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REVIEW ARTICLE

Trends in Biotechnology and Plant Sciences

Advances in Climate-Smart Agriculture (CSA) and Sustainable Farming: A Comprehensive Review of Strategies, Technologies, and Future Directions

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Abstract

Climate change keeps posing a hazard to the agricultural systems across the globe by escalating drought, rainfall fluctuations, and extreme temperatures. The Climate Smart Agriculture (CSA) provides a comprehensive concept essential to enhance agricultural productivity, resilience and considerable reduction in greenhouse gases. The paper draws a review of recent trends or the trends between the years 2020 and 2024 in terms of the agroecological approaches, digital innovation, policy formulation, and socio-economic frameworks conducive to the adoption of CSA. These include five core elements namely: crop diversification, agroforestry, conservation tillage, and livestock methane mitigation. The breakthrough of such technologies as precision irrigation, remote sensing, gene editing, and agrivoltaics systems is evaluated to multiply climate-resistant agricultural activities. Gender-friendly policy, carbon markets and decentralized governance are highly debated as far as promoting fair uptake is concerned. The case studies about the most powerful countries to display a practical example of applying the models of CSA in reality. Key barriers (complexity in regulation, technological inequalities, and behavioral blocks) are discussed, and the possibilities of future directions are foreseen, which imply digital chains and traceability in supply, transition plans of protein and regenerative farming paradigms. This detailed review aims to guide the CSA practices to be in line with global aspect of sustainability as well as meeting on issues of adaptation that is localized.

KEYWORDS
Climate-Smart Agriculture (CSA), Regenerative Agriculture, Remote Sensing and Precision Agriculture, CRISPR-Cas9 Enabled Crop Resilience, Agro-photovoltaics and Renewable Energy Integration.

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1 | INTRODUCTION

Climatic change is a top priority of food security, sustainability in the environment, and social-economic stability in the entire world that is creating the most concern (Awad et al., 2024). Globally, the average degree of surface temperature has already increased by about 1.1°C since the pre-industrial period, with expectations that it will continue to accelerate the rate at which extreme meteorological conditions and occurrence and intensities of weather extremes like droughts, floods and heatwaves occur (Forster et al., 2024). These imbalances of the climatic conditions affect the farm and farmer in an unequal way because it reduces their output, alters the crop season, and helps the eruption of pest diseases hence, putting food systems globally at risk (Kyaw et al., 2023). Cultivation can be subjected to the climatic alteration and it is also among the sources of climate alteration (Gruda et al., 2019). The industry is accountable to an overall composition of approximately 23% of anthropogenic greenhouse gas (GHG) emissions largely due to the emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) which occurs during crop farming, livestock and land variation. This is due to such processes being the source of why it is important to adopt climate-proof sustainable farming models (Abebaw, 2025). It is on this backdrop that Climate-Smart Agriculture (CSA) has emerged as a paradigm-shifting approach that aims at achieving three mutually reinforcing goals simultaneously: (1) increasing agricultural productivity and incomes in a sustainable manner; (2) developing and building resiliency to the effects of climate change; and (3) mitigating to the extent possible but outright eliminating the emission of greenhouse gases (Ma & Rahut, 2024).

CSA is not a single practice or technology as some people like to think but to the Food and Agriculture Organization (FAO, CSA can be discussed as an amalgamation of various strategies and practices e.g. sustainable land management, water efficiency, biodiversity conservation, and technologies innovation (Kabato et al., 2025). Against the twin backdrop crises of the urgent need to feed a global population that is set to grow to 9.7 billion people by 2050 and to avoid overwhelming planetary limits to resources and sinks, CSA offers an example of strategic interventions that can simultaneously enhance capacity to mitigate and to adapt to the onslaught of climate change. (Ma & Rahut, 2024). An existing body of evidence justifies such a thesis as the growing attention attached to such aspects of the CSA as automation, digital agriculture, and machine learning within the CSA frameworks (Araujo et al., 2023). In its report on the automation in agriculture is keen to state that some of the benefits of such innovation as precision farming, real-time crop monitoring by drones, and weather-data analytics are being able to increase their input efficiency and decrease the environmental impacts (Getahun et al., 2024). Smallholder farmers in low and middle-income countries could benefit, as well, because these technological advances provide means to streamline decision-making and eliminate susceptibility to climatic shocks (Uzhinskiy, 2023).

Agroecological solution is one of the major strategies in the CSA programs (Vicente-Vicente et al., 2023). Agroforestry is one of the nature-based solutions that have huge potential to restore ecosystem services and promote carbon sequestration and resilience of the socio-economic aspects of farming communities particularly in climate-sensitive zones such as Sub-Saharan Africa (Gupta et al., 2024). In addition to the mitigation properties provided by agroforestry systems, which store up to 200 tons of carbon in each hectare, the systems withstand heat stress impact on crops, retain moisture in the soil, and support farmer incomes (Panda, 2025). In addition to this, CSA does not focus on technical answers but on institutional and policy innovations. There is an emerging literature on the need to focus on inclusive governance, capacity building of farmers, financial mechanisms such as climate insurance, and gender-sensitive strategies that would make it possible to carry out a successful implementation of CSA practices (Njogu et al., 2024). As one example, top-down approaches did not result as significantly in increased adoption of sustainable land-use practices than bottom-up ones applied through community-based participatory models, which was shown to result in a 25-40% higher level of adoption (Sumari et al., 2025).

Systems thinking has found more use in CSA research and implementation in the recent years. This school of thought appreciates the fact that soil health, water use, energy inputs, biodiversity, and socio-economic results are interdependent (Jagustović et al., 2019). The greater variety of crops and livestock means more nutrients are shared and a more highly developed level of production is achieved, making farms more sustainable in the long term and reducing emissions and dependency to the outside world (Khatri et al., 2024). Such a change in input-, high-emission-efficient, monoculture to more diversified and climate-adaptive farming landscapes depends on integration at the system scale (Vidadala, 2024).

Lastly, the COVID-19 pandemic and the Russia-Ukraine war showed the insecurity of global food supply chains, causing the need of locally self-sufficient food systems again. (Bas, 2025). CSA provides a platform where such resilience is obtained by better resource utilization, reduced dependence on outside world and empowering local agents (Teklu et al., 2023). It is increasingly becoming clear that climate constructive ways of practice like conservation agriculture, intercropping, rainwater harvesting and solar-powered irrigation consolidate the annual crop production besides providing new green jobs and fostering inclusive countryside development (Liang et al., 2024).

With this aim in mind, this review seeks to synthesize the recent developments in the strategies of CSA, technological inventions, ecosystem-based studies, and the enabling policies, and in particular the weight on their scalability, positive changes to the environment, and socio-economic co-benefits. This review paper also aims to provide an exhaustive source of information to policymakers, researchers, and development practitioners, as well as farmers who need to shift towards more sustainable and climate-resilient farming systems by incorporating details and knowledge based on peer-reviewed literature, global reports, and case studies.

