

Review

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Review

Greenhouse Gases Emissions in Agricultural Crops and Management Practices: The Impact of the Integrated Crop Emission Mitigation Framework on Greenhouse Gas Reduction

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Highlights

- Synthesizes recent evidence on greenhouse gas emissions from agricultural crops and evaluates mitigation strategies across soil, crop, nutrient, and policy dimensions.
- Proposes the Integrated Crop Emission Mitigation Framework (ICEMF) as a novel pathway linking field-based practices with global emission reduction targets.
- Identifies key research gaps in long-term validation, socio-economic adoption, and regional variability, emphasizing the need for integrated, farmer-centered solutions.

Abstract

Greenhouse gas (GHG) emissions from agricultural crops remain a critical challenge for climate change mitigation. This review synthesizes evidence on cropland management interventions and global N₂O mitigation potential. Agricultural practices such as cover cropping, agroforestry, reduced tillage, and diversification show promise in reducing CO₂, CH₄, and N₂O emissions, yet uncertainties in measurement, verification, and socio-economic adoption persist. Complementing this, global-scale analysis underscores the dominant role of optimized nitrogen fertilization in curbing N₂O emissions while sustaining yields. To bridge gaps between practice-level interventions and global emission dynamics, this paper introduces the ICEMF, a novel approach combining field-based management strategies with spatially explicit emission modelling. Only peer-reviewed articles published in English between 2014 and 2025 were selected to ensure recent and reliable findings. The review highlights knowledge gaps, evaluates policy and technical trade-offs, and proposes ICEMF as a pathway toward scalable and adaptive mitigation strategies in agriculture.

Keywords: agricultural crops; greenhouse gas emissions; mitigation strategies; nitrous oxide reduction; soil carbon sequestration

1. Introduction

Agriculture is widely recognized as a major contributor to anthropogenic greenhouse gases (GHGs), emitting carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) through soil degradation, livestock-related processes, and intensive crop management [1]. These emissions account for a substantial share of global warming, with croplands serving both as significant sources

and potential sinks of GHGs through soil carbon sequestration and improved land management [2]. The need to mitigate these emissions has grown, as agriculture faces pressures from climate change, food security concerns, and sustainability goals [3,4].

Various agronomic interventions have been identified to reduce emissions, including cover cropping, reduced tillage, crop diversification, agroforestry, and organic amendments [5]. These practices enhance soil organic carbon stocks, reduce erosion, and improve resilience to extreme weather events [6]. However, the net benefits of such interventions are context-dependent, often influenced by soil type, climate, and farming system design [7]. In addition, monitoring, reporting, and verification (MRV) frameworks face methodological inconsistencies that limit the reliability of estimates [8].

Nitrous oxide emissions are of particular concern because of their high global warming potential and direct link to nitrogen fertilizer application [9]. Global analyses indicate that N_2O emissions from croplands have quadrupled over the last six decades, with hotspots in Asia and intensive horticultural systems [10]. Strategies such as the “4R” nutrient stewardship (right source, rate, time, and placement) and precision irrigation have been highlighted as effective measures to reduce N_2O while sustaining yields [3]. Crop-specific assessments show maize, rice, wheat, and vegetable systems to be the most significant contributors, and therefore prime targets for mitigation [11].

Despite promising technical potentials, adoption of mitigation strategies is constrained by socio-economic realities [12]. Barriers include land tenure insecurity, lack of capital, risk perception, and compatibility with traditional practices [13]. Policy frameworks, incentive structures, and market-based mechanisms, such as carbon credits, influence adoption rates but bring additional challenges of equity and verification [14]. As a result, biophysical estimates often overstate mitigation potential without accounting for the socio-economic conditions of real farming systems [15].

To address these complexities, this review introduces the ICEMF, a novel synthesis approach that couples practice-level evidence with spatially explicit modeling of N_2O and Soil Organic Carbon (SOC) outcomes. The framework integrates empirical data, regional modeling, and socio-economic adoption pathways, offering a decision-support tool for scalable interventions [16]. By combining technological, agronomic, and policy perspectives, ICEMF provides a roadmap for reducing agricultural GHGs while maintaining productivity [17–19].

The ICEMF proposed in this study is primarily a conceptual and methodological tool designed to connect field-level management practices with regional and global emission mitigation models. ICEMF integrates empirical data, spatially explicit emission modelling, and socio-economic adoption pathways, offering a decision-support tool for scalable and adaptive mitigation strategies. While ICEMF is currently in a theoretical stage, its application potential is illustrated through a schematic representation (Figure 1), which visualizes the connection between farm-level practices and their broader impacts on global mitigation targets. This schematic aims to clarify how ICEMF bridges the gap between technical agronomic strategies and global emission modeling. Moreover, this figure illustrates the conceptual flow of ICEMF, connecting field-level agricultural practices with spatially explicit emission modeling, regional/global emission models, and socio-economic adoption pathways. It visualizes how farm-level practices contribute to broader global emission mitigation targets, highlighting the integration of empirical data, technical strategies, and socio-economic factors for scalable and adaptive mitigation solutions.

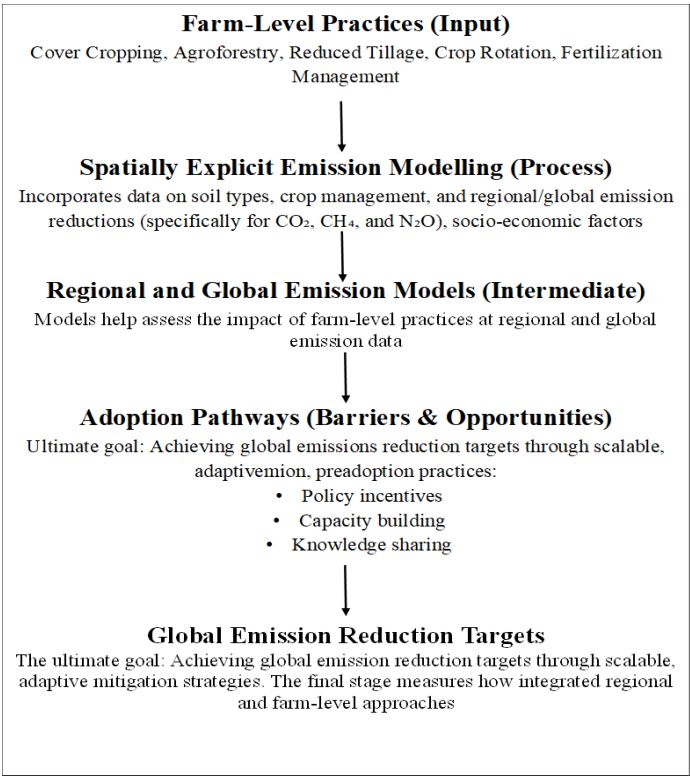


Figure 1. Schematic Representation of the Integrated Crop Emission Mitigation Framework.

1.1. Contributions

The novel contributions of this study are:

1. Proposes the ICEMF as a hybrid approach that unites field-level management practices with global-scale emission modeling.
2. Provides a dual synthesis of practice-based interventions and spatially explicit N₂O mitigation assessments, highlighting synergies often overlooked in single-focus reviews.
3. Identifies critical policy–practice trade-offs and socio-economic adoption barriers, offering a roadmap for aligning climate targets with farmer-centric solutions.

