



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(3): 164-167
Received: 13-12-2025
Accepted: 19-01-2026

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Climate-smart agriculture: Strategies for climate resilience and reduction of greenhouse gas emissions

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i3c.5009>

Abstract

Agriculture accounts for nearly 24% of global anthropogenic greenhouse gas (GHG) emissions and is highly susceptible to the adverse impacts of climate change, including rising temperatures, erratic rainfall patterns, and extreme weather events that threaten global food security, particularly in tropical and subtropical smallholder farming systems. To address these challenges, Climate-Smart Agriculture (CSA) has emerged as an integrated approach aimed at simultaneously enhancing agricultural productivity and farmers' incomes in a sustainable manner, strengthening adaptation and resilience to climate variability, and reducing greenhouse gas emissions wherever feasible.

Several management practices have been identified as key CSA strategies. These include alternate wetting and drying (AWD) in rice cultivation, which can reduce methane (CH₄) emissions by 30-45% and lower net global warming potential (GWP) by 20-40% when combined with proper nitrogen management. Other important practices involve zero tillage and conservation agriculture to enhance soil carbon sequestration, agroforestry systems to improve ecosystem resilience and carbon storage, and enhanced nitrogen use efficiency through 4R nutrient stewardship and nitrification inhibitors. Additionally, precision irrigation techniques, direct-seeded rice cultivation, and digital agricultural technologies such as ICT-based advisories, remote sensing, and artificial intelligence contribute to improving resource-use efficiency and climate resilience.

Evidence suggests that integrated CSA packages often perform better than individual practices by minimizing trade-offs, such as increased nitrous oxide (N₂O) emissions, while maximizing co-benefits related to yield stability, resource efficiency, and farmer livelihoods. In rice-wheat production systems, the adoption of CSA practices can lead to 20-35% water savings and improved farm profitability. However, widespread adoption remains limited due to several constraints, including small landholdings, financial limitations, institutional barriers, knowledge gaps, and challenges in monitoring, reporting, and verification (MRV). Therefore, effective scaling of CSA requires context-specific strategies, farmer-centric extension services, robust monitoring systems, and alignment with global frameworks such as the Paris Agreement's Nationally Determined Contributions (NDCs) and the Sustainable Development Goals (SDGs 2 and 13). While CSA provides a scientifically robust pathway toward resilient and low-emission agricultural systems, further research is necessary to address issues related to policy incentives, equity, and synergistic implementation.

Keywords: Climate-smart agriculture, greenhouse gas emissions, nitrogen use efficiency, rice-wheat cropping system, climate change adaptation

1. Introduction

The environment supporting agricultural production is being rapidly changed by global climate change, exposing crops, livestock, and fisheries to increased mean temperatures, changed seasonality, and more frequent extremes like heatwaves, droughts, and heavy rainfall events that interfere with phenology, water supply, and pest-disease dynamics (Sakashita *et al.*, 2017; Zhao *et al.*, 2023) [56, 83]. In many areas, especially in the tropics and subtropics where smallholder systems are prevalent, observational research and model syntheses attribute these changes to yield declines and increasing interannual variability for basic cereals (Li *et al.*, 2025; Nelson *et al.*, 2018) [35, 46]. Moreover, agricultural systems play a significant role in the budget for

anthropogenic greenhouse gases (GHGs) due to emissions from enteric fermentation, land-use change (deforestation/peatland conversion), methane from paddy rice, and nitrous oxide from fertilizer and manure management (Adlan *et al.*, 2025; Menegat *et al.*, 2022) [1, 39]. According to recent global syntheses, a significant portion of anthropogenic emissions is attributed to land-related and food-system activities (estimates vary depending on accounting options), highlighting agriculture's dual position as a vital sector for mitigation and a sufferer of climate consequences (Adlan *et al.*, 2025; Li *et al.*, 2025) [1, 35]. This dual nature served as the impetus for the creation of the Climate-Smart Agriculture (CSA) concept, which was presented and expanded upon in FAO and partner guidelines as an integrative framework aimed at (i) increasing productivity and incomes in a sustainable manner, (ii) adapting to and strengthening resilience to climate change, and (iii) reducing and/or eliminating greenhouse gas emissions where practical. The three goals of CSA are primarily accomplished through contextually relevant packages that combine nature-based techniques, enhanced management, and digital/precision technology. CSA is offered as a framework for decision-making rather than a set list of behaviors (Xuan *et al.*, 2025) [77]. Agroforestry and diverse rotations for resilience and carbon sequestration are two examples of CSA-aligned treatments that are documented in empirical and review research (Quandt *et al.*, 2023; Muthuri *et al.*, 2023) [53, 42]. In order to lower N_2O and increase nitrogen usage efficiency, nutrient management, nitrification inhibitors, and deep N placement are employed (Hassan *et al.*, 2022; Hu *et al.*, 2014) [25, 28]. Rice CH_4 can be

reduced while yields are maintained by using water-saving irrigation and alternating wetting-and-drying (AWD) (Chen *et al.*, 2024; Carrijo *et al.*, 2017) [15, 12]. There are still significant implementation and knowledge gaps despite encouraging case studies. First, many initiatives have trade-offs: unless well planned and managed, productivity-boosting methods may occasionally result in short-term emissions increases (or vice versa) (Adlan *et al.*, 2025; Howe *et al.*, 2014) [1, 27]. Second, the wide and equitable scaling of CSA alternatives across locations and farm sizes is limited by socioeconomic restrictions (land tenure, labor, and finance), biophysical condition variation, and institutional capability (Xuan *et al.*, 2025; Sanyaolu *et al.*, 2024) [77, 57]. Third, comprehensive cross-site comparisons and policy-level accounting are made more difficult by the ongoing development of standardized, harmonized measurements and scalable monitoring techniques for CSA outcomes (productivity, resilience, and GHGs) (Zhao *et al.*, 2023; Li *et al.*, 2025) [83, 35]. Integrated research agendas that incorporate field trials, long-term monitoring, up-scaled modeling, socioeconomic studies of adoption routes, and policy tools to align farmer incentives are necessary to close these gaps (Xuan *et al.*, 2025; Sanyaolu *et al.*, 2024; Bodirsky *et al.*, 2025) [77, 57, 9]. To put it briefly, CSA is a practical way to balance productivity, adaptation, and mitigation objectives, according to scientific evidence. However, in order to fully realize its potential at scale, better outcome measurement, context-sensitive intervention packages, and policies that specifically manage trade-offs and distributional impacts are required.