2. Main Strategies for Climate Smart Agriculture

2.1 Agroecological Changes: Different Systems for Sustainable Agriculture

The most popular agroecological practice to be found in CSA framing is crop diversification through intercropping, cover cropping, and crop rotation replaces monocultures in agriculture (Das, 2024)(Table 1). A global meta-analysis that showed that the effects are both location-specific yet diversified systems tend to create better biodiversity, pest suppression, soil health and yield stability on different agroecological zones. All these are attained without necessarily raising the cost of input or compromising in productivity (Beillouin et al., 2021). Over time, less nutrient cycling, smaller rates of erosion and an increase in the number of biological control agents are some of the positive ecosystem services that can offset slight yield trade-offs in the initial years with diversified cropping systems (Raveloaritiana & Wanger, 2024).

Table 1: Impact of Agroecological Strategies (Beillouin et al., 2021; Rosenstock et al., 2020)

Practices	Yield Stability	Carbon Sequestration (t CO_2 ha^{-1} yr^{-1})	Biodiversity Gain
Crop Diversification	+30%	0.2-0.5	+40% arthropods
Agroforestry	+25%	2.5-5.0	+60% bird species
Conservation Tillage	+15%	0.3-0.8	+30% soil microbes

Breakdown of crops contributes biological resiliency toward protecting against pests outbreaks and climatic fluctuation that is in direct connection to pillar of adaptation in CSA (Mihrete & Mihretu, 2025). In addition, farmers can diversify their risks by focusing on fewer monocultures and still be productive throughout changing weather patterns as well as have less reliance on synthetic products (Teklu et al., 2023). CSA is based on integration of trees wherever possible in agricultural systems, a practice commonly referred to as agroforestry since it can positively contribute to mitigation, resilience, and livelihoods at the same time (Keprate et al., 2024). It is noted that empirical evidence agroforestry systems based on both biomass carbon and soil carbon retain astronomical amounts of carbon whereas soil fertility, water saving and biodiversity are being maintained apart from carbon (Barman et al., 2024). In their retrospective, they were quantifying the prolonged carbon accession in systems like alley cropping, silvopasture and home garden layouts in tropical climates and temperate climates (Pancholi et al., 2023).

In addition to carbon, agroforestry, increases biodiversity, favorable micro-climes, and incomes of farmers due to a variety of products (e.g., fruit, fuelwood, fodder) (Gayo & Ngongolo, 2025). Agroforestry in areas such as sub-Saharan Africa can play an especially important role in providing essential ecosystem services and increasing household resilience as well as dietary diversity and therefore is appropriate in climate-sensitive regions(Nyathi et al., 2025). Agroforestry deals with all three pillars of CSA: Better productivity (Soil health), climate adaptation (Shade and microclimate buffering), and mitigation (Carbon storage). Agroforestry systems tend to be sustainable, scalable and socially friendly due to the fact that they utilize local species, as well as a conventional knowledge (Kabato et al., 2025).

2.2 Increasing Resource Use Efficiency

Efficient water and nutrient use has a multipurpose because it enhances sustainability and cutting on emissions (Lakhiar et al., 2024). The CSA practices among them that slowed the obtainment of soil organic carbon pools and increased nitrogen use efficiency by as much as 30% comprise zero tillage, residue retention, and precision nutrient application, which reduced N_2O emissions (Jat et al., 2020). Cover crops retain the moisture of the soil, suppress weeds and gain microbes (Henzel et al., 2025). The opportunities of technologies such as moisture sensors and automated machines, smart phone connected advisory services, and variable rate irrigation systems so as to customize the inputs in relation to the conditions of the fields (Lakhiar et al., 2024). These high-tech devices contribute to saving the usage of water and fertilizer and optimize yields and reduce greenhouse gas emissions especially in the areas where water shortage is in existence and nutrient overflow is a problem (Aziz et al., 2025).

Biochar made by pyrolysis of biomass can be used to increase soil water holding capacity, nutrient concentrations and a source of long-term carbon sequestration (Elkhlifi et al., 2023). New findings indicate that biochar usage has the potential to increase crop production to more than 340%, in slapstick soils and sequesters fixed carbon in soils lasting thousands of years (Dwibedi et al., 2023). Great potential to recapture worn out soils, reduce input necessities and sink carbon in a constant manner is a direct fit of such advantages with mitigation and resilience pillars of CSA, thereby giving an efficient asset to re-capture degraded soils (Kabato et al., 2025).

2.3 Soil Carbon Plans: Methane Reductions and the use of Regenerative Practices to sequester Carbon.

The greatest source of greenhouse gases that affect the environment is enteric fermentation in livestock, but there are solutions which hold promise (Ahmed et al., 2024). The adoption of feed supplements containing 3-nitrooxypropanol (3-NOP), seaweed products and other vegetable oils that have the potential of reducing methane by up to 80% having minimal to no impact on productivity (Lileikis et al., 2023). Meta-analyses prove the effectiveness of decreasing GHG without adversely affecting the health or milk production of animals. The suggested models are based on the interaction between the artificial intelligence and the additive performance using microbiome profiles targeting individual feed strategies resulting in the maximum inhibition of methane (Dwibedi et al., 2023). These interventions present cost-effective mitigation options to scale within the dairy systems in Asia and Africa by the smallholders (Jafri et al., 2024).

Lower tillage, composting, intercropping and rotational grazing approaches among others, which have been coined to be regenerative, enhance soil organic carbon and resilience (Qamar et al., 2024). An AI-powered program proved that cover cropping, compost-addition buffers soils against extreme weather, going to maintain soil organic carbon and prevent carbon outflows (Kayusi et al., 2025). The independent experiments that involved enhanced weathering (use of basalt dust) sequestered 15.4 ± 4.1 t CO_2 ha^{-1} and augmented returns of 12 to 16% in maize soy rotations during a four-year period (Beerling et al., 2024). That evidence backs up the possibility of the potential of regenerative models to sequester carbon and, optimally, increase yields. Such practices have also aided in the improvement of soil health, biodiversity, and resilience hence complying with climate adaptation, long-term sustainability of agriculture, and complete compatibility with mitigation strategies of CSA globally and throughout the many different agricultural landscapes (Kabato et al., 2025) (Fig. 1).

