



Innovative Strategies to Enhance Plant Climate Change Adaptation and Resilience

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Summary

Accelerating climate-resilient agriculture calls for a multi-faceted approach rooted in innovation, inclusiveness, and institutional alignment. The frontier of research—covering AI-IoT systems, digital twins, nanosensors, drones, and precision agriculture—has revolutionary promise. However, this rests on field testing, user-centric design, and fair access to technologies. Parallel investments in digital literacy, infrastructure, and inter-disciplinary collaboration are needed to drive technological potential to farmer empowerment.

Keywords: Global warming, Agriculture, Heat Stress, genomic selection, artificial intelligence

Introduction to Climate Change and Agriculture

Overview Of Climate Change

Climate change refers to a long-term and significant change in measures of climate such as rainfall, temperature, wind, or snow patterns. Global warming and greenhouse gas (GHG) emissions are considered major factors responsible for accelerating the degree of climate change. Climate change is no longer a distant threat; it is a defining challenge of the 21st century. The planet is heating up faster than at any point in human history, characterized by rising temperatures, shifting precipitation patterns, more frequent extreme weather events, and elevated atmospheric CO₂ levels. CO₂ is the single largest contributor to global warming. Human activity is expected to increase Earth's surface temperature (EST) by 1.07 °C and CO₂ by 40% between 1850–1900 and 2010–2019 (Adak et al., 2023).

Why Agriculture Is Highly Affected

Due to its extreme sensitivity to weather, agriculture is susceptible to changes in the environment. The most delicate stages of crop development are flowering and grain filling. Unpredictable rainfall patterns make it challenging to plan when to sow and harvest staple crops like wheat, rice, and maize, and heat stress during critical growth phases reduces yields by causing droughts that lower soil moisture and can result in wilting,

leaf curling, etc. (Malhi et al., 2021). Productivity is also threatened by salinization, soil deterioration, and expanding pest ranges. (Bibi & Rahman, 2023).

Need for Adaptation and Resilience

Livestock systems are affected too, with heat stress leading to reduced feed intake, growth rates, and milk production (Bibi & Rahman, 2023). Tropical and subtropical zones have high baseline temperatures, so even small temperature increases have large effects on their ecosystems, that why countries in the Global South tend to be most at risk due to limited adaptive capacity (Smith & Johnson, 2024). In the face of escalating climate threats, the most immediate and practical solutions lie in the adaptation of agriculture through improved crop varieties, efficient water management, and increased soil health. From this perspective, the scientific community emphasizes adapting to current challenges, defined as a system's ability to absorb shocks and recover functionality rather than waiting for the ideal conditions (Topa et al., 2025). Through resilience breeding and climate-smart agriculture practices, we can mitigate the adverse effects of climatic shifts.

Notably, several practices, including conservation agriculture, crop diversification, and biochar amendments, offer promise for both adaptation and mitigation goals. Building resilient agricultural systems is therefore critical not just for food security and rural livelihoods, but also for aligning with the broader objectives of sustainable development and climate action. These efforts collectively strengthen the capacity of agriculture to withstand and recover from environmental stress.

Climate Change Impacts on Agriculture

Agriculture is expected to be significantly impacted by climate change, both directly and indirectly, in terms of crops, soil, animals, and pests.

Temperature Rise and Heat Stress

Even though climate change is a gradual process that involves only modest variations in temperature and precipitation over extended periods of time, it nevertheless affects many soil processes, especially those that are connected to soil fertility. Changes in soil moisture conditions and subsequent increases in soil temperature and CO₂ levels are anticipated to be the primary impacts of climate change on soils. It is anticipated that the processes and characteristics of soil that are crucial for reestablishing soil fertility and productivity will be affected differently by global climate change. Heatwaves are also involved. In 2022, regions of Sindh saw more than 49 °C, which is lethal for crop flowering and yields. Simultaneously, farmers experience shorter winters, longer summers, delayed sowing, and increased pest pressure, which reduce the productivity of high-yielding crop varieties and innovation in cultivation. Temperature increases and an increase in CO₂ are predicted to be the main effects of climate change. An increase in CO₂ and a rise in temperature and salinity are predicted to be the main effects of climate change (Bibi & Rahman, 2023).

Irregular Rainfall and Droughts

Crop production is susceptible to climate variability, and changes in rainfall patterns, rising temperatures, and CO₂ levels brought on by climate change could result in a significant drop in crop yield. Changes in temperature, moisture content, wet-drying and freeze-thawing cycles, and other factors can affect how soil

microorganisms develop and behave. Changes brought about by climate change can affect the composition and activity of soil microbial communities as well as alter soil properties like pH, cation exchange capacity (CEC), and water holding capacity (WE), as well as the degree of interaction between microorganisms needed for the breakdown of organic pollutants in soil and soil organic carbon stocks. Additionally, during the past few decades, there has been a rise in extreme weather events like droughts, heat waves, and floods caused by excessive rainfall, which has led to alarming rates of leaching, soil erosion, and runoff. It is difficult to increase food production to satisfy growing demands brought on by population growth while also taking climate change issues into consideration.(Bibi & Rahman, 2023)

Flooding And Salinity Issues

Pakistan's main farming areas are already being affected by climate change, which has big effects on how much food can be grown and how well crops do. Crops like wheat, rice, and fruits have been hit hard by higher temperatures and heat stress. This was especially clear during the 2022 heatwave in India and Pakistan, where some places reached over 49°C. This shows how much the region depends on important crops that are valuable.

A rise in temperature by 1.5 to 3 degrees could reduce crop production by 7 to 21% in areas like Swat. Even a 1-degree increase in key farming areas of Pakistan could cut wheat production by 5 to 7% (Ali & Erenstein, 2017). However, cooler, high-altitude areas like Chitral might gain from these temperature changes. In the semi-arid regions of Punjab and Sindh, rice production is also very sensitive to heat. Forecasts show that rice yields could drop by 15 to 36% between 2012 and 2099 because of the ongoing rise in temperatures (Ali & Erenstein, 2017).