1.2. Review Context and Objectives

The literature on greenhouse gas emissions in agriculture highlights both the scale of the problem and the diverse mitigation strategies proposed to balance productivity with sustainability. Table 1 shows summary of research gaps. Ullah, Farooque [20] reviewed biochar production processes and demonstrated its potential to reduce soil-based GHG emissions by enhancing carbon storage, soil quality, and microbial activity. Zhu and Miller [21] found that tomato production systems vary widely in emissions, highlighting precision agriculture and low-carbon energy as key interventions. [22] applied a harmonized methodology to soybean production studies, finding significant variability in GHG emissions driven by fertilizer use, irrigation, and regional differences. According to Yuan, Lian [23], examined greenhouse gas emissions from constructed wetlands, emphasizing the role of planting strategies and management practices in reducing secondary pollution. Kabato, Getnet [3] assessed climate-smart agriculture strategies, underscoring the benefits of integrated practices like biochar application, agroforestry, and regenerative agriculture for soil health and emission mitigation. Another study by Symeon, Akamati [24] explored manure management approaches, including anaerobic digestion and composting, as viable tools to reduce GHG emissions in livestock systems. [25] evaluated chicken meat production in South Korea, showing that feed production contributed the largest share of emissions and recommending local feed sourcing and better manure management. [26] synthesized evidence on converting cropland to

grassland in peat soils, concluding that effects on CO₂, CH₄, and N₂O emissions remain ambiguous and context-dependent. According to Kukah, Jin [27] reviewed the role of carbon trading, finding that it reduces GHG emissions through innovations in low-carbon technologies, renewable energy, and ecosystem restoration. The study demonstrated that recoupled crop-livestock systems in China could reduce agricultural GHG emissions by over 40%, highlighting their potential for sustainable intensification [28].

Agricultural crop systems are central to global food security but simultaneously represent a major source of GHG emissions, particularly CO₂, CH₄, and N₂O. Despite extensive research on individual mitigation practices, the sector continues to face significant challenges in balancing productivity with climate goals. Measurement uncertainties, limited socio-economic adoption of climate-smart practices, and policy–practice mismatches hinder the scalability of effective solutions. Moreover, most existing approaches focus narrowly on either technical interventions or emission inventories, leaving a gap in integrated frameworks that connect farm-level practices with regional and global mitigation outcomes. This disconnect underscores the urgent need for a comprehensive synthesis that not only reviews emission sources and mitigation strategies but also provides a structured pathway for practical, verifiable, and context-specific solutions to reduce agricultural GHG emissions.

Across the reviewed studies, several recurring gaps emerge. Many mitigation strategies such as biochar application, climate-smart agriculture, and crop–livestock integration show strong potential, yet lack long-term field validation and region-specific performance data. Methodological inconsistencies in life cycle assessments of crops like tomatoes and soybeans limit comparability, highlighting the need for standardized boundaries and harmonized reporting. Ecosystem-based solutions such as constructed wetlands and land-use shifts provide valuable insights, but their greenhouse gas outcomes remain context-dependent and uncertain, requiring more robust monitoring frameworks. Socio-economic and policy barriers, including adoption constraints, insufficient incentives, and integration challenges with existing farming systems, are also insufficiently addressed, limiting scalability. Addressing these gaps through interdisciplinary, multi-scalar studies will be critical to designing effective, verifiable, and farmer-centered greenhouse gas mitigation strategies in agriculture.

The novel objectives of this study are:

1. To systematically review GHG emissions from agricultural crop systems and evaluate the effectiveness of diverse management practices.
2. To assess the global mitigation potential of N₂O emissions through optimized nitrogen fertilization and complementary agronomic interventions.
3. To develop and propose the ICEMF framework as a novel, scalable strategy for integrating technical, environmental, and socio-economic dimensions of GHG mitigation in agriculture.

Table 1. Summarizes the main research gaps.

Ref. No.	Focus Area	Key Findings	Research Gaps
Ullah, Farooque [20]	Biochar production and soil GHG mitigation	Biochar reduces GHG emissions, improves soil carbon storage and microbial activity	Long-term field trials, co-analysis of biochar aging, better tracking of carbon storage and CO ₂ sources
Zhu and Miller [21]	Tomato production life cycle assessment (LCA studies)	Median emissions vary widely across open-field, Climate-Uncontrolled Protected Environments (CUPE), and climate-controlled protected environments (CCPE) systems	Lack of standardized boundaries in (LCA), limited decarbonization strategies validated in practice

Luci�, Raposo [22]	Soybean production	Harmonized Life Cycle Inventories (LCIs) reveal variability across regions and systems	Insufficient residue management data, limited fertilizer/irrigation detail, weak global representativity
Yuan, Lian [23]	Constructed wetlands	Plant choice and management strongly influence GHG outcomes	Need for emission reduction strategies tied to plant diversity/harvesting, more ecosystem-level assessments
Kabato, Getnet [3]	Climate-smart agriculture	Integrated climate-smart agriculture (CSA) practices improve soil health and reduce GHG emissions	Site-specific optimization missing, socio-economic and adoption barriers underexplored
Symeon, Akamati [24]	Manure management in livestock systems	Composting, anaerobic digestion, and storage improvements reduce emissions	Limited evidence in non-ruminant species, policy and incentive support underdeveloped
Kang, Hwang [25]	Chicken meat production (LCA)	Feed production is the largest emission contributor	More data on local feed alternatives, integration of manure management with production systems
Holzkn�cht, Land [26]	Cropland-to-grassland conversion in peat soils	Mixed results on CO��, CH��, and N��O changes	Uncertain long-term impacts, insufficient clarity on soil type and fertilizer use effects
Kukah, Jin [27]	Carbon trading and emissions reduction	Supports emission cuts via low-carbon technologies and offsets	Limited agricultural sector focus, need for integration with farm-level practices
Cai, Zhang [28]	Recoupled crop-livestock systems in China	Potential 40% emission reduction through system integration	Regional scalability uncertain, lack of long-term adoption studies, limited socio-economic analysis

1.3. Evaluating the Limitations of Current Agricultural GHG Mitigation Frameworks and the Potential of ICEMF to Bridge the Gaps

While the ICEMF offers a novel approach to bridging field-based practices with global emission reduction targets, several existing frameworks share similar goals of mitigating GHG emissions in agriculture. However, these frameworks often face significant challenges related to adoption, scalability, and integration of socio-economic factors. Below, we discuss a few of these frameworks and explain how ICEMF is positioned to overcome their limitations.

1.3.1. The 4R Nutrient Stewardship

The 4R Nutrient Stewardship framework: Right Source at Right Rate, Right Time, and Right Place has been widely adopted globally as a science-based approach to optimize nitrogen fertilizer use [29], with documented potential to reduce N  O emissions by 55-64% when combined with enhanced-efficiency fertilizers and improve nitrogen recovery efficiency [30,31]. While effective in many commercial farming contexts, the 4R framework faces significant challenges in context-specific

adoption, as implementation is highly site-specific and regional challenges vary considerably across continents and farming systems [3,32]. The application of precision fertilization techniques aligned with 4R principles is often limited by technology access and knowledge gaps, especially in smallholder farming systems where farmers face barriers including limited resources, training, and financial support [33]. These constraints are particularly acute in sub-Saharan Africa, where low digital literacy, high equipment costs, and weak extension services impede implementation [34]. Additionally, the benefits of nutrient use efficiency optimization can be inconsistent across different soil types and climatic conditions, as regional environmental factors often equal or exceed the effects of specific fertilizer management practices on N₂O emissions and nutrient losses [31]. Soil emissions occur in spatially and temporally variable 'hot spots' and 'hot moments,' driven by complex interactions among soil properties, weather, and microbial processes, making outcomes difficult to predict and generalize across regions [35,36]. ICEMF integrates spatially explicit emission models and considers socio-economic adoption pathways, ensuring that practices like precision fertilization are scalable and adaptable to local conditions. ICEMF's inclusion of farmer decision-making factors, including financial incentives and training programs, helps overcome adoption barriers seen in the 4R framework.