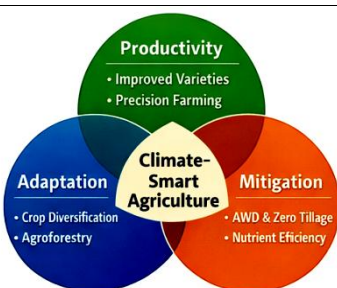


Figure 1. Conceptual framework of Climate-Smart Agriculture.

Figure 3. Methane Emissions in Rice Fields

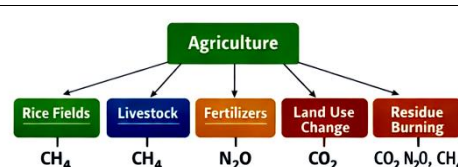
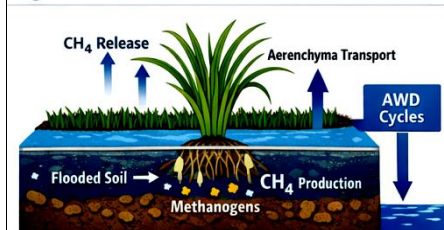
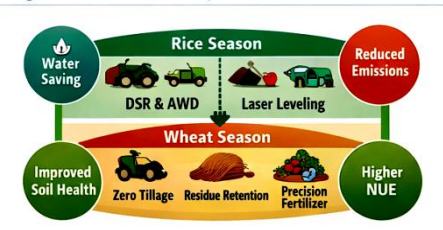


Figure 2. Agricultural greenhouse gas emission pathways.

Figure 4. CSA in rice-wheat system



2. Climate Change and Agricultural Emissions

2.1 Sources of Greenhouse Gas Emissions in Agriculture Methane (CH_4) from Rice Fields and Livestock

Microbial methanogenesis is the process that produces methane in anaerobic environments. In agriculture, enteric fermentation in ruminant animals and flooded rice paddies are the two main sources. Rice systems that are flooded produce oxygen-limited soil conditions that encourage the activity of methanogenic archaea. After anaerobic breakdown of organic substrates made from crop leftovers, root exudates, and soil organic matter, CH_4 is released by ebullition, diffusion, or plant aerenchyma tissues. Water management techniques have a significant impact on CH_4 emissions, according to global meta-analyses. The greatest emissions are caused by continuous flooding, but Alternate

Wetting and Drying (AWD) can cut methane by 30-70% without significantly reducing yield, while any increases in N_2O need to be closely watched (Linguist *et al.*, 2015; Runkle *et al.*, 2019) [38, 55]. The main source of livestock methane is enteric fermentation in ruminants including buffalo, sheep, and cattle. Carbon dioxide and hydrogen are broken down during digestion by methanogens in the rumen. Between 30 and 40% of the world's anthropogenic CH_4 emissions come from livestock. Improved forage quality, feed additives like 3-NOP, dietary lipid supplementation, and genetic selection for feed efficiency are examples of mitigation techniques (Speelman *et al.*, 2014; Xia *et al.*, 2023) [61, 76].

Nitrous Oxide (N_2O) from Nitrogen Fertilizers

In agricultural soils, nitrogen fertilizer application is followed by

nitrification and denitrification processes, which are the main sources of nitrous oxide. Its potential to cause global warming over a 100-year period is around 273 times greater than that of CO₂. Temperature, compaction, soil moisture, and nitrogen application rates all raise N₂O emissions (Butterbach-Bahl *et al.*, 2013)^[11]. When nitrogen intake surpasses crop demand, N₂O emissions rise nonlinearly, according to a worldwide meta-analysis by Hu *et al.*, (2014)^[28]. While preserving production, enhanced-efficiency fertilizers, nitrification inhibitors (such as DCD and DMPP), precise nutrient distribution, and better timing greatly lower emission intensity (AKIYAMA *et al.*, 2010; Bai *et al.*, 2015)^[3, 8].

Carbon Dioxide (CO₂) from Land-Use Change and Residue Burning: The primary causes of carbon dioxide emissions in

agriculture are biomass burning, soil carbon loss, and changes in land use. Carbon stored in forests, peatlands, and grasslands is released into the atmosphere in significant amounts when they are converted to farmland. CO₂ emissions are still mostly caused by tropical deforestation for agricultural growth (Pendrill *et al.*, 2019)^[49]. CO₂ emissions are also influenced by the carbon depletion of the soil caused by extensive tillage. Reduced tillage and conservation agriculture have shown promise in improving soil carbon sequestration (Lal *et al.*, 2015)^[34]. Another major source of CO₂ is the open burning of agricultural leftovers, especially in South Asia. In addition to CO₂, residue burning releases CH₄, N₂O, and black carbon, which deteriorates air quality and causes regional climate forcing (Munthali *et al.*, 2019)^[41].