The agriculture sector in Pakistan has been severely hit by the 2010 and 2014 devastating floods and the prolonged droughts of 1999-2003; the production of major crops like wheat, rice, sugarcane, and cotton has also been severely impacted in the past two decades (Saddique et al., 2022). Ridge drought events are regular and usually coincide with heat stress episodes, adversely affecting the rain-fed and irrigated agricultural systems . Farmers in the irrigated regions of Punjab and Sindh have observed a trend of shorter winters, longer summers, and erratic monsoon patterns, resulting in lower crop yields, increasing pest infestations, and delayed planting decisions (Saddique et al., 2022).

Flash floods and glacial melt further threaten Pakistani farming Pakistani floods of 2010, 2011, and 2022 affected approximately 55–60 million people and caused over 3500 deaths. The 2011 floods affected over 21,000 km², displaced 5.9 million people, and damaged 1,500 km of roads, 382 km of railway, 500 km² of forest, and over 16,000 km² of cropland. The 2012 floods affected 13,157 km² of land in 22 districts in Pakistan, damaging 2950 km² of cropland, 1681 km of roads, and 110 km of railway.(Qamer et al., 2023)

Effects On Pests, Diseases, And Weeds

Climate variability also causes elevated pest and disease, which erodes gains in modern agriculture. Heat and humidity changes accelerate pest life cycles, eroding the effectiveness of improved seed and management practices. The consequences of erratic rainfall and extreme events are stark in Pakistan. The 2022 flood during monsoon that dropped 190–450% more-than-normal rain overwhelmed one-third of the nation(Qamer et al., 2023). The floods wiped out farming gains and short-circuited mechanization and infrastructure development essential to the growth of Pakistani agriculture.

Recurring catastrophic occurrences have had lasting impacts. Since the year 2022, numerous farmers in Nowshera district of Khyber Pakhtunkhwa province have experienced the loss of between 50% of their maize and vegetables from the occurrences, leading to food shortages and fields still filled with debris months after the occurrences (Franklin, n.d.). The destruction has disproportionately affected smallholder farms, demonstrating how climate shocks exacerbate rural inequality and hinder widespread agricultural growth.

Collectively, these problems risk productivity and progress. To progress its agriculture through more production, climate-resilient technology, mechanization, and agricultural infrastructure climate adaptation and resilience must be integrated at all levels. This involves the production of heat- and drought-tolerant varieties of crops, optimized planting schedules, water-saving irrigation, efficient flood protection, and pest-disease surveillance. Now we will discuss adaptation and resilience-strengthening approaches applicable to Pakistan's context.

Adaptation Strategies in Agricultural Systems

Climate change adaptation is seen as fundamental to counteract climate change alongside mitigation efforts throughout the world. Adaptation, a multidimensional, complex, and multi-scale process, has been characterized as adjustments to behavior or economic structures that reduce vulnerability of society to scarcity or threatening environmental change. Adapting agricultural production systems to climate change is a priority since its impact on agriculture is already apparent, and the trends will continue, even if adaptation can dramatically reduce the negative economic effects (Shrestha et al., 2018). Despite numerous adaptation options already in practice, more adaptation options than those of the current level are required to reduce future impacts (UNFCCC, 2007). Impacts of climate change on smallholder farms will be locally specific and difficult to quantify due to the variability and complexity of farming systems and farmers' livelihood. The challenge of understanding climate change impacts at farm level can be enhanced by recording local knowledge, attitudes and practices (Debela et al., 2015). Less is reported locally on how and what adaptation is being practiced. To advance Pakistan's agriculture in a changing climate, farmers and policymakers are embracing innovative, context-specific adaptation strategies that enhance productivity, resilience, and sustainability.

Crop Calendar Adjustment

The shifting of the crop calendar remains essential to crop management. Farmers in Punjab and Sindh provinces are increasingly shifting their planting dates and harvesting dates to avoid the severe heat conditions and pre-monsoon rains associated with the monsoon season. One key example of this change is with sowing wheat, which is being carried out 2 to 3 weeks earlier than was previously being carried out in central Punjab. Beyond avoiding the stress associated with the severity of March heat, this earlier change enables enhanced grain filling and an increase in the stability of total yields. (Hussain et al., 2020) Among the various adaptation approaches, one of the most practical and sustainable solutions and reliable methods is breeding for climate-resilient Crops as an adaptation strategy. To counteract increasing climate variability, the cultivation and marketing of climate-tolerant crops offer an anticipatory adaptation option to safeguard agriculture. They are bred or engineered to withstand abiotic stresses such as drought, heat, salinity, and flooding, which are increasing with global climate change. Achieving such resilience demands advanced breeding approaches that can accelerate the development of stress-tolerant genotypes. Among

these, genomic selection (GS) has emerged as a powerful strategy, enabling breeders to predict an individual's performance based on genome-wide marker data. GS bypasses traditional phenotypic screening and integrates key steps training population development, genotyping, phenotyping, and genomic estimated breeding value (GEBV) prediction into a streamlined workflow (Figure 1).

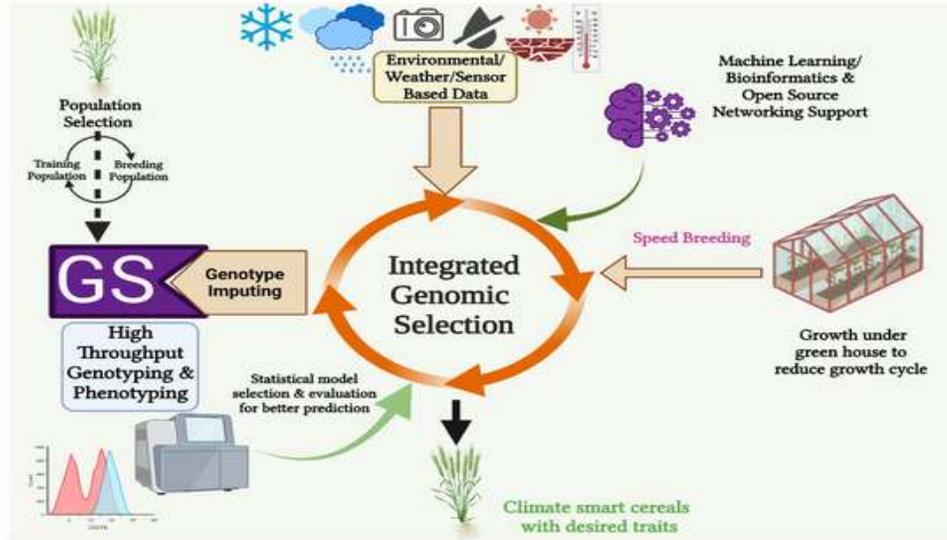


Figure 1. Components and workflow of integrated genomic selection in climate-smart cereal crops.