1.3.2. Climate-Smart Agriculture (CSA)

CSA aims to integrate climate adaptation, mitigation, and food security in a single framework [37,38]. While CSA has promoted practices such as agroforestry, crop diversification, and conservation tillage [39,40], it often lacks a clear mechanism for scaling these practices across diverse agricultural systems [41]. The climate-smart village approach has attempted to provide an integrative strategy for scaling adaptation options, yet implementation remains challenging across heterogeneous farming contexts [41]. Moreover, CSA's emphasis on climate resilience sometimes overlooks the socio-economic conditions that influence farmers' willingness to adopt these practices [42,43]. Recent evidence demonstrates that adoption barriers extend beyond technical feasibility to include economic constraints, limited extension access, and institutional factors [44,45]. Studies across West Africa reveal that while farmers recognize benefits of CSA practices, barriers such as high initial investment costs, lack of credit access, insufficient labor, and inadequate knowledge significantly impede widespread adoption [46]. Similarly, research from southern Ethiopia and European food supply chains confirms that socio-economic factors including household wealth, market access, cooperative membership, and policy support critically determine technology adoption and farm sustainability outcomes [47,48]. The gap between indigenous knowledge systems and Western scientific approaches further complicates effective adaptation strategies, suggesting that CSA frameworks must better integrate local contexts and traditional practices to achieve meaningful impact [49]. ICEMF provides a more integrated approach by combining technical practices with spatially explicit emission modeling and socio-economic adoption data. This makes ICEMF more actionable at the farm level, particularly in addressing barriers to farmer adoption and economic feasibility in low-resource regions.

1.3.3. Low-Emission Development Strategies (LEDS)

LEDS are national frameworks integrating climate mitigation with development planning across sectors, including agriculture [50]. While valuable for macro-level policy coordination, LEDS face substantial implementation challenges in agriculture. Critical gaps exist between policy objectives and farm-level realities, particularly regarding the technical feasibility and economic viability of mitigation strategies for smallholder systems [51,52]. Research in Sub-Saharan Africa demonstrates that, despite progressive CSA policies, adoption remains constrained by limited access to technology, inadequate extension services, insufficient financial resources, and weak institutional capacity [53,54]. Agricultural mitigation policies face sociopolitical barriers including competing priorities around food security and affordability, organized lobby pressures, and redistributive effects [51]. Studies across Kenya, Tanzania, Ethiopia, and Rwanda reveal persistent challenges in

operationalizing LEDS locally due to trade-offs between agricultural expansion and environmental goals, donor dependence, and insufficient integration of local knowledge [53]. The effectiveness of agricultural LEDS is fundamentally constrained by disconnects between national goals and farm-level adoption realities, with conventional top-down systems inadequate for promoting equitable access to climate-smart practices [52,54]. ICEMF fills the gap by integrating farm-level interventions with regional and global emission models, offering a scalable and adaptive solution that bridges the gap between national policies and local agricultural practices. Its focus on farmer-centered solutions and policy incentives ensures that emission reduction strategies are both practical and achievable.

1.3.4. Integrated Assessment Models (IAMs)

IAMs are global frameworks that integrate economic, energy, land-use, agricultural, and climate systems to evaluate the impacts of climate policies on agricultural emissions [55,56]. While valuable for global policy analysis and identifying cost-effective mitigation pathways [57], IAMs face substantial limitations for real-world agricultural implementation. Critical gaps exist in capturing local specificities essential for farm-level adoption, as these models rely on highly aggregated regional representations that obscure within-region heterogeneity of farming systems, soil conditions, and farmer capacities [58,59]. IAMs have been criticized for problematic assumptions that underestimate transformation urgency and inadequately incorporate behavioral, institutional, and socio-political barriers to technology adoption [60]. Specifically, IAMs represent agricultural mitigation through technology diffusion functions assuming rational economic optimization, without adequately capturing complex socio-economic factors driving farmer decisions, including risk aversion, cultural compatibility, perceived usefulness, financial constraints, extension service access, and social network influences [61–63]. Research demonstrates that farmer technology adoption depends on multidimensional factors beyond economic calculations, with psychological dimensions (environmental values, innovation aversion), socio-demographics (age, education, farm size), resource endowments (land, labor, capital), and institutional contexts (extension services, policy incentives) all playing critical yet under-represented roles in IAM frameworks [64,65]. Consequently, while IAMs provide important macro-scale strategic insights, their agricultural projections lack the granularity and behavioral realism needed for context-specific implementation, necessitating complementary bottom-up approaches explicitly incorporating farmer heterogeneity and socio-institutional adoption determinants [59,64]. ICEMF offers a more granular approach by integrating field-level practices with global emission models. Unlike IAMs, ICEMF accounts for regional variations in soil types, climate, and farming systems, making it more relevant for on-the-ground implementation. Furthermore, ICEMF's inclusion of socio-economic adoption pathways ensures that mitigation strategies are not only technically feasible but also economically viable for farmers.

2. Materials and Methods

The literature search was conducted using major academic databases such as Scopus, Web of Science, and ScienceDirect to ensure comprehensive coverage of peer-reviewed studies on greenhouse gas emissions from agricultural crops and mitigation strategies. Keywords and combinations including “greenhouse gas emissions,” “agricultural crops,” “mitigation,” “management practices,” and “climate-smart agriculture” were applied to identify relevant studies published between 2016 and 2025. Additional references were traced through citation tracking of key articles to capture significant contributions not directly retrieved in the initial search.

Studies were included if they focused on greenhouse gas emissions from agricultural crop systems and examined mitigation or management strategies with relevance to CO₂, CH₄, or N₂O. Experimental field studies, meta-analyses, and systematic reviews were all considered to capture a broad spectrum of evidence. Only peer-reviewed articles published in English between 2014 and 2025 were selected to ensure recent and reliable findings. Exclusion criteria comprised studies that addressed emissions unrelated to crops (e.g., purely livestock systems), articles without empirical or

methodological relevance, non-English publications, and grey literature such as reports or opinion pieces. To begin with, more than 200 studies were recognized and managed for suitability. A total of 148 studies were selected for review after duplication elimination and language consideration, which were subsequently analyzed and included in the review.

From the eligible studies, key information such as author details, year of publication, study location, crop type, greenhouse gases assessed, and mitigation practices investigated was systematically extracted. Data were organized into thematic categories including soil-based strategies, crop management interventions, nutrient optimization, and policy or socio-economic measures. A narrative synthesis approach was adopted to integrate findings across diverse study designs, with emphasis on identifying common trends, contradictions, and knowledge gaps. Where possible, comparisons were drawn between regional and global perspectives to highlight context-specific variations in emission sources and mitigation outcomes.

The analysis was structured around a thematic framework that links emission sources to management interventions and mitigation outcomes. Studies were grouped into categories reflecting crop and soil management, nutrient optimization, integrated systems, and policy measures, allowing for cross-comparison of strategies. While this framework supports a comprehensive synthesis, several limitations remain. Variability in study designs, life cycle assessment boundaries, and measurement techniques restrict direct comparability of results. In addition, regional disparities in data availability create potential biases toward well-studied systems, while socio-economic dimensions are often underreported. These limitations underscore the need for standardized methodologies and long-term, context-specific studies to strengthen the evidence base.

The ICEMF is designed as a conceptual framework that integrates empirical data from field-based management strategies with regional and global emission models. It incorporates factors such as soil types, crop management practices, and socio-economic conditions to provide region-specific estimates of CO₂, CH₄, and N₂O emissions. The framework uses spatially explicit emission models to predict the outcomes of different mitigation practices at various scales, from farm to global levels. This approach combines data from field studies, agronomic models, and socio-economic adoption pathways, helping policymakers and farmers make informed decisions about which mitigation strategies are most effective under specific conditions.