Table 1: Major Greenhouse Gas Sources in Agriculture, Mechanisms and Key References

GHG (Greenhouse Gases)	Major Agricultural Source	Emission Mechanism	Approx. Contribution / Significance	Key Mitigation Approaches	References
Methane (CH ₄)	Flooded rice paddies	Methanogenic archaea break down organic materials anaerobically in wet environments; CH ₄ is carried by the aerenchyma.	An estimated 8% to 12% of the world's anthropogenic CH ₄ emissions come from rice production.	Alternate Wetting & Drying (AWD), charcoal addition, sulfate additions, and mid-season drainage.	Sauniois <i>et al.</i> , 2020 ^[58]
Methane (CH ₄)	Enteric fermentation in ruminants.	Methanogens transform the hydrogen produced by microbial fermentation in the rumen into methane.	Approximately 30-40% of anthropogenic CH ₄ is caused by livestock.	Genetic selection, enhanced food quality, and feed additives (3-NOP, seaweed).	Carrillo <i>et al.</i> , 2021 ^[13]
Nitrous Oxide (N ₂ O)	Synthetic nitrogen fertilizers	After applying N to soils, nitrification and denitrification occur.	Approximately 60% of the world's N ₂ O emissions come from agriculture.	Slow-release fertilizers, nitrification inhibitors, and 4R nutrient management	Tian <i>et al.</i> , 2020 ^[64]
Nitrous Oxide (N ₂ O)	Manure management & livestock excreta	Microbial conversion of nitrate and ammonium in soils and manure.	swiftly growing source as a result of increased livestock production.	Anaerobic digestion, covered storage, and manure composting.	Bach <i>et al.</i> , 2010 ^[7]
Carbon Dioxide (CO ₂)	Land-use change (deforestation for agriculture)	After land removal, oxidation of soil organic carbon and biomass carbon.	The primary cause of AFOLU emissions worldwide.	Agroforestry, sustainable intensification, and deforestation were avoided.	Griscom <i>et al.</i> , 2017 ^[23]
Carbon Dioxide (CO ₂)	Soil carbon loss from intensive tillage	Increased oxidation of soil organic carbon by microbes.	Depletion of SOC over time causes an increase in atmospheric CO ₂ .	Cover crops and conservation tillage.	Peters <i>et al.</i> , 2015 ^[50]
Carbon Dioxide (CO ₂)	Crop residue burning	When biomass is burned, CO ₂ and other transient climatic pollutants are released.	High levels of seasonal emissions in East and South Asia.	mulching, bioenergy utilization, and residue incorporation	Clougherty <i>et al.</i> , 2009 ^[16]

3. Pillars of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) refers to integrated methods that promote resilience, mitigation, and productivity all at the same time. The sustainable growth in productivity, which includes actions that boost agricultural production while enhancing ability to deal with climate change, is one of its main foundations.

3.1 Sustainable Increase in Productivity

In order to supply the growing demand for food under climate change without increasing agricultural acreage or harming ecosystems, sustainable productivity increase in agriculture is crucial. Innovations that increase yields, enhance resource efficiency, and fortify resistance to climatic stresses are encouraged by CSA.

Improved Stress-Tolerant Varieties

The development and implementation of climate-resilient crop varieties is a fundamental approach to increasing production in the face of climate change. Stress-tolerant cultivars are created to survive more frequent challenges brought on by global warming, such as heat, salinity, drought, and submergence. For instance, compared to standard varieties, drought-tolerant maize and submergence-tolerant rice have shown yield stability under harsh circumstances (Tester *et al.*, 2010; Raymond *et al.*, 2021)^[63, 54]. For example, The International Rice Research Institute (IRRI) has created climate-resilient rice cultivars such as DRR Dhan 42 (drought resistant) and Sub1 (submergence tolerant),

which lower the risk of crop failure in regions that are prone to drought and flooding, respectively (Emerick *et al.*, 2019)^[18].

Integrated Nutrient Management (INM)

In order to improve soil fertility, crop output, and nutrient usage efficiency while reducing environmental losses, Integrated Nutrient Management (INM) maximizes the utilization of both organic and inorganic fertilizer sources. INM enhances soil organic matter, helps maintain balanced soil nutrients, and lessens reliance on high concentrations of synthetic fertilizers, which, if overused, can increase nitrous oxide emissions (Awad *et al.*, 2023)^[6].

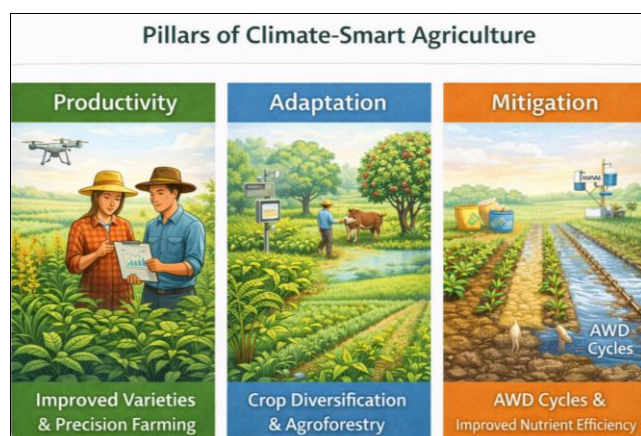
Integrated Pest Management (IPM)

By using a combination of chemical, biological, mechanical, and cultural methods to control insect populations below levels of economic harm, integrated pest management, or IPM, lessens the need for chemical pesticides. In addition to lowering input costs and adverse environmental externalities like pesticide runoff and pollinator damage, IPM improves crop health. According to several systematic reviews, cropping systems that use IPM have higher yield stability and biodiversity (Hardman *et al.*, 2016)^[24].

Precision Farming

Precision farming maximizes field-scale management by utilizing cutting-edge technology including GPS, remote sensing, drones, sensors, variable rate application, and decision

support systems. Precision techniques reduce waste and emissions while increasing productivity and resource usage efficiency by matching inputs (pesticides, fertilizer, and water) with crop demands at high spatial resolution. Precision methods, especially in irrigated areas, have been shown to dramatically boost yields while consuming less water and fertilizer (Gebbers *et al.*, 2010; Zhang *et al.*, 2012)^[21, 80].