Water-Efficient Irrigation Methods

Contemporary agriculture practices like deficit irrigation and drip irrigation are being identified and practiced increasingly. For Pakistan, a nation famous for water scarcity and limited freshwater resources, it is a pressing need to attain maximum yield from crops with the minimum amount of water. This very important goal can only be attained if the farmers are provided with detailed information regarding High-Efficiency Irrigation Systems (HEIS), e.g., the technology used in bubblers, drip irrigation, and sprinkler irrigation. In the DI Khan district, a large project named SoLAR was started by (Ismail et al., 2023) this project provides a long-term solution that enhances agricultural resilience by utilizing solar-powered irrigation. Such innovation has the potential to transform erstwhile barren land into productive agricultural land, giving farmers the opportunity to experiment with more varieties of crops than the mere wheat staples, and branch into other crops like cotton and maize. Deficit irrigation, where less water than the optimum amount needed to satisfy full crop demand is used, is the answer to enhancing water productivity. It stabilizes farmers' income levels and lessens nutrient depletion, which is particularly significant for arid and semi-arid areas like South Punjab and Balochistan, where water is increasingly in shortage, according to (Suna et al., 2023). Since agriculture consumes more than 90% of Pakistan's use of freshwater resources, the use of these water-saving practices is essential for formulating water sustainability in the country.

Agroforestry And Diversification

Agroforestry and diversification are main adaptation strategies to climate change, particularly for smallholder producers who are usually most exposed to its effects. They possess many benefits, such as income diversification, enhanced soil health, carbon sequestration, and enhanced climate variability resilience.

Agroforestry integrates woody perennials with agricultural production and livestock, establishing a multi-functional strategy that promotes adaptation and mitigation activities (Pancholi et al., 2023). Agroforestry systems, for instance, can greatly contribute to climate resilience by enhancing several environmental factors, including the regulation of soil erosion, stabilization of the microclimate, and provision of windbreaks (Quandt, 2020). The systems further offer important products such as fruits, fodder, and firewood, which are important in case of climate-related issues, including droughts and floods.

Diversification, especially of income and crops, is also an effective climate adaptation measure. In Niger, large percentages of households have practiced crop diversification, income diversification, and shifted planting dates as their primary adaptation practices. These adaptation practices have been found to positively affect household income and food security, as evident in enhanced vulnerability to climate variability (Prajapati et al., 2024).

Furthermore, the bringing together of adaptation and mitigation actions, as embodied in sustainable agroforestry, is key to the realization of synergistic gains. Agroforestry is a major player in carbon sequestration, conservation of ecosystems, and sustainable land management, all of which are essential for climate change adaptation and mitigation (Prajapati et al., 2024).

Therefore, diversification and agroforestry are key to establishing climate resilience and supporting sustainability. They are a comprehensive approach to establishing ecological and economic stability, particularly for smallholder producers in vulnerable regions.

Institutional Systems and Computerized Support Systems

Institutional and digital infrastructures increasingly support climate change adaptation policies to respond to the multifaceted challenges of environmental change. Institutions rely on climate change adaptation because they facilitate the creation of policy frameworks, build governance systems, and facilitate international coordination. For example, most countries have developed national adaptation plans with institutional innovations to address important challenges, such as horizontal policy integration across different sectors and vertical integration across different levels of governance. Such plans typically involve state and non-state actors to enhance decision-making processes (Bauer et al., 2012).

Institutional backing of climate adaptation is central to the solution to policy-making and implementation barriers. Even though these measures are effective, barriers like limited fiscal capacity, along with having weak institutional arrangements, pose tremendous challenges to their widespread application (Bashiru &

Oseni, 2025). Furthermore, digital support structures, such as advanced data infrastructure, along with technology-based solutions, are becoming increasingly central to climate adaptation.

The overall effectiveness of these adaptation measures depends on the synergy of institutional resilience and technology innovation, towards constructing institutions capable of adapting to the dynamic reality of climate change issues. Institutional frameworks must transform to provide flexible, inclusive, and innovative solutions that enhance resilience at local, national, and international levels. By exploiting institutional and digital capital, societies are better placed to deal with the complexities of climate adaptation and enhance capacities to adapt for future imperatives.

such as Pakistan's Land Information and Management System (LIMS), reinforce adaptation further. Introduced in 2023, LIMS supplies farmers with satellite-based information on weather, soil condition, water utilization, and pest monitoring.

Building Resilience in Farming Communities

Sustainable Soil and Water Management

Strengthening agricultural communities encompasses a variety of methods. They range from sustainable soil and water management, farmers' education, local adaptation, and traditional practices. Integrated Crop Production Management (ICPM) is evidence of the integrated method by employing a combination of strategies. Such strategies encompass constant rotation of crops, organic manure, conservation of water, and planting trees in combination with crops to improve crop growth and soil conditions (Chouhan et al., 2023).

It is extremely important to have healthy and fertile soil. It keeps the soil productive for decades and minimizes harmful effects on the environment by adopting practices such as the application of organic matter, cover crops, and minimal tillage. These practices enhance the mobility of nutrients within the soil and beneficial soil microbiota, thus enhancing soil health in sustainable agriculture (Mamatha et al., 2024). (Mamatha et al., 2024).

Water management is one of the ways of being resilient and adaptable. Drip and sprinkler irrigation are some of the traditional ways of managing water, which conserve water and utilize resources effectively. These are typically complemented by new technology and equipment, like precision agriculture, which applies sensors and data to optimize resource utilization (Rastogi et al., 2024).

Farmer Education and Knowledge Transfer

Climate change adaptation in agriculture requires personalized approaches to counteract adverse weather conditions. Improved land management, climate services, and access to finance can assist farmers in climate change adaptation, but it must be managed sensitively so that it does not have any adverse unintended consequences (Guodaar et al., 2020). Participatory approaches in agricultural counseling bridge the knowledge gap. Participatory approaches empower farmers by encouraging farmers to learn together and develop solutions suitable to their specific situations (Prajapati et al., 2025).