3. Thematic Analysis

Figure 2 shows thematic analysis of the reviewed literature reveals that mitigation strategies in agricultural crop systems can be broadly grouped into five categories: soil-based approaches (e.g., biochar application, conservation tillage), crop-based practices (e.g., diversification, agroforestry, cover cropping), nutrient management (e.g., precision fertilization, 4R stewardship), integrated systems (e.g., crop–livestock recoupling, constructed wetlands), and policy or socio-economic interventions (e.g., carbon trading, CSA policies). This categorization highlights both the diversity and interconnectedness of approaches, with many practices offering co-benefits such as enhanced soil health, improved productivity, and resilience to climate variability. However, adoption remains uneven, and their effectiveness is often context-specific, emphasizing the need for adaptive frameworks like the ICEMF to harmonize local practices with global climate targets.

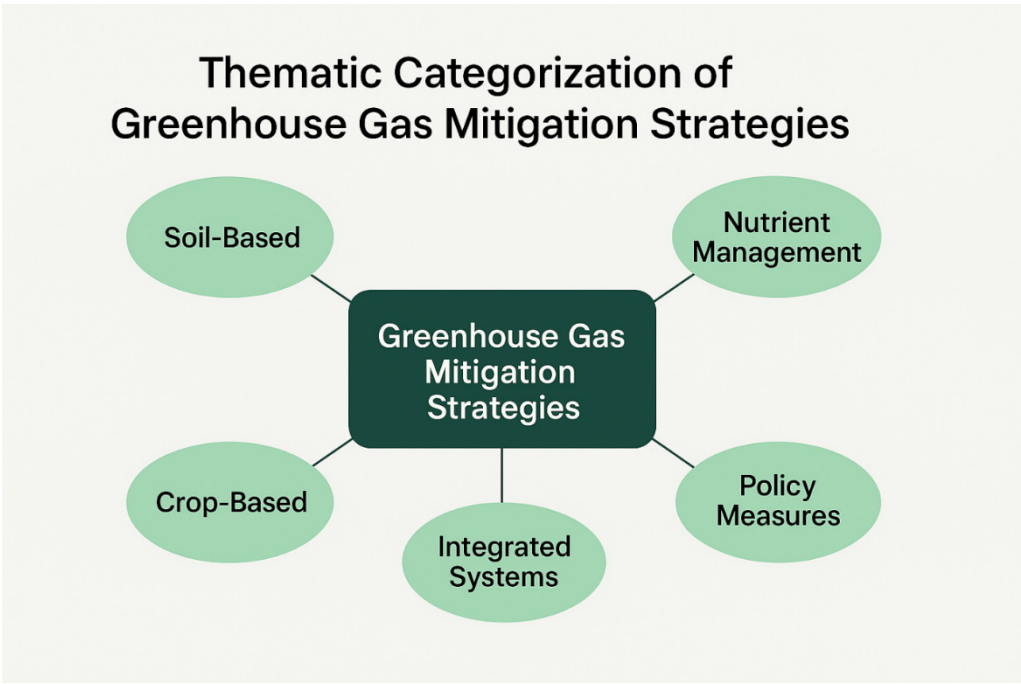


Figure 2. Thematic categorization of GHG mitigation strategies in agricultural crop systems (soil-based, crop-based, nutrient management, integrated systems, and policy measures).

3.1. Sources and Trends of Greenhouse Gas Emissions in Agriculture

Agricultural systems contribute significantly to global GHG emissions, primarily through CO₂, CH₄, and N₂O [66]. Soil organic matter degradation, excessive fertilizer use, and land-use change release CO₂, while enteric fermentation and flooded rice fields are major sources of CH₄. N₂O arises mainly from nitrogen fertilizer application and manure management, with its high global warming potential making it a critical focus for mitigation [67]. Recent studies indicate that global agricultural emissions have steadily increased over the past decades, with hotspots in Asia, Latin America, and Sub-Saharan Africa driven by crop intensification and rising fertilizer demand [68,69]. Seasonal variations, cropping intensity, and irrigation practices further influence emission patterns, underlining the complexity of agricultural GHG dynamics [70,71].

The study by Akram and Ali [72] examines the convergence hypothesis of GHG emissions across 93 countries from 1980 to 2017. Using the Phillips and Sul test, the study finds evidence of divergence in emissions trends, suggesting that countries follow different convergence paths. Clustering algorithms identify five distinct convergence clubs, indicating the need for region-specific policies. Figure 3 present the Greenhouse gas emissions in the agriculture sector across 93 Countries (1980-2017), as a group, based on the Phillips and Sul Panel Club Convergence Test. The findings emphasize the importance of considering these divergent paths when designing GHG mitigation strategies and the impact of policy transfers across countries. The study suggests that countries in Clubs 1–4 should adopt agricultural policies from Club 5, where GHG emissions are lower, particularly focusing on cleaner energy. Strategies to reduce GHG emissions include improving sector efficiency, fostering innovation, reducing deforestation, and using cleaner energy with subsidies. Additionally, addressing poverty and adopting low-cost energy technologies in agriculture are key to sustainable development in lower- and middle-income countries.

