to work in its climate plans, using Google Earth Engine through its statistics service to quickly figure out how much damage extreme weather has done to crops and to keep climate records up to date. The World Bank (2023) stresses that these monitoring systems need to be well-designed and properly tested so that farmers and policymakers can trust the results. A real-world example comes from India, where the Ama Krushi platform now serves 6.5 million farmers at a cost of just 18 cents per farmer each year, delivering returns of $9 to $15 for every dollar spent. Roy and George (2020) show that precision farming is a form of climate-smart agriculture because managing each part of a field differently reduces harm to the environment while making the farm more resilient to shocks. When digital tools are built properly and connected to existing farming advice networks, they can become both affordable for individual farmers and scalable enough to reach millions.

Getting these technologies into the hands of all farmers fairly is still a major challenge. Bolfe et al. (2020) found that Brazilian farmers often knew about digital tools but still could not adopt them because the equipment cost too much, the technology was too complicated to use, and they were unsure whether the investment would actually pay off. The World Bank (2024) confirms that most farming operations worldwide are still using only basic technology, with only modest progress in climate-smart tools and drones. In practical terms, this means smallholder farmers and those in developing regions are being left behind while larger, wealthier farms move ahead (Balogun et al., 2022). To fix this gap, technology needs to become cheaper, simpler to operate, and proven to deliver clear financial returns so that every farmer not just the big players can benefit from the digital agriculture revolution (Bhattacharya & Bansal, 2025).

Visser et al. (2021) raised an important concern about what they call "imprecision farming" the idea that digital tools can sometimes give bad advice because of poor data quality and built-in biases in the algorithms. They also found that computer models of farming ecosystems do not always match reality on the ground. Visser et al. (2021) warn against assuming that technology alone will solve every problem, and Dunchev and Aleksov (2025) agree that digital tools need to work hand-in-hand with the knowledge that local farmers have built up over generations. The research shows that digital agriculture has great potential, but it will not reach that potential until the industry fixes three key problems: making sure all farmers have fair access, improving the accuracy of the data and recommendations, and getting different systems to work together smoothly (Balogun et al., 2022; Bhattacharya & Bansal, 2025). For digital agriculture to truly transform farming, it needs to remove barriers so everyone can use it, keep data quality high, and blend new technology with the practical understanding that farmers already have.

4. Results and discussion

The thematic synthesis of climate change adaptation literature reveals that no single strategy sufficiently addresses the multidimensional challenges facing agricultural systems under climate change. Climate-Smart Agriculture (CSA) emerges as the broadest integrative framework, yet its "triple-win" promise of simultaneously enhancing productivity, resilience, and mitigation remains unevenly realized across contexts. While Rosenstock et al. (2016) identified persistent evidence gaps regarding simultaneous achievement of all three pillars, recent developments show increasing convergence toward integrated solutions that recognize local specificity as paramount. The comparison across strategies indicates that CSA functions most effectively not as a standardized technical package but as an umbrella concept requiring contextual calibration combining indigenous knowledge systems with scientific advances to overcome structural barriers including land tenure insecurity, limited market access, and inadequate climate information (Ariom et al., 2022; Okoronkwo et al., 2024). This interpretive finding suggests that the effectiveness of adaptation frameworks depends less on their theoretical comprehensiveness and more on their operational flexibility within existing socioeconomic constraints.

Conservation Agriculture (CA) and crop diversification demonstrate particularly strong biophysical adaptation pathways, though through markedly different mechanisms. CA enhances climate resilience through soil ecosystem modification, with documented carbon sequestration rates of 0.1–1.0 Mg C per hectare annually and water use efficiency improvements of 20–40%, enabling systems to sustain yields under 1.5°C warming where conventional approaches fail (Cárceles Rodríguez et al., 2022; Teng et al., 2024). Conversely, diversification operates through risk distribution rather than ecosystem stabilization, with functionally diverse systems reducing drought-induced yield losses by 20–30% compared to monocultures (Labeyrie et al., 2021). The critical distinction lies in their scalability constraints: CA requires minimal structural disruption to existing supply chains but demands precise adherence to all three principles minimal disturbance, permanent cover, and rotation to achieve benefits, whereas diversification necessitates fundamental reconfiguration of commodity markets, insurance frameworks, and equipment infrastructure currently optimized for monoculture production (Roesch-McNally et al., 2018; Bowman & Zilberman, 2013). These findings indicate that biophysical efficacy does not automatically translate to adoption feasibility, and that adaptation strategies must be evaluated against institutional inertia rather than purely agronomic criteria.