Use of Traditional Practices

Conventional practices of farming, rooted in cultural understanding and traditional knowledge, have a great impact on enhancing environmental sustainability and community resilience. Combining them with new practices, such as precision agriculture, enhances sustainability and resilience, biodiversity, and community identity (Adebimpe Oluwabukade Adefila et al., 2024). Agroforestry also incorporates tree with crops and livestock to enhance biodiversity, soil fertility, and ecosystem functions. It is a robust approach to sustainable land management and climate change adaptation (Kumar et al., 2023).

A combination of new technology, indigenous knowledge, and community backing can breed resilient and strong farming communities. This will help them to successfully cope with climate change and environmental issues. Together, these pressures challenge Pakistan's goal of advancing agriculture through productivity, innovation, and sustainable practices. Mitigation and adaptation must be coupled with resilience-building, incorporating climate-smart systems, early warning tools, and policy support, to protect and advance farming in changing climates.

Role of Technology in Climate Resilience

Early Warning Systems

Early Warning Systems (EWS) play a critical role in enhancing climate resilience as they provide timely detection and communication regarding climate-induced hazards (heatwaves, storms, floods, and droughts). These systems follow sequential steps, including danger detection, risk assessment, alert transmission, and mitigation planning ("Early Warning Systems Defined," 2014). Over a few decades, these systems have helped communities avoid the loss of life and assets significantly. Research conducted in Sahelian West Africa, the implementation of the SLAPIS system on the Sirba River shows the effective combination of hydrological forecasting and community-based participatory monitoring. This integrated approach notably improved early warning lead time and local adaptive response capacity (Tarchiani et al., 2020).

Similarly, people in transboundary flood plains like Elegu have understood the positive effects and the need for such innovative ideas that can help them escape by sharing warnings and collaborative preventive measures (Canwat, 2025). Some flood-focused reviews suggest that EWS must be more advanced than sending basic alerts. There is still a gap to integrate high-precision forecasting tools and strategic dissemination mechanisms to activate highly accurate community responses (Cools et al., 2016)

Precision Farming Tools

Precision Farming, also known as Digital Farming or Smart Farming, is a modern approach that integrates Internet of Things (IoT), robots, artificial intelligence (AI), GPS, sensors, and drones to smartly manage cropping systems in changing environments. These tools help farmers to apply the inputs exactly where, when, and how much they are required, thus reducing the input wastage and increasing crop yield, even in changing environments. Recent studies show that smart soil

sensors collect real-time data from pH, moisture, and nutrients available in the soil, provide the best solution, and ultimately help farmers to improve fertilizer and irrigation use(Eze et al., 2025).

Researchers have also found that IoT-supported irrigation systems saved 30% of irrigation water with the same quality and yield of tomatoes and blueberries in Michigan(Dong et al., 2024). Besides soil sensors, drones are also powerful tools in precision farming that keep an eye on the crop health at different times during the crop growth. They use special cameras and detect changes in height, health, leaf color, and overall plant growth. Modern AI-powered drones are also capable of detecting plant diseases early with 90% accuracy, helping farmers take precise and quick preventive measures(Agrawal & Arafat, 2024)

Mobile Apps for Weather and Crop Advice

Mobile applications for weather and crop advice have brought a major transformation in how smallholder farmers receive weather forecasts, crop management tips, and market updates that help them make data-driven decisions at the right time. The AgriCloud app is one of the most famous applications in South Africa, Zambia, and Indonesia. It collects real-time weather-related data from ECMWP and integrates it with local agriculture knowledge to give area-specific recommendations for planting, irrigation, spraying, and other soil management tasks. The fact that around 70% people use this application regularly shows its effectiveness in managing cropping-related problems in climate-sensitive areas(Walker, 2021)

Such mobile applications are of great importance and value, but there is still a need for developing user-friendly applications that can connect with mobile phones, have simple interfaces, and provide local language support for illiterate farmers. In Central Kenya, around 500 smallholder farmers were served, and all of them owned mobile phones, but only one out of four used such agro-meteorological apps. Those one-quarter farmers were literate and had smartphones. This illustrates the critical need and gap for creating USSD and SMS-based solutions to ensure broader reach(Krell et al., 2021)

Biotech Innovations

For centuries, biotechnology has always offered miraculous, time-saving, and powerful solutions to induce climate-resilience in agriculture. Different techniques (as shown in Figure 2) of this field can be used to make significant and desirable changes in plants. Genome editing using CRISPR/Cas9 is one of the modern innovations of this field. Using this technology, precise modifications in the plant's genome have been successfully done. The genes involved in stress responses, like the abscisic acid (ABA) signaling gene, prove a suitable genome transforming method for non-GMO and GMO breeding frameworks(Kaur et al., 2025). Using this technique, transcription factors like bZIP and AREB1 have been successfully edited in wheat and rice, ultimately causing their good survival in water stress while maintaining yield (Rai et al., 2023)

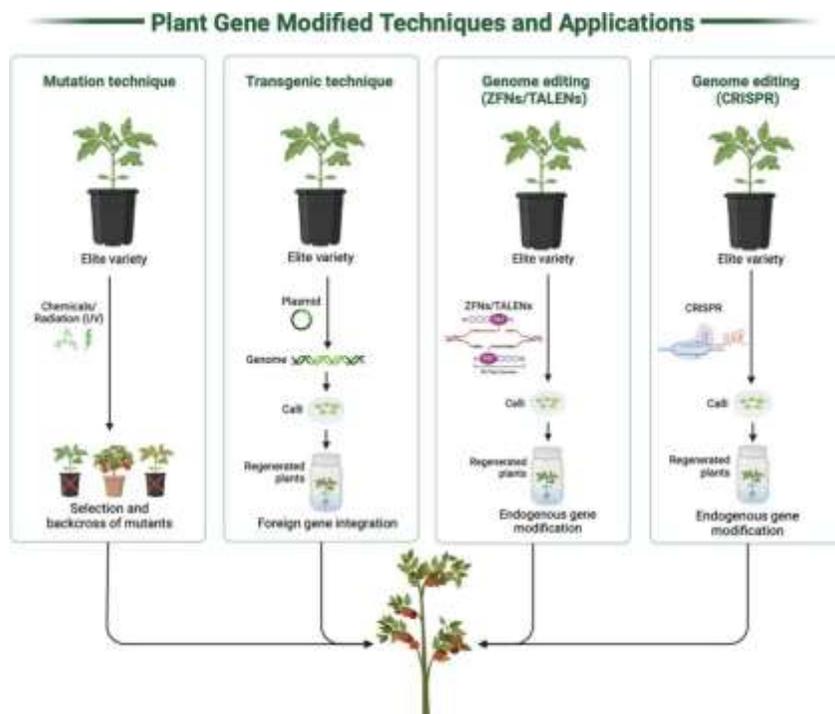


Figure 2: Techniques and Applications of Plant Gene Modification for Crop Improvement and Sustainability (<https://doi.org/10.1002/biot.202400457>)