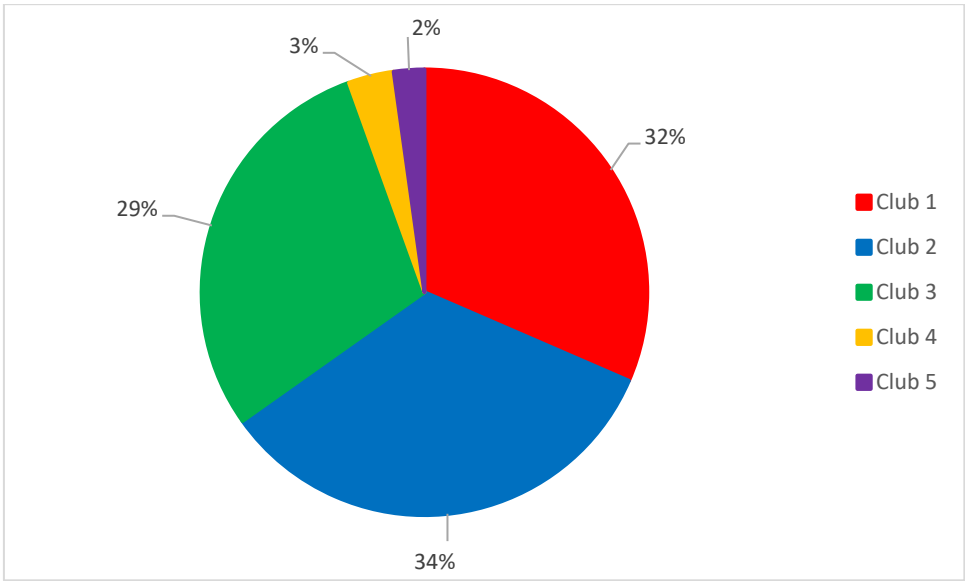
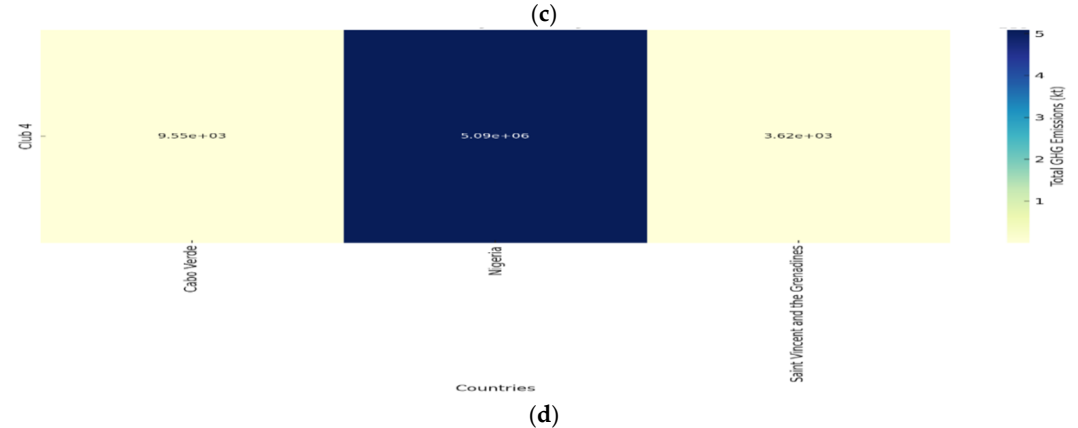
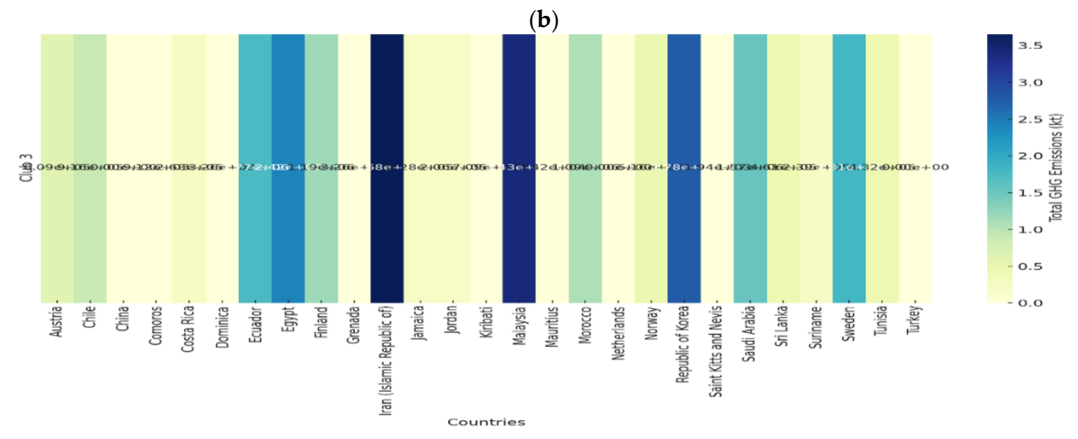
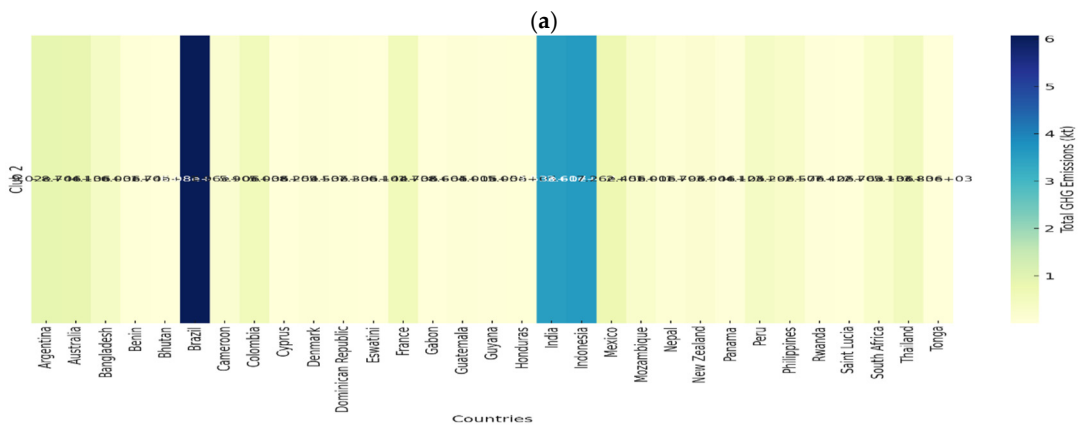
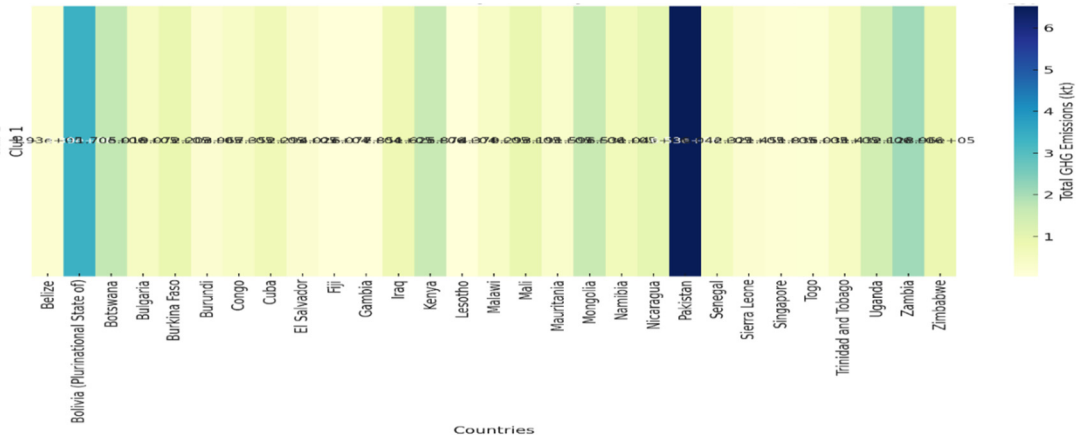


Figure 3. Global Disparities in Greenhouse Gas Emissions in the Agriculture Sector Across 93 Countries as a Group. Club 1: Belize, Bolivia (Plurinational State of), Botswana, Bulgaria, Burkina Faso, Burundi, Congo, Cuba, El Salvador, Fiji, Gambia, Iraq, Kenya, Lesotho, Malawi, Mali, Mauritania, Mongolia, Namibia, Nicaragua, Pakistan, Senegal, Sierra Leone, Singapore, Togo, Trinidad and Tobago, Uganda, Zambia, Zimbabwe. Club 2: Argentina, Australia, Bangladesh, Benin, Bhutan, Brazil, Cameroon, Colombia, Cyprus, Denmark, Dominican Republic, Eswatini, France, Gabon, Guatemala, Guyana, Honduras, India, Indonesia, Mexico, Mozambique, Nepal, New Zealand, Panama, Peru, Philip-pines, Rwanda, Saint Lucia, South Africa, Thailand, Tonga. Club 3: Austria, Chile, China, Comoros, Costa Rica, Dominica, Ecuador, Egypt, Finland, Grenada, Iran (Islamic Republic of), Jamaica, Jordan, Kiribati, Malaysia, Mauritius, Morocco, Netherlands, Norway, Republic of Korea, Saint Kitts and Nevis, Saudi Arabia, Sri Lanka, Suriname, Sweden, Tunisia, Turkey. Club 4: Cabo Verde, Nigeria, Saint Vincent and the Grenadines. Club 5: Seychelles, Switzerland. Group: Paraguay.