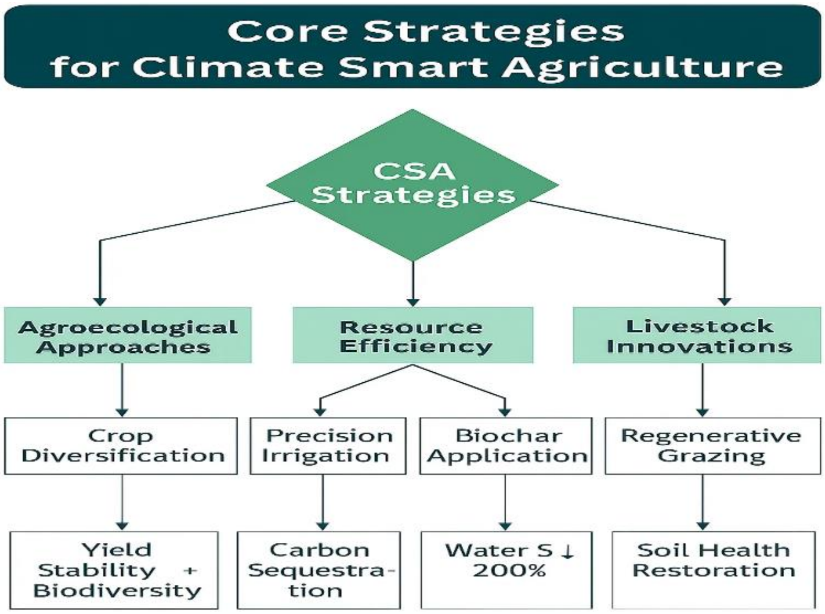

Fig. 1: Core Strategies for Climate Smart Agriculture.

3. Technological Innovations in Climate-Smart Agriculture

The pillar of effecting the change in traditional agricultural practices to ones, which are climate-smart and sustainable, is technological innovations (Okoronkwo et al., 2024). Until recently we have been producing food, organizing resources, and dealing with climate change in the same way as 30 years ago but modern tools are changing all these paradigms, including remote sensing tools, artificial intelligence (AI), gene editing technologies, and renewable energy solutions (Gryshova et al., 2024). Dwelling on these advanced technologies, basing on recent scholarly research, this section would show the current and future usefulness in realizing climate-resilient and sustainable agriculture (El Chami et al., 2020).

3.1 Remote Sensing and Precision Agriculture

Plot monitoring and management Remote sensing has changed significantly the manner in which farmers observe and direct their fields of land. Drones and UAVs (unmanned aerial vehicles) and satellite imagery supply high-definition real-time data which can aid in decision-making through farms (Martos et al., 2021). Remote sensing plays a central role in assessing crop health, moisture level on the soil, evapotranspiration, and disease outbreak (Wu et al., 2023). With the help of Geographic Information Systems (GIS) and remote sensing, monitoring of spatial variability can be precisely done in order to carry out site-specific interventions, a step that enhances the efficiency of inputs used and minimizes the damage caused to the environment (Fig. 2)(Surendran et al., 2024).

Advanced technologies that aid the monitoring of extreme weather patterns and its impacts on agriculture are remote sensing (Pande & Moharir, 2023). Governments and stakeholders can measure the level of drought conditions, flood areas, and the extent of heat stress and therefore act in time (Carvalho & Spataru, 2023). The improvement trend of sensors and resolution of imaging provide crops dynamics details. Additionally, remote sensing is used to assist in the estimation of carbon, both in soil and biomass to aid in quality accounting towards carbon trading or mitigation solutions (Han et al., 2024).

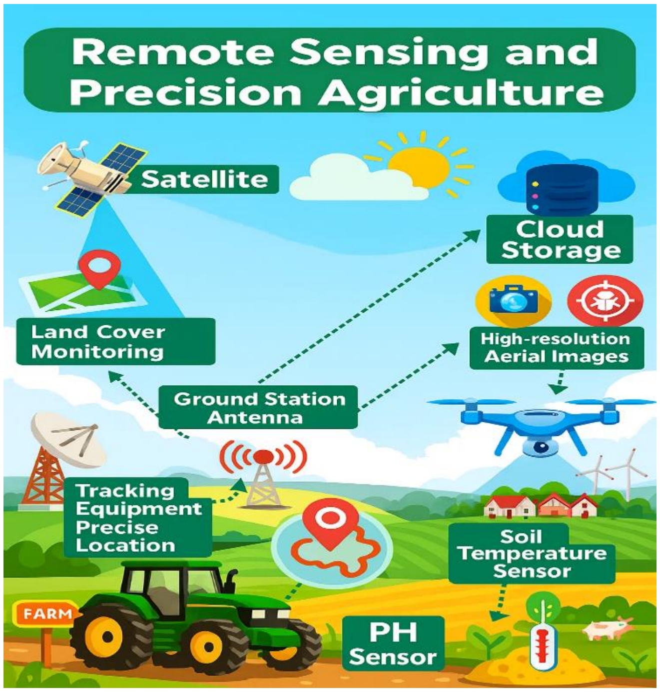

Fig. 2: Smart Climate Farming using Remote Sensing and Precision Farming Technologies.

3.2 Machine Learning and Big Data for Yield Prediction

Agricultural forecasting's are revolutionized by Machine Learning (ML) & big data analysis (Delfani et al., 2024). Anticipating yield outcomes through large-scale data integration metrics including weather, soil, market and genetic data, the ML models are able to provide remarkable accuracy (Van Klompenburg et al., 2020). A systematic review of the prediction of crop yield performed with the help of machine learning proved that the models based on Random Forests, Support Vector Machine, and Artificial Neural Networks are superior in their performance to more traditional statistical ones (Rashid et al., 2021). The advantages of the major are the advance warning system, the forecast of the market, the risk management (Sabir et al., 2024).

The technologies serve a central position in decision support systems as well. Predictive analytics allows the farmer to time the irrigation, addition of fertilizers and pesticides more precisely, decreasing wasteful use of resources (SS et al., 2024). Also, IoT sensor data captured in near-real-time in farm equipment or installations improves efficiency (Fuentes-Peñaillillo et al., 2024). Incorporating precision farming into mobile apps developed by AI based technologies using the needs of smallholders in developing countries brings a technology leveling element of precision farming (Van Klompenburg et al., 2020).

3.3 CRISPR and Genome Editing for Climate Resilience

The future of plant breeding is being transformed by the invention of more modern repercussions of tools of biotechnology including ones involving CRISPR-Cas9 and other uses of genome editing (Sun et al., 2024). In developing crops resistant to hot, drought, salinity and upcoming pathogens genome editing is useful (Ahmar et al., 2024). CRISPR shortens breeding cycles by a factor of 10, compared to the traditional methods: unlike traditional breeding, it allows specific rapid changes that cannot generate accumulated off-target effects over generations (Bhavanee et al., 2024).

Resilience of the gene-edited crops is evident and so is the lesser input dependency. As an example, photosynthetic efficiency and nitrogen absorbency of rice varieties have been improved by targeted changes in the genes (Chen et al., 2024). The stress-tolerant variants could be grown in a marginal environment, and this will deliver food security to the most climatically vulnerable areas (Singh et al., 2024). Also, CRISPR is being studied as a way to increase the microbe connections in soil promoting sequestration and recycling of carbon and nutrient cycling (Chauhan et al., 2024). Livestock improvement can also be looked into using CRISPR. Genetic engineering can produce disease-resistance breeds, optimized feed conversion ratios, and a climate resilient physiology that may cut methane emissions per unit produced of meat or milk. Nevertheless, the problem of regulations and social stigma will continue to be considerable factors hindering its use today (Sacarrão-Birrento et al., 2024).