3.2 Adaptation Strategies for Climate Resilience

A portfolio of complementary adaptation techniques that lessen susceptibility to fluctuating rainfall, heat stress, and catastrophic events while preserving or raising productivity is necessary to build climate resilience in farming systems. Despite their empirical backing and widespread promotion under Climate-Smart Agriculture, the following techniques have implementation challenges and knowledge gaps that need to be filled for widespread, equitable adoption.

Crop diversification

Crop diversification lowers risk by distributing yield variability among crops with varying sensitivity to climate stress. This is achieved through the intentional expansion of species, varieties, and cropping sequences in time and space (rotations, intercropping, relay cropping, and integrating pulses/horticulture with cereals). Diversification can increase soil fertility through legume rotations, prevent pest/disease build-up, and buffer yields against excessive rainfall and temperature shocks, according to empirical research employing panel and experimental data (Hufnagel *et al.*, 2020; Feng *et al.*, 2019)^[29, 20]. The remaining gaps include calculating the trade-offs between market access and diversification (income risk), creating portfolios for diversification tailored to particular agroecologies, and scaling diversification in areas with labor shortages and land fragmentation (Vernooy *et al.*, 2022)^[70].

Agroforestry systems

Agroforestry, or the integration of trees with crops and/or livestock, improves soil moisture retention, boosts carbon stocks, diversifies farm revenue, and improves microclimate buffering. Benefits for soil fertility, erosion prevention, and drought buffering are consistently reported by meta-analyses and region-specific studies, especially for smallholders in the semi-arid and humid tropics (Prajapati *et al.*, 2024; Zeratsion *et al.*, 2024)^[51, 79]. However, land-tenure restrictions, lengthy establishment durations, and the requirement for tree species selection that works with cropping systems limit the adoption of agroforestry; long-term trials and socioeconomic research are still required to optimize designs for quick resilience advantages (Prajapati *et al.*, 2024)^[51].

Conservation agriculture (CA)

Conservation agriculture, which consists of diverse rotations, permanent soil cover (cover crops or mulch), and decreased or zero tillage, can stabilize yields under fluctuating rainfall, enhance soil water retention, and lessen erosion. Though yield improvements vary depending on the context and adoption is sometimes limited by short-term yield perception, residual trade-offs (livestock feed vs. mulching), and equipment requirements, thorough impact assessments demonstrate that CA may stabilize output during unfavorable seasons (Michler *et al.*, 2019; Umar *et al.*, 2021)^[40, 66]. Long-term SOC dynamics under CA across agroecologies and socioeconomic levers to lower disadoption risk in smallholder settings are important research needs.

Water-saving technologies

Water-saving techniques, such as drip and micro-irrigation, deficit irrigation, precision scheduling, alternate wetting and drying in rice, and enhanced on-farm water harvesting, significantly boost water production and lessen drought susceptibility. Precision irrigation and AWD can maintain yields while reducing water consumption and, in rice, dramatically cut methane emissions, according to reviews and field syntheses. However, adoption is limited in many places by initial investment prices, maintenance needs, and dependable power/water delivery (Lakhari *et al.*, 2024; Linquist *et al.*, 2015)^[33, 38]. The availability of inexpensive sensor-based scheduling for smallholders and institutional tools (loans, subsidies, and service providers) to facilitate widespread use are significant gaps.

Climate-Resilient Villages / NICRA (ICAR) — India example

Water conservation, robust cultivars, livelihood diversification, capacity training, on-farm demonstrations, and contingency planning are all part of India's National Innovations in Climate Resilient Agriculture (NICRA) and associated "Climate-Resilient Village" (CRV) programs run by ICAR. Evaluations of several programs show that farmer awareness has increased, resilient practices have been adopted, and the risk of crop failure under extreme weather has decreased locally. However, they also point out that the effects vary by district, that there are gaps in long-term monitoring, and that stronger connections to market and credit systems are required to maintain adoption (Prem S. *et al.*, 2024; Naik *et al.*, 2025)^[52, 43]. National scaling is still guided by thorough, long-term effect studies and cost-benefit calculations.

3.3 Mitigation Strategies to Reduce GHG Emissions

Greenhouse-gas (GHG) emissions from agriculture must be reduced by a combination of field-level strategies that minimize emissions per unit area and per unit product (emission intensity) without compromising lives and production. Here, we summarize mechanisms, evidence of mitigation potential, co-benefits, and remaining knowledge gaps for five extensively researched mitigation strategies: Alternate Wetting and Drying (AWD), zero tillage, biochar application, soil carbon sequestration, and improvements in nitrogen use efficiency.

Alternate Wetting and Drying (AWD) in rice

AWD is a method of managing water in paddy rice that involves letting fields dry out (to a certain point) before flooding again. Methanogenesis in anaerobic paddy soils is interrupted by the deliberate aerobic intervals, which usually result in significant decreases in CH₄ emissions while frequently preserving yields.

The balance between reduced CH₄ and increased N₂O, as well as local soil/climate conditions, determines net GWP gains. Large meta-analyses and systematic reviews demonstrate that AWD typically reduces CH₄ by ~30-45% and can significantly reduce global warming potential (GWP). However, AWD frequently increases N₂O emissions. Strategies that combine AWD with deep N application, enhanced-efficiency fertilizers, or biochar amendment can improve net mitigation and counteract the increase in N₂O. Farmers' perceptions of the risks associated with yield consequences, water control infrastructure, and site-specific AWD intensity optimization are some of the implementation obstacles (Li *et al.*, 2024; Dahlgreen *et al.*, 2024) ^[36, 17]. Important gaps include socioeconomic research on farmer adoption, large-scale testing of combined management packages (AWD + N management), and long-term monitoring of AWD impacts across a range of soils and climates.