Similarly, microbiome engineering is another innovative technique that uses root-associated microbes and uses them to support a plant’s drought resistance. In wheat, symptoms related to water stress have been delayed by several days with improved root growth using the host-mediated microbiome selection (Jochum et al., 2019). Another amazing example, the introduction of drought-tolerant sunflower genes into wheat has shown good performance in the field with high biomass accumulation and stress resistance in dry conditions (Gupta, 2024).

Plant transformation is a pivotal technique in genetic engineering, allowing for the introduction of foreign DNA into a plant genome to achieve specific traits such as stress tolerance, disease resistance, or improved yield. The most commonly employed methods include *Agrobacterium*-mediated transformation, biolistic (gene gun) delivery, electroporation, and floral dip. Each method has unique advantages and limitations depending on the plant species and tissue type used. As shown in Figure 3, these transformation approaches differ in how they deliver genetic material into plant cells, but all contribute to the development of genetically enhanced crops (Choudhury & Rajam, 2021). With the rise of modern biotechnology, it's essential to distinguish between traditional transgenic approaches and the broader category of genetically modified organisms (GMOs). While both aim to improve plant performance and adaptability, they differ significantly in technique, regulation, and public acceptance. Recent developments in biotechnology have broadened the spectrum of genetic modification beyond classical transgenics. While the terms "transgenic plants" and "GMOs" are often used interchangeably, they represent distinct categories

within plant biotechnology. **Table 1** outlines the key differences between these two, highlighting the implications of their development techniques, regulatory pathways, and public reception. The following table provides a clear comparison to help clarify these distinctions.

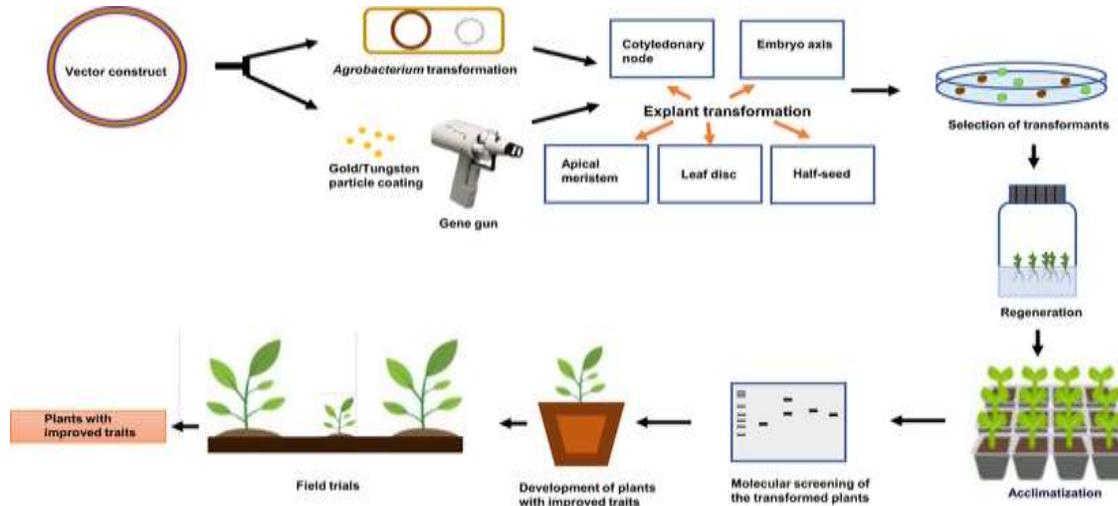


Figure 3. Schematic overview of commonly used plant genetic transformation methods, including Agrobacterium-mediated, biolistic, electroporation, and floral dip techniques. (Adapted from Choudhury & Rajam 2021)

Table: 1. Differences Between Transgenic Plants and Genetically Modified Organisms (GMOs)

Feature	Transgenic Plants	GMOs
Definition	Organisms that have foreign genes inserted into their genome via recombinant DNA technology.	Organisms whose genetic material has been altered in a way that does not occur naturally via mating or natural recombination.
Technique	Involves transferring specific genes from one organism into another.	May include transgenesis, but also includes techniques like gene editing, mutagenesis, etc.
Source of Genes	Genes can come from unrelated species (e.g., bacteria, viruses).	Genes can come from the same species or be synthetic.
Regulation	Strictly regulated due to use of foreign DNA.	Regulations vary depending on the technique used; gene-edited crops may face less regulation.
Public Perception	Often faces skepticism due to the "foreign gene" concept.	Varies; newer techniques like CRISPR are gaining more acceptance.
Example	Bt cotton with a gene from <i>Bacillus thuringiensis</i> .	CRISPR-edited rice for disease resistance without foreign DNA.

This distinction is critical when discussing biosafety, regulatory approval, and consumer acceptance in plant biotechnology. As gene-editing tools like CRISPR become more mainstream, understanding these nuances becomes even more relevant.