3.4 Agrivoltaics: Integrating Solar Energy with Farming

Agrivoltaics, (also called agro-photovoltaics or dual-use solar), is the co-location of solar energy installations with agriculture (a means of using the same space to generate both food and electricity) (Trommsdorff et al., 2022). Using land as agricultural farm and photovoltaic panel agricultural agrivoltaics is also becoming increasingly important as a climate-smart remedy (Jamil & Pearce, 2025). Agrivoltaic systems have the potential to improve land-use efficiency, stabilize the microclimate, generate renewable energy, and be an efficient land-use combination. Each of these designs also elevates solar panels into crop canopies to reduce water losses and crop resistance to both ends of the temperature spectrum (Trommsdorff et al., 2023). Agrivoltaics improve the income diversification of the farmer. The unused electricity can be sold back to the grid, employed to drive irrigation pumps, or cold stores and this will aid in reduction of post-harvest losses (Cinderby et al., 2024). Studies demonstrate that shade-tolerant crops such as spinach, lettuce and strawberries grow well on an agrivoltaic framework with the least or no penalties in yield consequences (Hermelink et al., 2024). This innovation can be of great help in making agriculture viable especially in arid and semi-arid areas (Alharbi et al., 2024).

Also, citizens benefit from the fact that agrivoltaics stimulates circular economies. Having all these in a single infrastructure; that is battery storage systems, rainwater harvesting and smart irrigation, maximizes its benefits (Jamil & Pearce, 2025). Constant studies aim to maximize panel orientation, crop suitability, and socio-economic modeling that supports the uptake by the smallholder farmers (Zuma-Netshiukhwi et al., 2025).

3.5 Internet of Things (IoT) and Smart Farming

Agriculture IoT applications that would be possible include laying sensors, actuators, and the exchange of information platforms that implement a linked farming setting (Dhal et al., 2024). Such technologies can conduct real-time monitoring of moisture, soil temperature, humidity and nutrient levels, activity of pests (Shahab et al., 2025). Because they are driven by soil moisture sensors and weather forecasts, smart irrigation systems use much less water, at the same time ensuring the best crop growing conditions (Et-Taibi et al., 2024).

Sensor data can be simply incorporated in mobile apps or Cloud based dashboards with the help of smart farm management systems (Morchid et al., 2024). This will help reasonable decision making especially in areas that are not accessible. Efficiency is also increased by the implementation of connected and automated equipment, smart tractors, autonomous machines using GPS and IoT devices, which facilitate variable rates of seeds, fertilizers, and pesticides. (Jiang et al., 2025). IoT also plays an extremely significant role in the domain of traceability and food safety. At the farm all the way to the fork, produce can be marked by the blockchain-connected IoT system through the supply chain and create a better sense of transparency and trust among consumers and regulatory bodies (Uyar et al., 2025).

3.6 Vertical Farming and Controlled Environment Agriculture (CEA)

Vertical farming and CEA technologies are the agricultural technologies that make use of LED lighting, hydroponics, aeroponics, and climate control systems to undertake indoor production of crops in stacked layers (Roy et al., 2024). These systems are characterized by year-round production, lesser land area covered and little amount of pesticides (Liebhard et al., 2024). Vertical farming is also very suitable to operate in a city environment; it contributes to resolving food miles issues and enhancing food security of the area (Akintuyi, 2024).

Lighting systems using high technology cause dispersion of spectrum and intensity of lights against crop development stages, and therefore increases photosynthesis and input utilization to the extent of maximum (Charles et al., 2023). Such changes in environmental parameters as the CO_2 content, temperature, and humidity are carefully balanced with the help of AI algorithms, and they also produce constant yields and nutrient density. CEA is also involved in the growth of medicinal crops and high-value crops that have strict demands. Combination with renewable power and closed-loop nutrient systems means CEA is a circular farming model. Nevertheless, the cost of energy and upfront investment are the major concerns (Sasmal et al., 2024).

3.7 Drone Technology in Crop Management

The more common uses are as an aerial scout, to apply pesticides and plant seeds, and track livestock with drones. With such capabilities of covering numerous areas within a very short time and at high accuracy, they are essential in current farming activities (Nahiyoon et al., 2024). Multispectral and hyperspectral cameras located to drones identify stress, diseases and nutrient deprivation earlier than it can be visibly identified (Hafeez et al., 2023).

The use of drones in reforestation and soil rehabilitation helps, too; it has been observed that the shedding plant and fertilizer into broken or inaccessible regions is possible with the use of drones. They are becoming a center piece in disaster response in climate vulnerable areas; e.g. in gauging the damage of floods or locating relief (Mohan et al., 2021). Drones that use thermal imaging can scan livestock to help ensure that the animals are healthy and can also be tracked so that biosecurity and efficiency are enhanced in livestock farming (Cao, 2023). With the changing regulations concerning the use of drones, the use of drones in farm management will most probably grow, particularly when used along with AI and IoT (Nahiyoon et al., 2024).

3.8 Bioinformatics and Digital Breeding Platforms

Bioinformatics are used to sort through sequences of genomic, transcriptomic, and phenotypic information to decrease breeding frequencies and the choice of traits (Mu et al., 2022). Multi-omics information is merged with digital breeding environments to generate plant performance under the emerging changes in weather (Mahmood et al., 2022). The platforms involve simulation-based modelling and AI to determine the best parental combinations and stacking strategy of traits. Phenotyping is being transformed by the power of digital twins, or virtual crop models being used to model crop growth under a variety of conditions across the environment (Jeon et al., 2023). This saves time and resources as breeders could test thousands of genotypes, which is important as it does not require the timeconsuming field screening (Afzal et al., 2023). Participatory breeding Participatory breeding practices are also enabled within digital breeding, with farmers and scientists co-designing varieties with conditions tailored to their situation. This liberalizes innovation and makes it have higher adoption (Atasoy, 2025).

4. Socioeconomic & Policy Dimensions of Climate-Smart Agriculture

Climate-smart agriculture (CSA) is a holistic approach, combining productivity, building resilience and reducing greenhouse gas emissions-but potential is reduced by socioeconomic context, and significant variation in policy environments across farming systems and regions (Ma & Rahut, 2024). In this part, the multiple research that was published within the past five years is synthesized to examine how policy, financial tools, equity, and institutional frameworks affect the use of CSA practices and their scaling factors (Fig.3) (Makate, 2019).