Zero tillage (conservation tillage / no-till)

Zero tillage can boost soil organic carbon (SOC) supplies in the upper soil horizon, minimize soil disturbance, and leave leftovers at the surface. According to meta-analyses, no-till frequently lowers CO₂ and N₂O emissions (via changed soil C dynamics and microbial processes) and enhances CH₄ absorption in some systems, which lowers total GWP in many situations. However, the impacts on net GHG balance are variable but typically positive. Crop type, soil texture, environment (dry vs. wet), residue management, and time-scale (short vs. long term) all affect how successful zero tillage is. Short-term increases in N₂O have occasionally been noted, especially when residue retention raises soil moisture and denitrification. Therefore, no-till mitigation usually necessitates a combination of cover crops, residue management, and nutrient optimization (Li *et al.*, 2023) ^[37].

Biochar application

Applying biochar, a stable, carbon-rich byproduct of pyrolyzing biomass wastes, to soils enhances their ability to retain nutrients, hold water, and store carbon for a long time. Biochar can (1) store carbon for decades to centuries (depending on feedstock and pyrolysis conditions), according to field and lab research, and (2) lower N₂O and CH₄ emissions in many soils by changing the makeup of the microbial population, pore structure, and oxygen transport. Co-benefits include better soil physical characteristics and nutrient usage efficiency; however, efficacy varies by soil type, biochar quality, and application rate. To guarantee net climate benefits (taking into consideration the supply of feedstock and pyrolysis energy), life-cycle assessments are required (Singh Yadav *et al.*, 2023) ^[59].

Carbon sequestration in soil

In order to sequester atmospheric CO₂ in soil organic matter, methods such as cover crops, residue retention, decreased tillage, diverse rotations, perennial systems, and organic supplements can be used. Recent syntheses highlight the promise as well as significant limitations: large-scale programs are complicated by leakage (emissions displaced elsewhere) and measurement uncertainty; permanence and additionality (that the increase would not have occurred without the intervention) are two major challenges for carbon accounting; and sequestration rates vary greatly by climate, soil, past land use, and management. However, well-thought-out soil-C initiatives, along with attentive oversight and incentives, can provide significant mitigation and agronomic co-benefits (resilience, soil health) (Zhang *et al.*, 2024) ^[81].

Efficient fertilizer use (improving Nitrogen Use Efficiency, NUE)

Enhancing NUE maintains or raises yields while lowering N₂O and NH₃ losses. Techniques include deep placement, split applications, the use of enhanced-efficiency fertilizers (such as urease and nitrification inhibitors, controlled-release formulations), the 4R nutrient stewardship (right source, rate, time, and place), and integration with precision tools (such as sensor-based scheduling and soil testing). Field tests demonstrate that urease/nitrification inhibitors combined with optimum N rates can significantly lower N₂O and NH₃ emissions (often >25-50%) and improve fertilizer recovery efficiency. Cost-effective access to better products, advice services, and compatibility with farmer incentives are necessary for scaling (Wang *et al.*, 2023) ^[73].

Overall synthesis and research priorities

Although the advantages of each mitigation strategy are quantifiable, their efficacy varies depending on the situation and may need trade-offs (for example, AWD reduces CH₄ but may increase N₂O). Integrated practice testing (packages that combine water, nitrogen, and carbon management); long-term, multi-site trials and robust monitoring (to assess permanence and side-effects); life-cycle and socioeconomic analyses; and extension and incentive mechanisms to enable farmer adoption without compromising livelihoods are among the top research and policy priorities.

4. Climate-Smart Technologies

Contemporary climate-smart technologies integrate digital tools, engineering, and agronomy to increase farming's productivity, cut down on resource consumption, and lessen its greenhouse gas impact. For low-emission and climate-resilient agriculture, the four technologies listed below are some of the most popular.

Direct-Seeded Rice (DSR)

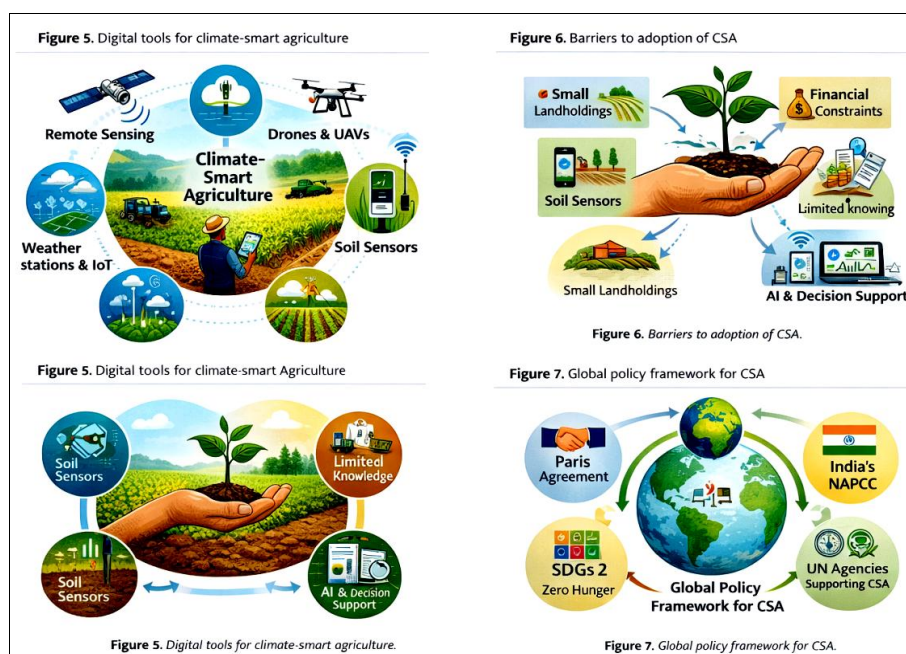
Direct-seeding of rice (DSR) involves putting seed into the field either wet or dry, replacing manual nursery rearing and transplanted puddled rice (PTR). Mechanistically, DSR usually calls for less continual flooding and puddling, which shortens the time and breadth of anaerobic soil conditions that promote methanogenesis. This can reduce CH₄ emissions and save labor and water. When weed, fertilizer, and seedling management are improved, DSR frequently results in equivalent yields while lowering water usage (and methane), according to reviews and meta-analyses. The limits imposed by DSR, however, are shifted toward weed pressure, the necessity for tailored agronomy (stale-seedbed, herbicide techniques, appropriate cultivars), and the possibility of increased N₂O (if aerobic soils are treated incorrectly). Mechanized sowing choices, site-specific fertilizer programs, and integrated weed management are necessary for scaling DSR (Chaudhary *et al.*, 2023) ^[14].