Water management and digital agriculture represent technologically intensive pathways that offer substantial efficiency gains but exacerbate equity concerns across the global agricultural landscape. Integrated water strategies combining precision irrigation, soil moisture enhancement, and watershed-level governance can reduce water consumption by 20–40% while maintaining yields, yet poorly planned expansion risks groundwater depletion and inter-community conflict (Chartzoulakis & Bertaki, 2015; Rosa, 2022). Similarly, digital agriculture enables 15–30% reductions in input costs through precise resource application and predictive analytics, with platforms like India's Ama Krushi demonstrating scalable, cost-effective delivery models (Balasundram et al., 2023; Roy & George, 2020). However, both strategies currently exhibit pronounced accessibility gradients: smallholder farmers in developing regions face exclusion due to capital requirements, technological complexity, and inadequate digital infrastructure, creating what Bolfe et al. (2020) and Balogun et al. (2022) identify as a "two-tiered adaptation landscape" where wealthier, larger operations capture benefits while vulnerable populations bear disproportionate climate risk. The interpretive implication is that technological innovation without parallel institutional mechanisms for equitable diffusion may inadvertently deepen existing agricultural inequalities rather than ameliorate them.

Cross-strategy comparison reveals a fundamental tension between specialization and integration as competing logics for agricultural adaptation. Specialized approaches such as Regenerative Agriculture's focus on soil carbon or Sustainable Intensification's yield optimization deliver measurable outcomes within narrow domains but omit critical dimensions of climate resilience (LaCanne & Lundgren, 2018; Pretty et al., 2018). Integrated frameworks like CSA and agroecology accommodate broader objectives but risk conceptual incoherence without the ecological specificity or yield accountability of their specialized counterparts (Newell & Taylor, 2018). The literature indicates that successful adaptation increasingly depends on hybrid configurations that combine the biophysical robustness of CA and diversification with the efficiency gains of precision water and digital technologies, all embedded within enabling institutional environments that address land tenure, market access, and knowledge transfer (van Zonneveld et al., 2020; Petersen-Rockney et al., 2021). This interpretive synthesis suggests that the future of climate adaptation lies not in selecting optimal strategies but in designing context-specific assemblages that align biophysical potential with socioeconomic feasibility.

The cumulative evidence underscores that transformative adaptation requiring fundamental system reconfiguration rather than incremental adjustment has become necessary because climate impacts now exceed the buffering capacity of minor operational changes (Wilson et al., 2020; Vermeulen et al., 2018). For smallholder systems managing 500 million farms globally, this transformation demands particular attention to structural barriers, including insecure land tenure, limited market access, and institutional weaknesses that constrain adaptive capacity (Petersen-Rockney et al., 2021). The convergence of findings across strategies points toward a policy imperative: effective adaptation requires coordinated interventions that simultaneously address biophysical management, technological access, and institutional reform. Without this integrated governance approach, individual strategy efficacy will remain fragmented, and the agricultural sector will fail to achieve the systemic resilience necessary to maintain food security under accelerating climate change.

4.1. Key Findings

This review identifies several critical findings regarding climate change adaptation in agricultural systems. No single adaptation strategy whether Climate-Smart Agriculture, Conservation Agriculture, crop diversification, water management, or digital agriculture sufficiently addresses the full spectrum of climate risks; rather, effective adaptation requires context-specific combinations of biophysical, technological, and institutional interventions tailored to local agro-ecological and socioeconomic conditions. Conservation Agriculture and crop diversification demonstrate strong biophysical resilience pathways through soil carbon sequestration, water use efficiency gains, and yield stability under drought, yet their successful implementation depends on overcoming structural barriers including supply chain lock-in, equipment specialization, and market incentives that currently favor monoculture systems. Technologically intensive strategies such as precision irrigation and digital agriculture offer substantial efficiency improvements of 20–40% in resource use and 15–30% in input cost reduction, but their benefits remain concentrated among larger, wealthier farming operations, creating a significant equity gap for the 500 million smallholder farms that support nearly 2 billion people in developing regions. Most critically, transformative adaptation requiring fundamental reconfiguration of farming systems rather than incremental adjustments has become necessary because climate impacts now exceed the buffering capacity of minor operational changes, yet achieving such transformation demands simultaneous attention to land tenure security, market access, climate information systems, and participatory governance that integrates indigenous knowledge with scientific innovation.