4.1 Policy and Governance Strategies of Resilience

Adoption of CSA is based both on strategies of CSA adoption but also upon governance systems to back them up. Policy making approaches prohibiting on creation of resilient farming systems should be accommodating, adaptable and location specific (Teklu et al., 2023). In several nations, the best models proved to be the ones that involved decentralization of decision-making and local-level adjustments to interventions. Organizations as well as farmer cooperatives became new key institutions and expanded financial means, training, and negotiating in groups (Hellin et al., 2023). Moreover, those communities, which are involved in the making of such policies, bear higher adoption rates since policies seem to be pertinent and responsive to the life issues that they are facing. Such bottom-up system is in dramatic contrast with top-down one-size-fits-all programs that do not accommodate various agroecological and socio-cultural situations (Khoza et al., 2021).

4.2 Carbon Economics and Other Financial Incentives

Financially viable scaling of CSAs is based on well-established systems of incentives (Negra & Havemann, 2020). Recent studies have been conducted over carbon markets as a possible tool to bring the mitigation agendas of climate and the livelihood agendas together (Rakshit et al., 2025). Activities that put more carbon in the soil or less methane emissions by practicing better methods of livestock keeping can yield quantifiable credits (Bilotto et al., 2025). It may appear that winning on this tradeoff has been good on paper, however, some barriers to access have limited accessibility, mostly due to high cost of verification, difficulty of aggregating small holders land, and market consolidation, especially among marginalized farmers in developing nations (Okyere et al., 2025). When successfully operationalized, a carbon credit scheme will together with microfinance and climate-smart subsidies enable the prospect of a financial ecosystem to pay farmers to farm in a sustainable way at scale (Funke & Munyaradzi, 2025).

4.3 Barriers to Adoption and Strategies to Overcome Them

Even though CSA offers many opportunities, adoption varies between certain landscapes and farming systems. On the one hand, economic factors that limit adoption among smallholder farmers are invariable; they include prohibitive initial purchase costs and inability to access cheap credit (Finizola e Silva et al., 2024). Poor extension systems also further restrict access to responsive practices and reliable input which is often exacerbated by knowledge gaps (Thottadi & Singh, 2024). Horizontal governance between separate ministries of agriculture, climate, and energy becomes a fractured system of governance that leads to low policy coherence as well as the complications of implementing integrated CSA programming (Funke & Munyaradzi, 2025). There is also the issue of cultural resistance as well as lack of confidence in new practices which emerge mainly in traditional societies. Addressing these obstacles needs an in-built combination of capacity-building, financial inclusion, participatory planning and strong extension systems (Swanson et al., 2021). These gaps in the systems can be covered by cooperative models and climate responsive input packages as well as multi-stakeholder platforms (Antwi-Agyei et al., 2025).

4.4 Role of institutions: Extension and Partnerships

CSA delivery is institutional based. Digital advisory services, Participatory Farmer Field Schools (FFS), and climate literacy campaigns increase the awareness of the farmers and help to learn through peers (Osumba et al., 2021). Digital technologies such as e-advisory systems and mobile application make climate-smart information available to very distant communities, particularly when it is presented in local languages and pictures (Malik, 2023). Public private partnership is also another practice that has worked in making cost-savings and scaling technologies (Prutzer et al., 2023). In Kenya, they have been in a position to expand their access to drought resistant seeds and irrigation systems due to collaboration between financial institution, non-governmental organizations and the agriculture departments within the counties level (Waaswa et al., 2024). The rural infrastructure development such as roads, marketplaces, and storage facilities are also investments in order to make CSA translate into income resilience and climate-adaptive livelihoods (Acharyya, 2022).

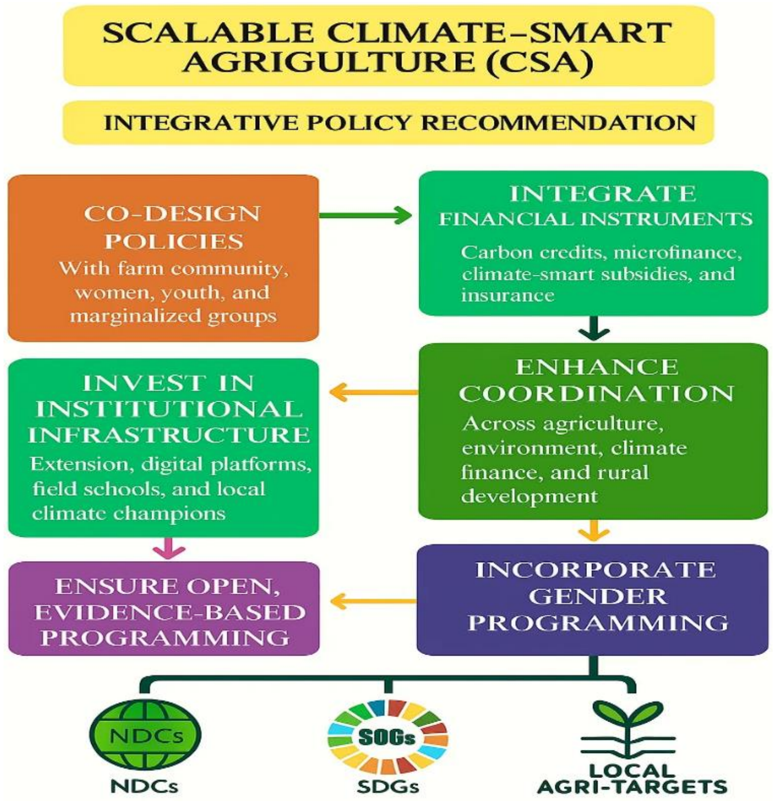

Fig. 3: Integrative Policy Recommendation for Up-Scale of Climate Smart Agriculture (CSA).

5. Case Studies in Climate-Smart Agriculture Implementation

Climate-Smart Agriculture (CSA) is applied and implemented differently in different locations and this depends on the priorities of nations, level of technological preparedness, the environment and policies on the ground (Hussain et al., 2021). A number of modern economies have embraced groundbreaking CSA strategies which have become guides in the world (Acharyya, 2022). Evidence in countries with selected CSA frameworks built-in to national agricultural policy and research programs, including country examples of how sustainable intensification, climate resiliency, and low-carbon development models can be scaled, is synthesized in this section (Davila et al., 2024).

5.1 China: Integrating Climate Resilience through Digital Agriculture and Aquaculture

China has soared its head leading the use of the digital technologies and the integrated farm systems to realize the CSA objectives (Wang et al., 2025). A case of a dual-adaptive and mitigative working system could be the rice-shrimp agricultural system Mekong Delta (Dang, 2020). The sequencing rice farming with shrimp farming at particular interval periods during the different seasons allows a farmer to increase his or her income resilience, save water utilization, and achieve a higher land time efficiency (Liao et al., 2024). This practice has become very common in southern China with subsidies and technical extension programs of the government. Furthermore, the IoT- and AI-driven monitoring and smart irrigation systems have been used to ensure minimal water losses and low emissions of methane taking place in the paddy fields(Liu & Liu, 2023).