Case Studies and Examples

Climate-smart villages in South Asia

In South Asia, Climate Smart Villages (CSV) have been introduced as community-level projects. These projects assist small farmers in managing the changing climatic factors while improving food quality and production. India, Bangladesh, and Nepal, with the help of the CGIAR and CCAFS programs, adopted this model and enabled their farmers to use climate-resilient cropping practices. Farmers in these villages use water-saving methods, drought-tolerant seeds, ICT-based weather services, and reduced tillage practices due to CSV systems. Studies showed that farmers from CSV adapt better to climate-related risks, use less water, and gain more yield than the non-CSV farmers. CSV has now gained popularity as a successful model for promoting climate-smart agriculture in smallholder farming systems (Aggarwal et al., 2018)

Pakistan's experience with heat-resistant wheat

Heat stress is a major problem in Pakistan, especially during the wheat growing season. To cope with this issue, scientists have worked a lot to develop heat-resistant wheat varieties using different techniques. Pakistan's leading research institutes, like CIMMYT and NARC have developed many varieties that can withstand heat stress. They conducted trials of spring wheat lines under delayed sowing conditions to provoke terminal heat stress. Results revealed that the advanced lines of Punjab-11 maintained cooler canopy temperature, higher yield, and elevated chlorophyll content (Rehman et al., 2021).

At Bahauddin Zakariya University, field trials of commercial spring wheat have also been conducted in early and late dates. **Fakhr-e-Bhakkar** and **Bhakkar Star** stood out with a high grain yield of 3.335t/ha and 6.97t/ha. The results promised their robust performance during late planting scenarios, which is common in Pakistan (Dr. Babar Islam, 2025).

Farmer-led innovations

Farmer-led innovations also make a great contribution to climate-resilient agriculture. In South Asia, farmers not only adopt external technologies but also make their own solutions. In Pakistan and India, farmers have started intercropping legumes with cereals to increase soil fertility. This way, they have created their soils more nutrient-enriched and reduced the pest attacks without any external involvement. Similarly, in some areas, farmers adopted furrow-bed planting as an efficient irrigation technique to manage water shortage. These self-made efforts come from knowledge, experience, and experimentation. Supporting such innovative techniques and farmer-to-farmer knowledge sharing will help to scale climate-resilient agriculture faster and cost-effectively.

Challenges and Limitations

Lack of funding

Lack of funding is a significant barrier to widespread adaptation of climate-resilient agriculture. The smallholder farmers face problems in getting financial support for innovations like drought-resistant seeds, a climate information system, and efficient irrigation methods. As per the Climate Policy Initiative (CPI), only \$10 billion was directed to climate-resilient agriculture of smallholder farmers. However, the need of the time was \$240 billion per year, showing a great gap in climate finance for agriculture. In some areas, the public and private sectors fail badly in meeting the financial needs in Sub-Saharan Africa.

Lack of funding not only delays the innovation but also sets standards among farmers. The better-resourced farmers get advantages over the poorer ones, creating an environment of inequality. To fill up this gap, more financial support but targeted investments, and subsidies are needed. Investments focused on women-led farms, smallholder farmers, and marginalized communities can also show promising outcomes. Following such an approach will cause innovation to be widespread, benefiting the entire agricultural system.

Policy And Institutional Gaps

Unorganized institutions and weak policies are one of the reasons that stop farmers from adopting climate resilience. In Pakistan, higher organizations know the importance of this topic but still cannot do anything because of weak policy and management systems, fewer staff, and enough money (Khan et al., 2020). Similarly, in Ghana and South Africa, the climate-smart agricultural practices are poorly embedded into the local and national systems. This is all due to a lack of institutional capacities to effectively follow the policies at the grassroots level (Diko et al., 2021). Scaling climate-resilient interventions effectively calls for enhanced institutional cooperation, targeted resource investment, and alignment of policy initiatives across governance layers.

Awareness And Training Barriers

The presence of resources and policy support alone is insufficient for the successful adoption of climate-smart methods, particularly in areas where training and awareness are lacking. Rural populations face digital illiteracy and weak extension networks. A study from China demonstrated that farmers with better digital skills were more inclined to adopt low-carbon, climate-resilient technologies, highlighting knowledge gaps as a critical barrier (Yuan et al., 2025a).

A global review also highlighted that awareness gaps—particularly prevalent in Sub-Saharan Africa—significantly hinder the adoption of climate-smart tools. Strengthening farmer outreach through participatory education, technology training, and accessible extension systems is necessary to improve adoption rates (Yuan et al., 2025b).

Future Directions and Conclusion

Innovations And Research Prospects

New opportunities are being opened up by emerging technologies for climate-smart agriculture and precision agriculture. Emerging technologies like AI-based IoT systems, digital twins, nanosensors, and vertical farming are pilot-tested in different parts of the world. Kumar & Nayak (2024), for instance, pilot-tested an IoT–AI system for high-resolution, real-time local weather forecasting to guide farm decision-making, highlighting the need for further empirical testing and digital literacy among farmers (Das & Nayak, 2025). In contrast, Babar & Akan (2024) clarified the concept of the Internet of Everything (IoE), which integrates IoT, blockchain, nanoscale sensors, and biotechnologies, with immense possibilities in enhancing the effectiveness of the use of resources, disease control, and molecular-level robustness (Babar & Akan, 2024).

At the same time, farm-level technologies such as drone-enabled spraying and sensor-enabled irrigation are being tested on the ground, with great outcomes. Now the directions like field testing of IoT/AI platforms in smallholder settings, upscaling of digital twin applications for resource optimization, integration of nanosensor networks for real-time soil and pathogen detection, and convergence of agritech and biotech with precision agriculture for enhanced crop quality and resilience. Scientists, engineers, and policymakers in collaboration will be leading the charge in upscaling these technologies for global food security.

Policy Integration And Youth Involvement

Climate-adaptation and agricultural policy convergence is crucial to create integrated, actionable policies that promote resilience and sustainability. Converging climate change adaptation (CCA) with agricultural planning in Nepal is emerging to involve intersectoral coordination of water, energy, forestry, and disaster management sectors. Multi-level governance institutions—subnational and national coordination—are required for coordinating local plans into broader climate goals and increasing implementation capacity. Policymaking should therefore be guided by new evidence, localized to agroecological contexts, and shaped to promote inclusive access to technology, extension facilities, and climate finance support (Nepal et al., 2024).

While youth engagement in forming and implementing agricultural policy increases innovation and social justice, a scoping review of African food systems indicates that youth participation in entrepreneurship, advocacy, and policy is presently constrained by production models and negative stereotypes of agriculture as low-status work. The FAO and networks of African youth are actively working to put youth voices on the table and push for policies that provide youth with access to land, credit, training, and leadership in agrifood system transformation. International youth engagement models—such as the U.S. EPA's National Youth Advisory Council—also

demonstrate the energy and potential of Gen Z and millennials when they are included in environmental decision-making.