Building on the study by Akram and Ali (2021)[72], which examines the convergence hypothesis of GHG emissions across 93 countries from 1980 to 2017, we have generated heatmaps for each of the identified convergence clubs, showing total emissions from 1990 to 2020. The heatmaps visually represent the emissions trends within each club, highlighting the divergent paths observed in the study. These visualizations support the need for region-specific GHG mitigation strategies, emphasizing the importance of targeted policies that reflect the unique emission patterns of each club. The findings underscore the role of tailored interventions to address the emissions disparities across countries. The data for these heatmaps is sourced from the FAOSTAT Database (FAO, 2020). Figure 4 presents heatmaps illustrating the total greenhouse gas emissions (in kilotons) across five regional convergence clubs, as identified through the Phillips and Sul convergence test [72]. These heatmaps visually represent emissions trends from 1990 to 2020, highlighting the disparities in emission patterns across regions. This regional analysis underscores the need for context-specific mitigation strategies and informs the ICEMF framework by emphasizing the importance of spatially explicit emission modeling.



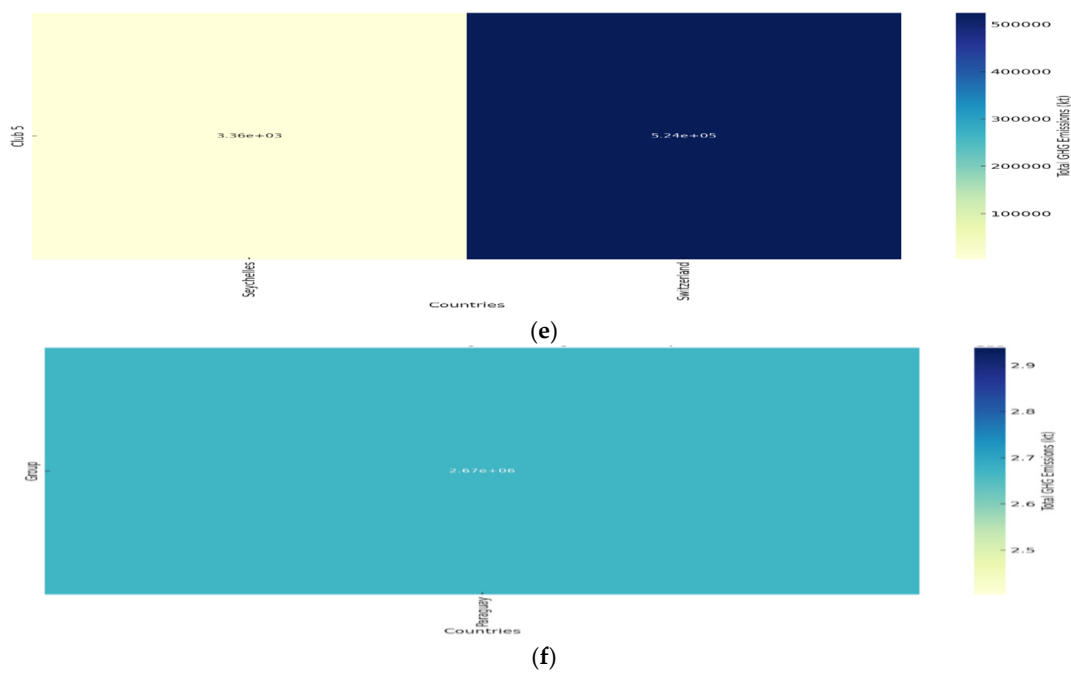


Figure 4. Heatmaps illustrate total greenhouse gas emissions (in kilotons) in agriculture sector from 1990 to 2020 for countries within five distinct regional clubs: Club 1 (a), Club 2 (b), Club 3 (c), Club 4 (d), Club 5 (e), and a separate Paraguay group (f). Each heatmap shows the total emissions for each country within a specific club, with a colour gradient ranging from light yellow (low emissions) to dark red (high emissions), enabling a visual comparison of emissions across the different regions.

Mukwada, Taylor [73] reported that the trends also reveal significant regional disparities. Developed countries have shown modest declines in emissions due to improved nutrient-use efficiency, conservation tillage, and climate-smart practices, while developing nations continue to face steep increases as agricultural expansion meets food security demands. Studies highlight that rice and maize systems dominate CH₄ and N₂O contributions, respectively, while wheat and soybean systems contribute substantial CO₂ through soil and land-use related emissions [74]. Moreover, climate change feedback loops, including rising temperatures and extreme weather events, exacerbate emission rates and reduce the mitigation capacity of soils [75]. Although progress has been made in quantifying emissions, gaps remain in capturing indirect sources such as post-harvest processes and regional variability in emission factors, emphasizing the need for refined monitoring frameworks and targeted interventions [76]. Table 2 presents a summary of key studies highlighting the sources and trends of greenhouse gas emissions in agriculture, their drivers, and regional or system-specific notes.

Table 2. Sources and Trends of Greenhouse Gas Emissions in Agriculture.

Study	Greenhouse Gas Contribution	Key Drivers	Regional / System Notes
Wei, Dong [66]	CO ₂ , CH ₄ , N ₂ O	Developed vs. developing country emissions	Highlights disparities in contributions to climate change
Biswas, Chakma [67]	CH ₄ , N ₂ O	Agricultural soils and global warming potentials	Case study on emission patterns from Indian soils
Mateo-Sagasta, Zadeh [68]	CO ₂ , N ₂ O	Fertilizer runoff, water pollution	Links water pollution and agricultural emissions globally
van Loon, Hijbeek [69]	CH ₄ , N ₂ O	Intensification and cereal cropping	Sub-Saharan Africa identified as emission hotspot

Gerten, Heck [70]	CO ₂ , CH ₄	Cropland expansion, planetary boundaries	Food production scenarios and sustainability trade-offs
Kim, Grieco [71]	N ₂ O, CH ₄	Smallholder farming challenges	Focus on mitigation opportunities in Sub-Saharan Africa
Mukwada, Taylor [73]	Mixed (CO ₂ , CH ₄ , N ₂ O)	Climate variability and food insecurity	Case study from Lesotho, showing regional disparities
Mehmood, Wang [74]	CO ₂ , CH ₄	Irrigation management, soil processes	Winter wheat systems in North China Plain
El-Hawwary, Brenzinger [75]	CO ₂ , CH ₄ , N ₂ O	Abandonment of agriculture, soil processes	Highlights post-agriculture emission risks
Srivastava and Maity [76]	Mixed (CO ₂ , CH ₄ , N ₂ O)	Climate change adaptation, artificial intelligence and machine learning (AI-ML) tools	Stresses monitoring gaps and future opportunities

3.2. Evaluation of Crop and Soil Management Practices

Crop and soil management practices are central to reducing GHG emissions from agriculture. Conservation tillage, cover cropping, and crop diversification have been shown to enhance soil organic carbon stocks and reduce CO₂ release by minimizing soil disturbance and improving residue retention [77]. Agroforestry systems contribute to long-term carbon sequestration while also providing ecosystem services such as biodiversity support and microclimate regulation [78]. Biochar application has emerged as a promising soil amendment, capable of enhancing soil structure, microbial activity, and long-term carbon storage while mitigating CH₄ and N₂O fluxes [79]. In temperate agricultural regions, biochar demonstrates substantially more consistent and predictable soil CO₂ emissions mitigation effects compared to no-till agriculture, which exhibits high climate and soil-dependent variability [80]. Biochar application increases soil organic carbon sequestration by 61% across temperate zones [80], with moderate confidence intervals between 36 - 90%, and decreases annual CO₂ emissions by 13.0–17.6% within 1–2 years [81], whereas no-till effectiveness in temperate regions depends critically on soil texture, organic carbon content, and precipitation patterns [82], with future projections showing declining mitigation potential of only 1.4 - 1.7 Mg ha⁻¹ over 30 years under climate change scenarios [83]. The superior consistency of biochar in temperate climates stems from its intrinsic recalcitrance, with 97% of biochar carbon persisting in stable form with mean residence times of approximately 556 years [84], rendering it largely independent of temperate climate fluctuations in temperature and precipitation. In contrast, no-till effectiveness in temperate regions is fundamentally constrained by soil-specific properties and temporal dynamics of seasonal carbon fluxes [85], making it a less reliable climate mitigation strategy compared to biochar application. Biochar reduced N₂O emissions by 16.2% based on meta-analysis of 119 paired observations from 18 studies [86], whereas no-till agriculture reduced N₂O by 11% (95% CI: -19 to -1%) from 212 observations across 40 studies [87], indicating substantially greater variability in no-till effectiveness (Table 3).