It is added to the 14th Five-Year Plan in Agriculture of China, and there are good examples of using biochar, conservation tillage, and nitrogen-use efficiency amelioration (Wei et al., 2025). Real-time systems of soil diagnosis and pest prediction, which are data-driven, have enhanced input efficiency and reduced the emission of greenhouse gases. These initiatives correspond with the nationwide ecological civilization plan wherein there is a focus on the need to harmonize agricultural productivity with the need to safeguard the environment (Wen et al., 2025).

5.2 The Netherlands: High-Tech Greenhouse Systems and Circular Farming

The Netherlands, being one of the global leaders in controlled-environment farming, has made CSA operational based on greenhouse horticulture, precision farming and circular agriculture models (Abou Jaoude & Muñoz Sanz, 2025). Smart sensors, robotics and climate controlled greenhouse environments have helped the Dutch agriculture sector to realize one of the best input to output rations in the world especially in lawn fertilizers, water and nitrogen (Ahmed et al., 2024). Wageningen university and research (WUR) in collaboration with privately owned companies and cooperatives have created scalable CSA technologies like autonomous tractors, real-time crop health analysis drones, closed-loop nutrient systems that limit external chemicals (Poenaru et al., 2025).

One of the landmark projects is the so-called Farm of the Future, in which climate mitigation services are combined with the process of biodiversity and soil carbon monitored with geolocation devices (Reijneveld et al., 2024). They are CSA farms managed as living laboratories and subsidized by EU Common Agricultural Policy (CAP) subsidies that incentivize performance in ecological operations in reference to levels of production (Wojtynia et al., 2023). The export of Dutch CSA practices is growing because of the development cooperation programs and research platform internationally (Faling et al., 2018).

5.3 United States: Soil Carbon Markets and Regenerative Agriculture

In America, the concern towards CSA has been brought closer to climate policy particularly through the carbon markets schemes and sustainable agricultural practices (Tóth et al., 2025). In the recent past, the U.S. Department of Agriculture (USDA) has opened programs and more than 3 billion dollars funding under the Climate-Smart Commodities Initiative to test the connection between farmers to voluntary carbon markets and the compensation of some practice such as cover cropping, reduced tillage, and agroforest (O’Hara, 2024). Such activities however, do not only help to sequester carbon, but also increase water retention and nutrient cycling (Ali et al., 2025).

On the Midwestern corn belt, the private sector is developing systems such as Indigo Agriculture and Nori whereby soil carbon credits are quantified, verified and then monetized as a new revenue stream to farmers and are an environmental goal in terms of financial incentives (Sadiq et al., 2025). The key roles have been played by satellite imagery, remote sensing technologies, and AI-based yield model tools when it comes to accountability and traceability in these new CSA-based carbon markets (Del Rosario et al., 2021). Long-term trials to compare regenerative practices to conventional systems have also been used to develop science-policy interface at research institutes. These experiments detect the meaningful improvements in the input costs, biodiversity enhancement, and availability to resist climate change, especially in California and Arizona drought regions (Gosnell et al., 2020).

5.4 Australia: Drought-Resilient Systems and Climate Forecast Integration

CSA becomes a good example of how the movement operates over arid regions in Australia (Fleming et al., 2025). The nation has taken the advantage of superior decision-support tools in regards to climate modelling in helping farmers combat the rising number of severe and common droughts (Banerjee et al., 2024). In Australia, the Australian Grains Research and Development Corporation (GRDC) created risk-averse sowing strategies based on El Niño -Southern Oscillation (ENSO) forecasts in the states of Queensland and New South so that cereal growers could keep up with the weather anomalies, adjusting their planting times (Jakku et al., 2024). Additionally, Australia has engaged in climate-resistant crop breeding, making developed seed wheat which is drought and heat tolerant as the result of the partnership between the governments and the private sector. More advanced practices are very common, such as precision agriculture (GPS-guided machinery and automated irrigation, nutrient application that is variable-rate), which helps in minimizing cover greenhouse gases as well as in increasing resource-use efficiency (Darnell et al., 2018).

Australian Government runs the Future Drought Fund that funds innovation in CSA by providing grants to on-farm innovations, farmer field schools, and regional climate hub. Through these institutions, climate science integrated into local knowledge is achieved by maintaining CSA implementation that is scientifically and socially acceptable to the surrounding people (Fielke et al., 2025).

6. Challenges and Gaps

Although some improvements have been witnessed in integrating Climate-Smart Agriculture (CSA) into different agroecological zones, many structural, technology, institutional, and sociopolitical barriers have hampered mainstreaming of CSA and effectiveness of this farming practice on a larger scale (Kabato et al., 2025). Such restrictions also demonstrate that an adaptive, inclusive and interdisciplinary method is urgently required that not only goes beyond technological quick fix but also takes into account greater policy, ethical and situational considerations (Fig. 4)(Lescrauwaet et al., 2022).

6.1 Regulatory and Institutional Bottlenecks

The existence of strict, sometimes archaic regulatory systems is one of the most actively discussed obstacles on the path of implementation of innovative climate-smart technologies, especially gene-edited crops (Qaim, 2020). A critical reflection on the current status of global regulation about gene edited crops has given emphasis on how such trends have blocked the level of technological commitment especially in developing economies (Turnbull et al., 2021). Where a legislature, such as the European Union, classifies gene-edited crops the same as more traditional GMOs, the crops must undergo lengthy and expensive regulatory procedures that give people little incentive to innovate publicly or invest privately (Caradus, 2023). This limits the use of potentially transformative technologies like

CRISPR/Cas9 to produce drought resistant or nitrogen efficient crops needed to achieve climate resilience, and to sustainability (Mahto & Mahato, 2025).

In addition, although several countries (such as United States, Brazil, and Argentina) have simplified regulatory systems underpinning the distinction between gene-editing and transgenic modification, others (in Africa and Asia) are left stranded as they have not revised their biosafety provisions. Such legal ambiguity is not only a factor that slows the uptake but also creates a general anxiety in the populations that further complicates the deployment of CSA technologies which are so vital to the food security in a world that is changing due to its changing climatic regime (Akinbo et al., 2025).

6.2 Techno-Solutionism and the Politics of CSA

Although CSA has become a popular scientific and policy platform, conceptual and operationalization issues remain with it (Sætra & Selinger, 2024). There has been a discussion of CSA, which is techno-solutionist in nature, a reliance on using a lot of technological solutions without due consideration to social, economic, and political issues that can cause agricultural vulnerability (Yadav & Lachney, 2023). To give an example, the implementation of certain interventions which include use of climate-resilient seeds, precision agriculture, or carbon market could typically be implemented in a top-down approach and neglect to consider the local knowledge systems, as well as the systemic challenges like insecurity of land tenure, access to credit, or gender inequality (Khoza et al., 2021).