Precision irrigation (drip / sprinkler / smart scheduling)

The crop root zone receives water from precision irrigation systems (drip, micro-sprinkler, and sensor-driven controllers) at times and rates that are adjusted to meet crop needs. Together with lowering pumping energy costs and increasing water productivity (yield per unit of water), they can also lessen drought vulnerability when used in conjunction with scheduling algorithms. According to recent data-driven reviews, precision irrigation is increasingly integrating wireless networks, IoT sensors, and machine learning control loops to optimize irrigation at the parcel scale. The advantages of this approach

include lower water consumption and higher yields, but the drawbacks include upfront costs, sensor maintenance, and the requirement for local technical assistance. Low-cost soil

moisture sensors and service-provider models offer viable adoption paths for many smallholder and rainfed environments (Violino *et al.*, 2023)^[71].



5. ICT and weather-advisory systems (agromet services)

ICT-based agrometeorological advisories translate local agronomic knowledge and weather forecasts into signals that are relevant to a farm and may be used for planting dates, pest/disease alerts, irrigation timing, and contingency planning. Uptake depends on localizing predictions, co-developing with users (two-way communication), and delivering information on time (SMS, apps, IVR, radio). Case studies show that customized, participatory advisories integrated into extension services significantly improve farmer decision-making and adaptation capabilities; nevertheless, efficacy is dependent on forecast accuracy, communication infrastructure, literacy, and trust. Priorities for research include scalability, impact assessment, and combining market signals and short-term warnings with seasonal predictions (Walker *et al.*, 2021)^[72].

Remote sensing & AI-based decision tools

Machine learning (ML) and deep learning models in conjunction with satellite, unmanned aerial vehicle (UAV), and proximate sensors provide scalable crop monitoring, yield forecasting, water stress detection, and early pest/disease alarms. In order to provide decision support (variable-rate irrigation/fertilizer maps, disease risk maps), AI models combine meteorological and soil data with spatiotemporal indicators (NDVI, LAI, thermal stress proxies) obtained from remote sensing. Strong gains in categorization and forecast accuracy are demonstrated by reviews, and operational methods for monitoring at the national level are expanding. The requirement for user-centric interfaces and reliable explainability, (2) data gaps under frequent cloud cover, (3) the necessity for ground-truth data for model training, and (4) fair access for smallholders are the main limitations. On-device (low-bandwidth) inference, multi-sensor fusion, and thorough field validation across agroecologies should be the main areas of future research (Karmakar *et al.*, 2024; Sishodia *et al.*, 2020)^[31, 60].

Short synthesis — co-benefits and implementation gaps

When combined, these technologies have the potential to: (a)

lower water consumption and greenhouse gas emissions (DSR, AWD + precision irrigation); (b) increase resource-use efficiency (precision irrigation, remote sensing-guided application); and (c) enhance farmer resilience and decision-making (agromet ICT, AI tools). However, in addition to being technological, adoption obstacles include social and institutional: trust, legal frameworks, data/service business models, capital costs, and local capability are important. Priorities for research include long-term field validation, cost-benefit and equity analyses, developing low-cost service models for smallholders, and integrated technology packages (*e.g.*, DSR + precision irrigation + agromet advisories).

6. Policy Framework and Global Initiatives

The Paris Agreement

An inclusive "pledge-and-review" framework was established by the 2015 Paris Agreement, whereby nations submit Nationally Determined Contributions (NDCs) and then amend them on a regular basis to increase ambition. The Agreement replaced the top-down, legally mandated approach to climate governance with a hybrid model that incorporates national action into a global cycle of transparency and stock-take. Although academics emphasize that Paris's ratcheting/peer-pressure mechanism and its inclusion of mitigation, adaptation, and financing are its strongest points, they also point out that implementation and funding continue to be major obstacles (UNFCCC; FALKNER *et al.*, 2016)^[19].

India's National Action Plan on Climate Change (NAPCC)

The NAPCC of India was founded in 2008 and has eight "national missions": maintaining Himalayan ecosystems, water, sustainable agriculture, solar energy, improved energy efficiency, a "green India" goal, and climate change strategy. Development and climate goals are expressly linked in the NAPCC policy package (co-benefits). NAPCC boosted institutional capacity and mission-oriented programs, according to policy evaluations, but implementation has been inconsistent across missions and states; researchers urge improved

monitoring, more precise goals, and better funding sources to turn mission plans into long-term results (NAPCC2008)^[22].

Sustainable Development Goals (SDG 2 & SDG 13) and their interactions

Agricultural policies that boost productivity without harming ecosystems can help achieve SDG 2 (Zero Hunger/Sustainable Agriculture) and SDG 13 (Climate Action). However, there are trade-offs (e.g., intensification that increases yields but raises emissions unless paired with low-carbon practices) between the two goals. When creating policy packages that simultaneously aim food security and climate resilience, it is essential to find synergies and trade-offs across objectives using the frameworks and empirical mapping tools provided by the SDG-interactions literature (Nilsson *et al.*, 2018)^[47].

Role of the United Nations Framework Convention on Climate Change (UNFCCC)

The primary international forum for collective rule negotiations, monitoring NDCs, mobilizing climate funding, and hosting technology and capacity-building initiatives (such as the Green Climate Fund and the Technology Mechanism) is still the United Nations Framework Convention on Climate Change. While highlighting the UNFCCC's changing function as a treaty author, convenor, transparency facilitator, and venue for finance/adaptation planning, recent governance studies also highlight the ongoing equitable and financial issues facing poor nations (Kuyper *et al.*, 2018)^[32].