Here are a few recommendations for moving forward:

- 1: Strengthen policy responses at all levels of government, bringing together climate and agriculture planning
- 2: Mainstream youth participation in policy advisory frameworks and implementation processes;
- 3: Provide youth-focused financing and training for agripreneurs, especially in green as well as digital skills.
- 4: Monitor progress and share best local practice between regions to inform adaptive policymaking.

Summary And Final Thoughts

In short, policy designs need to change so that climate adaptation is synchronized with agrarian development, overcoming vertical and horizontal institutional gaps. Good governance requires transparent coordination among local, national, and transnational actors so that resources, training, and finance reach where they are required.

Just as important is youth engagement, whose entrepreneurial spirit and creativity can resuscitate agriculture. Policies need to transcend tokenism to substantive youth participation in decision-making, accompanied by financing, education, access to land, and mentorship programs. Lessons drawn from Africa and key international institutions such as FAO and EPA highlight the way youth engagement can bring innovative results and improved accountability.

In the end, it is driving equitable and resilient agri-futures that relies on the alignment of technological innovation with social inclusion and strong policy systems. With research investment, youth engagement, and mainstreaming climate action through agricultural policy, stakeholders can drive a transition towards resilient food systems that can absorb climate risks while mitigating inequalities and food insecurity.

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REFERENCES

Aggarwal, P. K., Jarvis, A., Campbell, B. M., Zougmore, R. B., Khatri-Chhetri, A., Vermeulen, S. J., Loboguerrero, A. M., Sebastian, L. S., Kinyangi, J., Bonilla-Findji, O., Radeny, M.,

- Recha, J., Martinez-Baron, D., Ramirez-Villegas, J., Huyer, S., Thornton, P., Wollenberg, E., Hansen, J., Alvarez-Toro, P., ... Yen, B. T. (2018). The climate-smart village approach: Framework of an integrative strategy for scaling up adaptation options in agriculture. *Ecology and Society*, 23(1). <https://doi.org/10.5751/es-09844-230114>
- Agrawal, J., & Arafat, M. Y. (2024). Transforming Farming: A Review of AI-Powered UAV Technologies in Precision Agriculture. *Drones*, 8(11), 664. <https://doi.org/10.3390/drones8110664>
- Babar, A. Z., & Akan, O. B. (2024). *Sustainable and Precision Agriculture with the Internet of Everything (IoE)* (Version 3). arXiv. <https://doi.org/10.48550/ARXIV.2404.06341>
- Bibi, F., & Rahman, A. (2023). An Overview of Climate Change Impacts on Agriculture and Their Mitigation Strategies. *Agriculture*, 13(8), 1508. <https://doi.org/10.3390/agriculture13081508>
- Canwat, V. (2025). Social innovations and drivers in flood early warning systems: A community-based transboundary perspective from Elegu flood plain in Northern Uganda. *Journal of Flood Risk Management*, 18(1). <https://doi.org/10.1111/jfr3.12930>
- Choudhury, A., & Rajam, M. V. (2021). Genetic transformation of legumes: An update. *Plant Cell Reports*, 40(10), 1813–1830. <https://doi.org/10.1007/s00299-021-02749-7>
- Cools, J., Innocenti, D., & O'Brien, S. (2016). Lessons from flood early warning systems. *Environmental Science & Policy*, 58, 117–122. <https://doi.org/10.1016/j.envsci.2016.01.006>
- Das, S. K., & Nayak, P. (2025). *Integration of IoT- AI powered local weather forecasting: A Game-Changer for Agriculture* (Version 1). arXiv. <https://doi.org/10.48550/ARXIV.2501.14754>
- Debela, N., Mohammed, C., Bridle, K., Corkrey, R., & McNeil, D. (2015). Perception of climate change and its impact by smallholders in pastoral/agropastoral systems of Borana, South Ethiopia. *SpringerPlus*, 4(1). <https://doi.org/10.1186/s40064-015-1012-9>
- Diko, S. K., Okyere, S. A., Opoku Mensah, S., Ahmed, A., Yamoah, O., & Kita, M. (2021). Are local development plans mainstreaming climate-smart agriculture? A mixed-content analysis of medium-term development plans in semi-arid Ghana. *Socio-Ecological Practice Research*, 3(2), 185–206. <https://doi.org/10.1007/s42532-021-00079-2>
- Dong, Y., Werling, B., Cao, Z., & Li, G. (2024). Implementation of an in-field IoT system for precision irrigation management. *Frontiers in Water*, 6. <https://doi.org/10.3389/frwa.2024.1353597>
- Dr. Babar Islam, M. O. F. (2025). *EVALUATION OF SPRING WHEAT GENOTYPES FOR TOLERANCE TO HEAT STRESS BASED ON YIELD AND RELATED TRAITS*. <https://doi.org/10.5281/ZENODO.14921257>
- Early Warning Systems Defined. (2014). In I. Kelman & M. H. Glantz, *Reducing Disaster: Early Warning Systems For Climate Change* (pp. 89–108). Springer Netherlands. https://doi.org/10.1007/978-94-017-8598-3_5
- Eze, V. H. U., Eze, E. C., Alaneme, G. U., Bubu, P. E., Nnadi, E. O. E., & Okon, M. B. (2025). Integrating IoT sensors and machine learning for sustainable precision agroecology: Enhancing crop resilience and resource efficiency through data-driven strategies, challenges, and future prospects. *Discover Agriculture*, 3(1). <https://doi.org/10.1007/s44279-025-00247-y>
- Gupta, P. K. (2024). Drought-tolerant transgenic wheat HB4®: A hope for the future. *Trends in Biotechnology*, 42(7), 807–809. <https://doi.org/10.1016/j.tibtech.2023.12.007>