Table 3. Recommended management strategies for N₂O mitigation in temperate agricultural regions.

Strategy	Mean N ₂ O Reduction (%)	Meta-Analysis Details	95% Confidence Interval	Study
Biochar Alone (20 Mg ha ⁻¹)	16.2%	n = 119 observations, 18 studies	9.8 - 22.6% (estimated)	[86]
Biochar + Fertilizer	38.8%	n = 250+ observations, pooled from 18 meta-analyses	Highly variable	[88]

Biochar (Field Studies Only)	18%	n = 33 field studies (27 Asia, 5 North America, 1 Europe)	-10% to +35%	[89]
No-Till/Reduced Tillage	11%	n = 212 observations, 40 publications	-19% to +1%	[87]
Conservation Tillage	-17.8% (Increase)	n = 212 observations, 40 publications	Temperate moderate; Tropical +70.1%	[90]

Research has identified multiple interconnected mechanisms through which biochar reduces soil N₂O emissions in agricultural systems. Rather than operating through a single pathway, biochar's effectiveness derives from synergistic interactions among five primary mechanisms, each contributing differentially to overall N₂O reduction (Figure 5 a). Nitrogen immobilization and adsorption represent the first major mechanism (30% of effect), operating through direct adsorption of NH₄⁺ and NO₃⁻ onto biochar's aromatic carbon surface, thereby reducing substrate availability for nitrification and denitrification pathways that produce N₂O [91]. Complete denitrification enhancement represents the second dominant mechanism (30% of effect), functioning through biochar's electron shuttle effect that facilitates electron transfer to soil denitrifying microorganisms and promotes the final reduction of N₂O to N₂ through upregulation of nosZ genes encoding N₂O reductase [92].

Three secondary mechanisms contribute the remaining 40% of mitigation effect: soil physical modification (17.5%) through increases in mesopore size and specific surface area that enhance aeration; soil pH modification (12.5%) through the liming effect that reduces nitrification in acidic soils; and microbial community shifts (10%) that reduce ammonia-oxidizing archaea while promoting N₂O-reducing bacteria [91,93]. These interconnected mechanisms produce consistent field-observed N₂O reductions of 18-54%, with substantially greater reductions (84%) when biochar is combined with nitrogen fertilization [88,89,94].

The high variability in no-till N₂O responses ranging from 19% reductions to 70% increases [87,90] stems from the fundamentally production-enhancing nature of its primary mechanisms (Figure 5 b). Unlike biochar, which operates through multiple N₂O reduction pathways, no-till's mechanisms predominantly enhance conditions favorable for N₂O production. The dominant mechanism, enhanced denitrification through moisture accumulation (47.5%), creates anaerobic microsites where incomplete denitrification predominates. No-till significantly increased soil denitrification by 85% compared to conventional tillage, with a 33% increase in the (nirK + nirS)/nosZ gene ratio, indicating that N₂O is released rather than being further reduced to N₂ [95]. This moisture-induced denitrification is particularly problematic in humid temperate regions where water-filled pore space frequently exceeds 70%, creating sustained anaerobic conditions. Substrate availability from residue accumulation (22.5%) and soil compaction effects (17.5%) further promote N₂O production by providing carbon for denitrifiers and restricting oxygen penetration [95,96]. Variable nitrification responses (12.5%) add complexity depending on local moisture regimes [96]. The mechanistic basis for no-till's inconsistency contrasts fundamentally with biochar's reliability. Where biochar's mechanisms actively convert N₂O to N₂ and immobilize nitrogen substrates, no-till's mechanisms create conditions favoring N₂O production. This explains why meta-analysis shows conservation tillage increased N₂O by 17.8% on average [90], despite some studies reporting reductions. For temperate regions prioritizing consistent N₂O mitigation, biochar's reduction-focused mechanisms represent a more reliable approach than no-till's production-enhancing pathways.

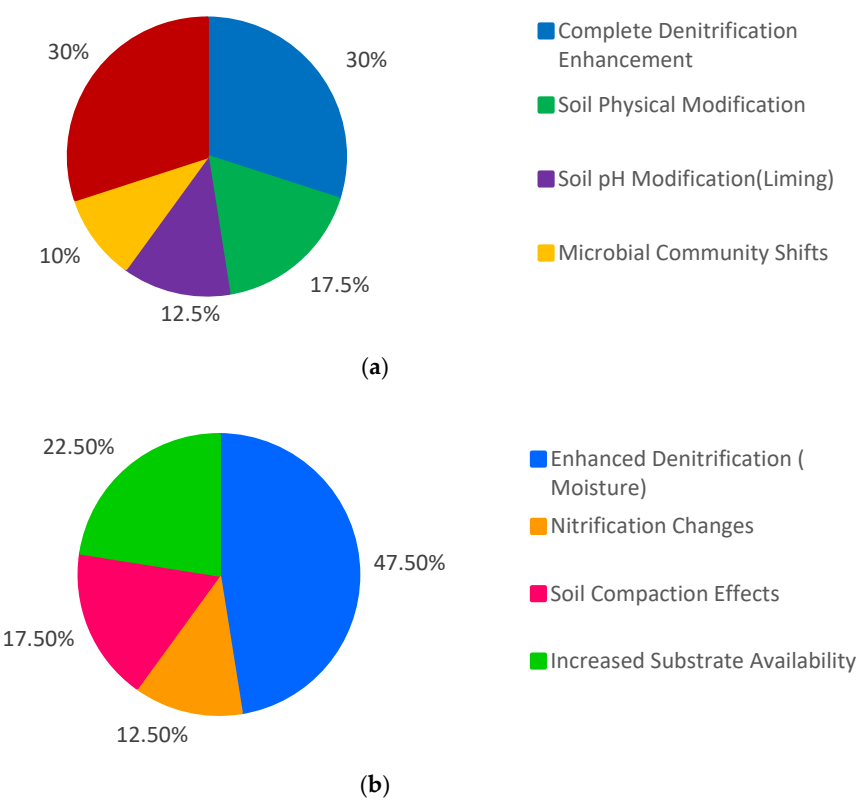


Figure 5. Mechanism distribution comparison reveals opposing pathways driving divergent N₂O outcomes. (a) Biochar: Five reduction-focused mechanisms nitrogen immobilization (30%), complete denitrification enhancement (30%), physical modification (17.5%), pH modification (12.5%), and microbial shifts (10%) produce consistent 18-54% N₂O reductions [91,92,94]. (b) No-till: Four production-enhancing mechanisms enhanced denitrification via moisture (47.5%), substrate accumulation (22.5%), compaction (17.5%), and variable nitrification (12.5%) produce variable outcomes from -19% to +70% (Mei et al., 2018; Van Kessel et al., 2020; Xue et al., 2023)[87,90,95]. Mechanism direction explains consistency: biochar promotes N₂O→N₂ conversion; no-till creates anaerobic conditions favoring N₂O production. This fundamental difference accounts for biochar's superior reliability for N₂O mitigation in temperate agricultural systems.