Role of the United Nations (UN)

The UN organizes multilateral funding and institutions (such as FAO, UNDP, and UNEP) that operationalize climate adaptation and capacity building, coordinates normative frameworks (such as the 2030 Agenda/SDGs), and promotes international reporting and monitoring on sustainable development and climate effects. In order to operationalize CSA at scale, the UN also offers platforms for technical collaboration that connect food systems, disaster risk reduction, and climate policy (UNClimate2023).

7. Case Studies — Climate-Smart Agriculture

CSA in the rice-wheat cropping system (South Asia)

The Indo-Gangetic Plains' predominant grain cycle is rice-wheat, although it confronts challenges from depleting groundwater, residue-burning issues, degraded soil, and increased greenhouse gas emissions. Direct-seeded rice (DSR), zero-till wheat, residue retention, crop diversification (including legumes), laser leveling, and precision nutrient management are examples of climate-smart interventions that boost system water productivity, lower energy and labor requirements, and enhance soil health while preserving or increasing system yields. In South Asia, multi-site syntheses and on-farm demonstrations show that combining resource-conserving technology results in 20-35% irrigation savings, better wheat planting timeliness, and increased system profitability. In order to scale practically, consideration must be given to mechanization and service delivery, residual trade-offs with cattle, and weed control in DSR (Ullah *et al.*, 2021)^[65].

Agroforestry carbon-sequestration models (India and beyond)

The carbon pools above and below ground are continuously increased by agroforestry systems (agri-silviculture, agri-horticulture, and silvo-pasture) in comparison to solitary

cropping. System type, tree species, age, previous land use, and rainfall all affect sequestration, according to recent meta-analyses and modeling studies that quantify soil C increases (average +25% compared to conventional systems in India). Allometric equations, biomass growth curves, and soil organic carbon turnover are all integrated into agroforestry models to produce reliable estimations of carbon stocks and sequestration rates that are helpful for carbon-finance and landscape MRV projects. Standardized MRV methods, commercial incentives for tree products, and tenure are some of the obstacles to uptake.

Climate-Resilient Village model (India — NICRA examples)

The ICAR-NICRA network's Climate-Resilient Village (CRV) demonstrations in India include livestock assistance, soil-water conservation, water harvesting, robust varieties, and emergency preparation. Increased farmer knowledge, more adoption of certain resilient measures, localized decreases in crop failure risk, and immediate financial gains are all demonstrated by mixed-method assessments. Results differ between districts, though, and maintaining effects at scale requires institutional support for supply chain and infrastructure upkeep, longer-term monitoring, and stronger market and credit ties. Current empirical evaluations place a strong emphasis on integrating CRVs into broader rural development pathways and customizing packages to local vulnerabilities (Naik *et al.*, 2025)^[44].

Adoption of Alternate Wetting and Drying (AWD) in paddy fields

AWD permits regulated soil drying intervals, which lowers water input and methane emissions. According to meta-analyses, moderate AWD may reduce watering by about 20% to 30% with little to no yield loss; adoption studies pinpoint the factors that influence and hinder this, including farmer education, land ownership, terrain, soil type, irrigation control accessibility, and reliable extension services. AWD increases agricultural yields and water production in Bangladesh, the Philippines, and India, according to country casework, while institutional backing and local demonstration lower perceived risk. Diffusion is accelerated by policy initiatives such as farmer field schools, demonstration pumps, and training (Carrijo *et al.*, 2017; Alauddin *et al.*, 2020; Hossain *et al.*, 2022)^[12, 4, 26].

8. Challenges in Adoption of Climate-Smart Agriculture (CSA)

Despite its technological potential, Climate-Smart Agriculture's (CSA) widespread acceptance is still unequal, especially in poor nations. Implementation is hampered by a number of institutional, financial, informational, and structural obstacles.



Small landholdings

The small size and extreme fragmentation of farms in many low- and middle-income nations restrict the economies of scale and mechanization choices needed for CSA technologies like zero tillage and precision irrigation. Because they are risk averse and have little safeguards against crop failure, smallholders frequently place a higher priority on short-term food security than on long-term climate initiatives. Although marginal farmers incur greater relative transaction and information costs, empirical research indicates that farm size has a favorable impact on the adoption of capital-intensive climate-smart activities (Aryal *et al.*, 2021) ^[5]. Water management and agroforestry planning are two landscape-level operations that are made more difficult by fragmentation.

Financial constraints

Drip systems, better seed, robotic sowing, sensors, and other CSA technology usually demand an upfront expenditure that many smallholders cannot afford without access to financing. The motivation to invest in new techniques is decreased by high perceived risk and unclear rewards. Research shows that despite availability to financing, crop insurance, and subsidies greatly boosts the uptake of CSA, liquidity issues continue to be the main obstacle (Nakasone *et al.*, 2016) ^[45]. Scaling is further slowed by the restricted availability of climate money at the local level.

Limited awareness and knowledge gaps

CSA adoption is closely related to extension assistance, training, and awareness. Improved techniques are less likely to be adopted by farmers who do not have access to trustworthy climatic data or technical advice. Research indicates that knowledge and acceptance of adaption methods are greatly enhanced by involvement in farmer field schools and extension programs (Yiridomoh *et al.*, 2025) ^[78]. But many rural communities have poor digital access and understaffed extension systems.

Policy and institutional gaps

Weak policy coordination, unclear land tenure, and inconsistent subsidy structures often undermine CSA scaling. While many countries include CSA in national strategies, implementation frameworks and monitoring mechanisms remain fragmented. Institutional analyses highlight the need for integrated governance that aligns agriculture, water, forestry, and climate policies to avoid conflicting incentives (Wolff *et al.*, 2018) ^[75].