4.2. Barriers to Climate Change Adaptation in Agricultural Systems

The implementation of climate adaptation strategies across agricultural systems faces persistent and interconnected barriers that span biophysical, socioeconomic, technological, and institutional dimensions. Smallholder farmers in developing regions encounter a triple threat of climate exposure compounded by resource limitations, economic constraints, and weak institutional support, including insecure land tenure, restricted market access, and inadequate climate information systems that collectively undermine adaptive capacity. Technological adoption remains heavily skewed toward large commercial operations, as precision irrigation, digital agriculture tools, and advanced monitoring systems require capital investments, technical literacy, and digital infrastructure that remain out of reach for the 500 million smallholder farms managing limited resource bases. Cultural and knowledge barriers further complicate implementation, with top-down programming frequently failing to recognize traditional practices that offer effective, locally appropriate solutions, while agricultural extension services continue to emphasize monoculture systems even where diversification would enhance resilience. Policy and market structures reinforce these obstacles through crop insurance programs that penalize heterogeneous fields, commodity supply chains optimized for single-species production, and climate funding mechanisms that struggle to reach the most vulnerable farming communities, creating systemic inertia that resists the transformative reconfiguration necessary for effective climate adaptation.

4.3. Policy implication

Effective climate adaptation in agricultural systems demands policy frameworks that move beyond fragmented, single-strategy interventions toward integrated governance approaches addressing biophysical management, technological equity, and institutional reform simultaneously. Policymakers must prioritize participatory design processes that embed indigenous knowledge systems within scientific and technological innovation, ensuring that adaptation programs recognize locally appropriate traditional practices rather than imposing standardized technical solutions that fail to account for contextual specificity. Critical institutional reforms include securing land tenure rights, expanding climate information access, and restructuring market incentives and crop insurance frameworks to support diversified production systems rather than reinforcing monoculture lock-in. Equitable technology diffusion requires targeted subsidies, simplified digital interfaces, and proven financial returns to bridge the growing adaptation gap between large commercial operations and smallholder farmers, alongside watershed-level water governance that balances agricultural productivity with ecosystem sustainability and inter-community equity. Ultimately, transformative adaptation will only succeed if policy coordination aligns climate-smart agricultural funding with broader rural development objectives, creating enabling environments where conservation agriculture, functional crop diversification, precision resource management, and digital advisory services operate as interconnected components of resilient food systems rather than isolated interventions.

5. Conclusion

This review demonstrates that agricultural climate adaptation has entered an era requiring transformative rather than incremental change, as the scale and pace of climate impacts now exceed what isolated technical adjustments can address. The central takeaway is that resilience emerges not from selecting a single optimal strategy but from designing context-specific assemblages that align biophysical potential with socioeconomic feasibility combining the soil ecosystem benefits of conservation agriculture, the risk distribution of functional diversification, the efficiency gains of precision water management, and the decision-support capacity of digital tools within enabling institutional environments. Policy must therefore shift from promoting individual practices to building integrated governance frameworks that secure land tenure, restructure market incentives away from monoculture lock-in, and ensure equitable technology access for the 500 million smallholder farms that remain disproportionately exposed to climate risk. Future research should prioritize longitudinal studies measuring the simultaneous achievement of productivity, resilience, and mitigation outcomes across diverse farming systems; investigate the socio-economic impacts and adoption pathways of conservation agriculture in smallholder contexts; and develop participatory methodologies that effectively blend indigenous knowledge with digital innovation to overcome the equity gaps and algorithmic biases currently limiting technological solutions. Without such convergent advances in science, policy, and practice, the agricultural sector will fail to achieve the systemic transformation necessary to sustain global food security under accelerating climate change.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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