- Ismail, M., Mujtaba, A., Ahmed, E., Saleem, M. A., & Jakhro, M. I. (2023). Adoption of Drip Irrigation System in Southern Punjab-Pakistan: Challenges and Options. *Journal of Food and Agricultural Technology Research*, 2(Issue 01), Article Issue 01. <https://doi.org/10.69501/t9zxc087>
- Jochum, M. D., McWilliams, K. L., Pierson, E. A., & Jo, Y.-K. (2019). Host-mediated microbiome engineering (HMME) of drought tolerance in the wheat rhizosphere. *PLOS ONE*, 14(12), e0225933. <https://doi.org/10.1371/journal.pone.0225933>
- Kaur, N., Qadir, M., Francis, D. V., Alok, A., Tiwari, S., & Ahmed, Z. F. R. (2025). CRISPR/Cas9: A sustainable technology to enhance climate resilience in major Staple Crops. *Frontiers in Genome Editing*, 7. <https://doi.org/10.3389/fgeed.2025.1533197>
- Khan, N. A., Gao, Q., & Abid, M. (2020). Public institutions' capacities regarding climate change adaptation and risk management support in agriculture: The case of Punjab Province, Pakistan. *Scientific Reports*, 10(1). <https://doi.org/10.1038/s41598-020-71011-z>
- Krell, N. T., Giroux, S. A., Guido, Z., Hannah, C., Lopus, S. E., Caylor, K. K., & Evans, T. P. (2021). Smallholder farmers' use of mobile phone services in central Kenya. *Climate and Development*, 13(3), 215–227. <https://doi.org/10.1080/17565529.2020.1748847>
- Nepal, P., Paudel, B., Zhang, Y., Khanal, N. R., Liu, L., Wang, Z., Rai, M. K., & Sigdel, S. R. (2024). Integration of climate change adaptation into agricultural policies in Nepal: A diagnostic assessment. *Environmental Development*, 52, 101085. <https://doi.org/10.1016/j.envdev.2024.101085>
- Qamer, F. M., Abbas, S., Ahmad, B., Hussain, A., Salman, A., Muhammad, S., Nawaz, M., Shrestha, S., Iqbal, B., & Thapa, S. (2023). A framework for multi-sensor satellite data to evaluate crop production losses: The case study of 2022 Pakistan floods. *Scientific Reports*, 13(1), 4240. <https://doi.org/10.1038/s41598-023-30347-y>
- Rai, G. K., Khanday, D. M., Kumar, P., Magotra, I., Choudhary, S. M., Kosser, R., Kalunke, R., Giordano, M., Corrado, G., Roupheal, Y., & Pandey, S. (2023). Enhancing Crop Resilience to Drought Stress through CRISPR-Cas9 Genome Editing. *Plants*, 12(12), 2306. <https://doi.org/10.3390/plants12122306>
- Rehman, H. U., Tariq, A., Ashraf, I., Ahmed, M., Muscolo, A., Basra, S. M. A., & Reynolds, M. (2021). Evaluation of Physiological and Morphological Traits for Improving Spring Wheat Adaptation to Terminal Heat Stress. *Plants*, 10(3), 455. <https://doi.org/10.3390/plants10030455>
- Saddique, N., Jehanzaib, M., Sarwar, A., Ahmed, E., Muzammil, M., Khan, M. I., Faheem, M., Buttar, N. A., Ali, S., & Bernhofer, C. (2022). A Systematic Review on Farmers' Adaptation Strategies in Pakistan toward Climate Change. *Atmosphere*, 13(8), 1280. <https://doi.org/10.3390/atmos13081280>
- Shrestha, R. P., Raut, N., Swe, L. M. M., & Tieng, T. (2018). Climate Change Adaptation Strategies in Agriculture: Cases from Southeast Asia. *Sustainable Agriculture Research*, 7(3), 39–51. <https://doi.org/10.22004/ag.econ.301826>
- Sinha, D., Maurya, A. K., Abdi, G., Majeed, M., Agarwal, R., Mukherjee, R., Ganguly, S., Aziz, R., Bhatia, M., Majgaonkar, A., Seal, S., Das, M., Banerjee, S., Chowdhury, S., Adeyemi, S. B., & Chen, J.-T. (2023). Integrated Genomic Selection for Accelerating Breeding Programs of Climate-Smart Cereals. *Genes*, 14(7), 1484. <https://doi.org/10.3390/genes14071484>

- Suna, T., Kumari, A., Paramaguru, P. K., & Kushwaha, N. L. (2023). Enhancing Agricultural Water Productivity Using Deficit Irrigation Practices in Water-Scarce Regions. In A. Naorem & D. Machiwal (Eds.), *Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches* (pp. 177–206). Springer Nature. https://doi.org/10.1007/978-981-19-9159-2_11
- Tarchiani, V., Massazza, G., Rosso, M., Tiepolo, M., Pezzoli, A., Housseini Ibrahim, M., Katiellou, G. L., Tamagnone, P., De Filippis, T., Rocchi, L., Marchi, V., & Rapisardi, E. (2020). Community and Impact Based Early Warning System for Flood Risk Preparedness: The Experience of the Sirba River in Niger. *Sustainability*, *12*(5), 1802. <https://doi.org/10.3390/su12051802>
- Țopa, D.-C., Căpșună, S., Calistru, A.-E., & Ailincăi, C. (2025). Sustainable Practices for Enhancing Soil Health and Crop Quality in Modern Agriculture: A Review. *Agriculture*, *15*(9), Article 9. <https://doi.org/10.3390/agriculture15090998>
- Walker, S. (2021). Development of Tailored Early Warning Agromet Advisories for Farmers in Zambia, Indonesia, and South Africa. *Frontiers in Climate*, *3*. <https://doi.org/10.3389/fclim.2021.710625>
- Yuan, Y., Sun, L., She, Z., & Chen, S. (2025a). Influence of Digital Literacy on Farmers' Adoption Behavior of Low-Carbon Agricultural Technology: Chain Intermediary Role Based on Capital Endowment and Adoption Willingness. *Sustainability*, *17*(5), 2187. <https://doi.org/10.3390/su17052187>
- Yuan, Y., Sun, L., She, Z., & Chen, S. (2025b). Influence of Digital Literacy on Farmers' Adoption Behavior of Low-Carbon Agricultural Technology: Chain Intermediary Role Based on Capital Endowment and Adoption Willingness. *Sustainability*, *17*(5), 2187. <https://doi.org/10.3390/su17052187>