This narrow-minded attitude towards techno-fix will effectively displace the role of smallholder farmers, especially women and indigenous populations where their vision of efficiency or resilience does not align with their realities (Celermajer et al., 2024). The very approach of CSA that has been practiced could pose a threat of furthering inequity rather than abolishing it, as it has elicited elite-dominated discourses on development, which presupposes hesitation in societies to be led democratically as well as prioritizes quantitative or measurable outcomes whether in raising yield or achieving emission reductions (Ngigi & Muange, 2022). It suggests that there is an immediate need to include the participatory CSA strategies that are developed in collaboration with local actors and that are integrated into wider interests in some rural developmental processes (Funke & Munyaradzi, 2025).

6.3 Socioeconomic Disparities and Access to Innovations

CSA interventions are also known to be resource-demanding thus adopting them is a difficult task among marginalized or low-resource farmers (Hanson et al., 2024). Technologically correct solutions include digital climate-modeling devices, smart phone agronomic advisors, or automated planting implements but because they are too costly, many of the smallholders in sub-Saharan Africa or South Asia may never realize the benefits (Aryal et al., 2020). Gender, class and ethnicity also determine who has access, or is excluded to use such innovations and who actually enjoys or suffers the outcome (Marion et al., 2024). This technological and digital divide is further coupled by the systemic lack of infrastructure, institutional and extension services and complication due to rural areas which has made the process of inclusive development paralyzed (Omweri, 2024).

Also there are blind spots in climate related finance and carbon market that has high transaction cost, it lacks transparency, and poor access to small-scale players (Chausson et al., 2023). Current carbon market systems are seldom fit to meet the needs of the agricultural industry and frequently excluded the contributions of smallholders to climate mitigation. This compromises the value of fairness in the process of climate governance and it requires the re-engineering of climate finance tools that are people accessible, culturally sensitive and transparent in their management processes (Bhattacharya et al., 2024).

6.4 Climate Variability and Uncertainty

CSA also has to grapple with the fact that climate change will be unpredictable in nature (Ahmad et al., 2024). Emerging new types of extreme events such as co-occurring drought and heatwaves (compound extremes) or new pressures of diseases are demanding a re-consideration of the effectiveness of well-established adaptation strategies (Niggli et al., 2022). These changes are many times not well absorbed or responded to by the farming systems due to the adaption capacity present within the systems leading to lack of preparation in advance and low institutional adaptation ability (Funke & Munyaradzi, 2025). Even the best of CSA programs can fail under this type of complex and cascading stressors. Such uncertainties explain why more complex climate models and early warning systems are needed, as are flexible governance arrangements that can be adapted to what is learned on the ground (Attoh & Amarnath, 2025). Above all, it requires a change of mindset-the previous attempts to mitigate climate effects with unchanging interventions must change into the development of the systemic resilience created based on diversity, decentralization, and learning (Martin et al., 2018).

6.5 Political Economy and Power Dynamics

The phenomenon of Climate-Smart Agriculture cannot have its own sustainability ethos without being subject to global political economy (Newell & Taylor, 2018). The heavily hitting agribusiness players are having greater influence over the language of CSA, controlling research agendas as well as financial resources. The problem here is that it commercializes CSA and is likely to change it from being about market justice in economic, in ecological terms to market growth (Funke & Munyaradzi, 2025). The importance of investigating not only the agenda setter in CSA, beneficiaries of its processes, or who is made invisible by the very process of it. In addition, CSA frameworks because of the rights-based perspective, the rights of farmers to their seeds, the rights to land, or the rights to labor are not always given much focus on (Paprocki & McCarthy, 2024).

6.6 Emerging Global Risks

Lastly, CSA is being conducted against a backdrop of growing systemic risks on a global scale and the issue of climate vulnerability which interplays in critical ways with these other sources of systemic instability, such as geopolitical instability, pandemics, and supply chain interruptions (Hoffart et al., 2024). As an example, the delays in the supply chains of fertilizer that occurred with COVID-19 pandemic and the Ukraine crisis have worsened food insecurity and limited the adoption of CSA practices that require external input (Karume et al., 2024). Such events of global shocks prove the necessity of food system sovereignty and why it is vital to incorporate CSA into more comprehensive systems of circular economy, agroecology, and local food governance (Yıldırım et al., 2024).

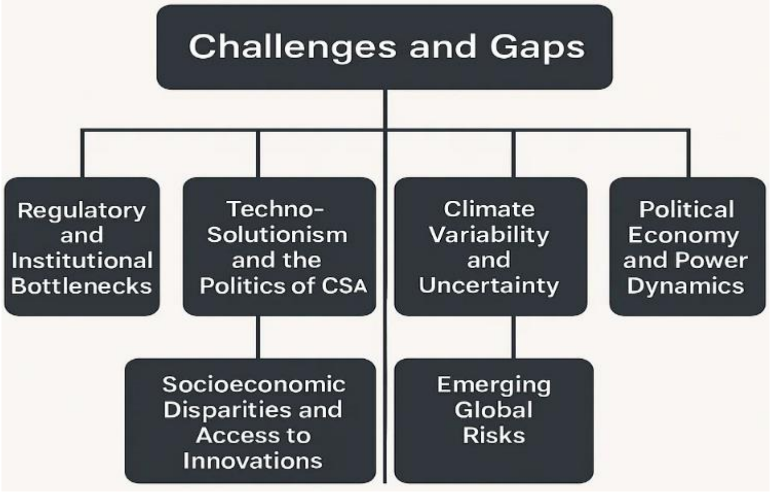

Fig. 4: Key Challenges and Gaps in Advancing Climate-Smart Agriculture (CSA).

7. Future Directions

7.1 Technological Innovations Driving the Future of Climate-Smart Agriculture

The fast-growing climate-smart agriculture (CSA) does not only exist along with the demand to respond to the change of climate by means of mitigation and adaptability but also develops with the support of technical advances, socioeconomic transformations, and global politics. Future CSA would need to incorporate interdisciplinary innovations so as to make the agricultural systems productive, fair, and capable of sustaining the growing climatic uncertainties. Forward-looking measures therefore need to include alternative protein systems, digital tools such as blockchain, and policy innovations that boost resilience and limit emissions.

Protein production systems change is one of the major avenues towards the future of CSA. Although traditional livestock rearing is a life sustaining and important source of food in the world, it is also the leading cause of greenhouse gas (GHG) emission, land and water pollution. More recent groundbreaking studies have pointed to the need to widely switch to alternative proteins, such as plant-based proteins, cultured meat and insect-based food as potentially being a game-changing environmental improvement to the global food system, not only because it is likely to yield more favorable nutritional consequences, but also due to its resiliency. Common investments driven by the citizens and companies in the pursuit of sustainable protein systems are growing, and so are consumer concerns about health and ecological problems. Such a shift will, however, necessitate new regulatory systems developed, training of consumers, and the reorganization of supply chains to adapt to emerging technologies of production.