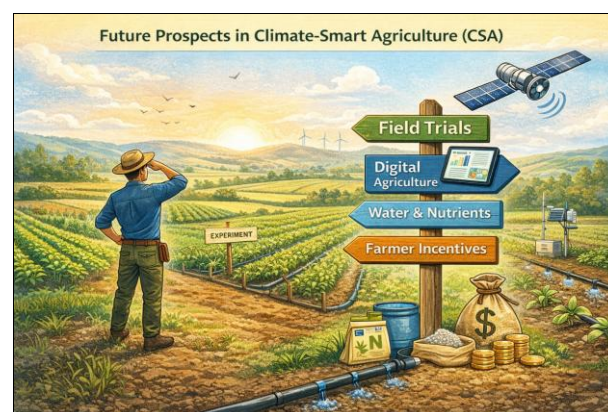
Measurement difficulties of carbon sequestration

It is still technically difficult to quantify soil carbon sequestration and emission reductions. Because soil carbon fluctuates across time and space, strong modeling and frequent sampling are necessary. Farmer involvement in carbon markets and performance-based incentives is restricted by uncertainty in measurement, reporting, and verification (MRV). In agricultural carbon initiatives, recent assessments highlight issues with permanence, additionality, and monitoring expenses (Bossio *et al.*, 2020) ^[10].

9. Future Research Directions in Climate-Smart Agriculture

Multidisciplinary research integrating agricultural science, soil biogeochemistry, modeling, digital technology, and socioeconomic analysis is necessary to advance Climate-Smart Agriculture (CSA). Enhancing resilience in the face of climate change, measuring mitigation potential, and increasing

predictive capability must be the main goals of future research.



Crop modeling under climate scenarios

A growing number of crop simulation models, including DSSAT, APSIM, and Aqua Crop, are being used to assess crop performance under anticipated rainfall and temperature conditions. To lower yield forecasting uncertainty, future studies should prioritize multi-model ensemble techniques, downscaled climate predictions, and integration of severe event analysis. Planning for adaptation can be improved by combining crop models with socioeconomic modules. Improving parameterization for heat stress, CO₂ fertilization effects, and genotype × environment interactions under future temperatures is crucial, according to recent studies (Webber *et al.*, 2018) ^[74].

Carbon budgeting in farming systems

One of the top research priorities is still quantifying net carbon balance at the farm and landscape scales. The dynamics of soil organic carbon, biomass inputs, residue management, and off-farm emissions must all be taken into account when creating a carbon budget. To enhance carbon accounting, new methods combine life-cycle assessment (LCA), eddy-covariance data, and process-based soil models. However, robust estimate is limited by permanence uncertainty and geographical heterogeneity (Zomer *et al.*, 2017) ^[84].

Integration of organic inputs (e.g., Jeevamrut) in CSA

Microbial bio-inoculants (including conventional formulations like Jeevamrut) and organic additions like compost and farmyard manure may improve carbon sequestration, nitrogen cycling, and soil microbial activity. Future studies ought to assess their long-term impacts on nutrient dynamics, soil health, and greenhouse gas emissions in the face of climatic variability. Quantifying yield stability and mitigation potential requires extensive field studies comparing the integration of organic and inorganic nutrients under stress (Agegnehu *et al.*, 2017) ^[2].

Nitrogen Use Efficiency (NUE) under climate-smart practices

To lower nitrous oxide emissions while maintaining yields, NUE must be improved. Real-time nutrient monitoring, climate-responsive fertilizer scheduling, crop genetic modification for N absorption efficiency, and enhanced-efficiency fertilizers should all be included into future research. According to studies, warming and changed precipitation patterns may cause more nitrogen losses, hence dynamic fertilizer management techniques are required (Zhang *et al.*, 2015) ^[82].

Digital agriculture for climate forecasting

Climate forecasting and agricultural advising systems are being

revolutionized by artificial intelligence, machine learning, IoT sensors, and satellite data. In order to give site-specific adaptive advice, future research should concentrate on combining crop models with real-time climatic data. Improving data fairness, accessibility, and explainability for smallholders is still a major concern (van Klompenburg *et al.* 2020)^[69].

10. Conclusion

A scientifically based framework for addressing the interrelated issues of food security, climate vulnerability, and greenhouse gas (GHG) abatement is provided by Climate-Smart Agriculture (CSA). Agriculture contributes significantly to greenhouse gas emissions through methane (CH₄) from rice and livestock, nitrous oxide (N₂O) from nitrogen fertilizers, and carbon dioxide (CO₂) from land-use change and soil carbon loss. It is also extremely vulnerable to rising temperatures, unpredictable rainfall, droughts, and floods. This dual function calls for coordinated approaches that lower emission intensity and increase production. When properly managed, mitigation techniques including Alternate Wetting and Drying (AWD), zero tillage, the use of biochar, enhanced nitrogen usage efficiency, and soil carbon sequestration can reduce emissions without sacrificing yields. At the same time, adaptation strategies that stabilize farm revenues under climate stress and increase system resilience include crop diversification, agroforestry, conservation agriculture, water-saving technology, and climate-resilient community projects. Resource efficiency and climate risk management are further improved by emerging climate-smart technologies including AI-driven decision tools, precision irrigation, Direct-Seeded Rice (DSR), and ICT-based advice services. However, institutional gaps, tiny landholdings, financial constraints, low knowledge, and difficulties quantifying carbon sequestration continue to limit uptake. Scaling CSA requires improving monitoring systems, farmer-centered extension services, research innovation, and policy integration. All things considered, CSA offers a logical route toward resilient, low-carbon, and sustainable agriculture systems in the face of rapid climate change.

Acknowledgements

We are deeply grateful to our supervisors for their mentorship and our institute for helping us to access different literature and providing an environment for focusing on research deeply.

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