Digital agriculture as well, especially through blockchain technology, is also the development of a paradigm shift in climate-smart agri-food systems. With a possible outcome to induce transparency, traceability, and efficiencies in the agricultural chain, blockchain technology can become one of the primary factors of climate adaptation and mitigation. Through blockchain, data collection would become real time, and immutable, decreasing fraud and carbon accounting would be less inaccurate. Such is a very important issue when applied to the scenario of carbon markets where they need to have stability in information as credit certification and trading. Furthermore, smallholder farmers can be empowered through blockchain technologies that will enhance market and credit access and access to climate advisory services. However, to achieve this potential, well-coordinated investment is going to be required in the digital infrastructure, work force training in farmers, and international harmonization of standards.

Machine learning (ML) and artificial intelligence (AI) will likely be greatly involved and helpful in upgrading CSA. Such technologies make it possible to predict weather with precision, give warning on pest and disease attacks, and support resource-efficient activities. Using big data, AI tools could provide real-time advice on irrigation, the application of fertilizers, and crop rotation, which could result in environmentally friendlier and higher productivity. The recent literature shows how the AI-enabled smart farming platforms can help to ensure greater yield stability despite variable climatic environment (e.g., Huang et al., 2022 and Singh et al, 2023). Also, the new AI powered crop phenotyping systems can help shorten the time through breeding programs and, in doing so, come up with more climate resilient varieties quicker than ever before has been possible with traditional approaches.

7.2 Inclusive and Circular Approaches for Systemic Transformation

The further infiltration of the elements of a circular economy is another key trend in the future of CSA. There is a need to do more on nutrient loop closure, reducing waste, and the utilization of organic imports towards climate-smart farming. The use of agroecological practices, compost and bio-based fertilizers will be put at the center stage of improving soil health, soil biodiversity, and ecological services. Next generation CSA systems are likely to go beyond field-scale to the landscape and regional scale, and apply integrated farming systems, to ensure efficient use of resources whilst maximizing ecological resilience, such as agroforestry, aquaponics and mixed crop-livestock systems.

Besides, youth and gender equity should be further emphasized in the future regarding CSA. Youth and women are still a minority in the agricultural innovation and policies process despite developing nations taking a leading position in agricultural innovation. The construction of inclusive CSA systems will necessitate interventions and demand gendered extension services, youth entrepreneurship programs and the popularization of digital tools that can be used by marginalized groups. Enhancing the empowerment of these groups is not only a question of justice but a springboard of a transformational change since they possess some knowledge, views, and adaptive capacities that are unique.

7.3 Advancing Gene Editing and Regenerative Practices for Climate Resilience

Gene-editing technologies such as CRISPR as well have many potentials in climate-resilient crop development. These methods enable us to make precise changes to the genomes of plants to improve other features like drought toleration, pest status and nutrient utilization. Nonetheless, regulation, ethics and attitudes are critical issues. Gene editing could reduce agriculture susceptibility to climate stresses to a great level, but international harmonization of biosafety policies and more effective stakeholder engagement is irreplaceable in bringing out these improvements.

The other aspect that is progressive is that regenerative agricultural practices such as conservation tillage, cover cropping and pasture cropping are used to increase soil organic matter and carbon sequestration. The practices not only assist goals around mitigation but also in the long-term survival and profitability. Regenerative agriculture potentially plays a critical role in the reversal of land degradation and increase in carbon stocks assuming performance-based incentives and payments on ecosystem services.

7.4 Governance, Finance, and Monitoring for Scalable CSA

Future development of CSA will also be characterized by policy alignment and international cooperation. Food systems are becoming a central issue in global climate negotiations, including COP processes, in national adaptation plans and nationally determined contributions (NDCs). The Global Climate Action (CSA) and related climate commitments (like the Paris Climate Agreement, Sustainable Development Goals (SDGs), and Kunming-Montreal Global Biodiversity Framework must be aligned with international frameworks. Another potential topic of future direction is opening of climate resilient seed systems that will be secured through the framework of equitable access and benefit- sharing. That is particularly the case against the backdrop of geopolitical risks, global biodiversity decline, and the emergence of new pests and diseases.

Wise investment strategies toward climate will be valuable in the next few years. The blending (de-risking) of government funding with the funding of the private sector is also catching on to CSA-related projects. Such institutions as the Green Climate Fund (GCF) and the World Bank are becoming more supportive of CSA activities based on these mechanisms. The second initiative in CSA finance should deal with the inclusion of smallholders, climate insurance and mobilization of local financial service provision. Quick mapping tools and weather indexed insurance need to be scaled up to safeguard vulnerable farmers against extreme weather events. Finally, effective sound monitoring, evaluation and learning (MEL) systems should offer guidance concerning CSA research and implementation in the future. The ability to track CSA indicators in real-time, including GHG emissions, the adaptive capacity, livelihood outcomes, would allow feedback to be used in policy finetuning and increase accountability. New technologies of remote sensing, satellite images, and survey instruments based on the mobile phone that have aimed to make this monitoring cheaper and more accessible. Context-sensitive and farmer-friendly MEL systems co-designed with farmers, extension agents and researchers mean that tools are relevant to the farmer and provide support to facilitate their use.

8. Conclusion

Climate Smart Agriculture is an emerging area where there has been a lot of progress over the past few years based on the international climate crisis and the increasing awareness of climate change, food security, and agriculture impacts. Agroecological innovations and high technologies have both played the role of strengthening the farming systems against rising climate risks. Diversified cropping, agroforestry and conservation tilling are among examples that have proved to increase soil health, biodiversity and climate resilience. In the interim, precision farming techniques and carbon savvy animal production have already started reducing the gap between productivity increase and decreased emissions.

Besides this development, there are several obstinate issues. Such advanced technologies as gene editing, precision sensors, and agrivoltaics need favorable regulatory environments, investment in capacity-building, and infrastructure, especially among smallholders. It is essential that equity in access to digital tools and climate finance be given priority so as not to worsen the inequalities already present in the rural communities. Inclusive governance, gender-responsiveness of programs and meaningful involvement of farmers in decision-making processes and monitoring processes are also key to the success of CSA. Policy contexts that make carbon markets and climate-smart subsidies easier to carry out have buoyed adoption in certain settings, but not all regions are institutionally prepared to expand these practices. The practice in the real world has shown that successful real-world implementation in countries like China, the Netherlands, Australia, and certain African countries, require coordination of research institutes, public agencies, and society of farmers.

Looking into the future, trend possibilities, which include using sustainable protein technology, supply chain visibility using blockchain, advising systems based on AI, and soil carbon tracking are other areas of CSA transformation to utilize in the future. To have an impact on a scale, such innovations need to be co-created with farmers, be integrated into national agricultural strategies, and (re)designed along global frameworks such as the UN Paris Agreement and the Sustainable Development Goals. Finally, the move to climate smart and sustainable agriculture rests on the gap between technology and social inclusiveness, good policy consistency and environmental restoration. The way ahead is in synergies, dynamic systems that appeal to inventions in the context of area needs and environment stewardship. Through the adoption of this diverse strategy, agricultural systems can only continue to thrive more sustainably in an ever-concerned uncertain future climate.

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