Crop rotation is a key practice in sustainable farming, involving the sequence of planting various crops in the same field over multiple seasons to enhance soil fertility and productivity. It is distinct from other methods, such as intercropping and monoculture (monocropping) [97]. Crop rotation increases soil carbon sequestration and lowers CO₂ emissions [98]. The case study by Lötjönen and Ollikainen [99] outlines the environmental benefits of crop rotation over monoculture, particularly in terms of reduced fertilization needs, lower nitrogen runoff, and decreased greenhouse gas emissions. Rotating legumes, like clover-wheat, also lowers GHGs emissions and nitrogen runoff [99,100]. Crop rotation helps reduce CO₂ emissions by improving soil organic matter (SOM) and minimizing the need for tillage and fertilizers. Systems that incorporate legumes and perennials enhance carbon input and sequestration over time [101,102]. Al-Musawi, Vona [103] highlights the significance of various crop rotation systems for both agricultural and environmental sustainability. The authors explain that crop rotation can notably improve soil structure and organic matter levels, as well as boost nutrient cycling. Additionally, when legumes are incorporated into rotations instead of monoculture systems in Europe, soil organic carbon increases by up to 18%. This practice also helps reduce greenhouse gas emissions, promote carbon sequestration, and lower nutrient leaching and pesticide runoff. Legume-based rotations also influence other greenhouse gases. By improving nitrogen efficiency, these rotations can decrease N₂O emissions by as much as 39% [104]. In flooded rice systems, rotating with upland crops like maize or sorghum can reduce CH₄ emissions by up to 84% by interrupting anaerobic soil conditions [105]. Similarly, improved irrigation techniques, such

as alternate wetting and drying (AWD) in rice systems, have demonstrated the potential to lower CH₄ emissions without reducing yields [106]. These strategies underscore the technical viability of soil- and crop-based interventions, though their outcomes are often highly context-specific and influenced by environmental and management factors [107].

Despite their potential, significant challenges limit the widespread adoption of these practices. Research indicates variability in mitigation outcomes due to soil type, climate conditions, and crop management intensity, making generalized recommendations difficult [108]. For example, while no-till farming may enhance soil carbon in temperate zones, its benefits in tropical systems remain inconsistent [109]. Economic and social barriers, including high costs of inputs, lack of farmer awareness, and limited access to technologies, also hinder uptake [110]. Moreover, long-term impacts are not always well documented, with short-term studies dominating the literature and leaving uncertainties about sustainability over decades [111]. Addressing these gaps requires integrative approaches that combine technical innovations with enabling policies, financial incentives, and knowledge-sharing networks to promote scalable, farmer-centered solutions [112]. Table 4 summarizes key studies on crop and soil management practices, highlighting their potential for GHG mitigation along with associated challenges and limitations.

Table 4. Evaluation of Crop and Soil Management Practices.

Study	Focus Area	Key Findings	Limitations / Challenges
Al Amosh and Khatib [77]	Conservation practices	Environmental innovations reduce carbon emissions	Context limited to healthcare sector, transferability to agriculture debated
Nungula, Chappa [78]	Agroforestry systems	Provides ecosystem services, improves soil carbon, biodiversity	Requires long-term investment and land-use planning
Ullah, Malekian [79]	Biochar application	Enhances soil structure, microbial activity, and reduces CH ₄ /N ₂ O	Feasibility depends on cost, production scalability
Setyanto, Pramono [106]	Irrigation practices (AWD in rice)	Reduced CH ₄ emissions without yield loss	Adoption limited by water management infrastructure
Sharna, Anik [107]	Adoption drivers	Social, institutional, and environmental factors shape soil management practices	Adoption uneven, influenced by local context
Lagacherie, Alvaro-Fuentes [108]	Soil resource management	Mitigation strategies proposed for Mediterranean soils	Region-specific insights, not widely generalizable
Somasundaram, Sinha [109]	No-till farming	Improved soil carbon in temperate systems	Benefits inconsistent in tropical conditions
Durga, Schmitter [110]	Irrigation barriers	Identifies socio-economic challenges in technology uptake	High cost and lack of farmer awareness
Hocherman, Trop [111]	Governance timelines	Reviews time lags in environmental policy outcomes	Limited focus on agricultural-specific governance
Vicente-Vicente, Borderieux [112]	Agroecology scaling	Highlight's role of knowledge-sharing and networks	Adoption dependent on community-level participation

Al-Musawi, Vona [103]	Crop rotation	Highlights benefits of crop rotation and discusses how crop rotation mitigates greenhouse gas emissions	focused on mainly temperate regions such as Europe and North America Adoption and outcomes among smallholder and subsistence farmers are limited
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3.3. Nitrous Oxide Mitigation through Nutrient Management

Agricultural systems are responsible for significant emissions of N₂O, one of the most potent greenhouse gases, mainly due to the application of nitrogen fertilizers and the use of manure. Nutrient management strategies therefore play a pivotal role in reducing N₂O emissions. The “4R” framework right source, right rate, right time, and right placement of fertilizers has consistently been shown to improve nitrogen use efficiency and curb unnecessary losses to the atmosphere [113]. The adoption of enhanced efficiency fertilizers, including slow-release formulations and nitrification inhibitors, further reduces emission intensity while maintaining crop productivity [114]. Precision agriculture technologies such as site-specific nutrient application and sensor-guided irrigation are also gaining traction for optimizing inputs and minimizing hotspots of N₂O production [115]. In rice-based systems, the integration of water-saving irrigation with balanced nutrient management offers significant reductions in both N₂O and CH₄ emissions, supporting multiple climate benefits [116].

However, widespread adoption of these approaches faces both technical and socio-economic challenges. Regional disparities in fertilizer access, affordability, and farmer training often limit implementation in smallholder-dominated agricultural systems [117]. In some contexts, nitrification inhibitors and enhanced efficiency fertilizers remain prohibitively expensive, while their long-term environmental effects are still debated [118]. Additionally, studies highlight a lack of harmonized emission factors for diverse cropping systems, leading to uncertainty in estimating mitigation potential at larger scales [119]. Research also underscores the need for long-term field experiments to validate laboratory or short-duration results, particularly in tropical and semi-arid regions [120]. Without supportive policies, subsidies, and knowledge-sharing mechanisms, the effectiveness of nutrient management as a mitigation strategy will remain underutilized [121,122]. Table 5 outlines key studies on nutrient management strategies for nitrous oxide mitigation, emphasizing technical advances, adoption barriers, and future research needs.

Table 5. Nitrous Oxide Mitigation through Nutrient Management.

Study	Focus Area	Key Findings	Limitations / Challenges
Pandit, Adhikari [113]	4R Nutrient Stewardship	Improved NUE, reduced maize yield gap, and higher profitability	Requires farmer training and monitoring systems
Getahun, Kefale [114]	Precision agriculture	Systematic review shows potential for sustainable production	Limited adoption in smallholder systems
Dirlik, Uğurlar [115]	Sensor-guided irrigation	Reduced water uses and improved efficiency in tomato production	High initial technology cost
Wang, Zhang [116]	Water-saving irrigation in rice	Lowered CH ₄ and N ₂ O emissions, improved water efficiency	Dependent on irrigation infrastructure
Benson [117]	Fertilizer access in Malawi	Highlights regional disparities in affordability and access	Smallholders face affordability barriers

Tyagi, Ahmad [118]	Nitrogenous fertilizers	Discusses sustainability challenges and mitigation strategies	Enhanced fertilizers costly, long-term effects uncertain
Nemecek, Schnetzer [119]	Crop inventories	Provided harmonized GHG emission factors	Data gaps across cropping systems
Kamdi, Swain [120]	Field experiments in sorghum	Developed adaptation strategies for semi-arid tropics	Needs long-term validation across regions
Shah and Wu [121]	Soil and crop strategies	Ensured productivity and sustainability	Requires integration with policy support
Rowe, Withers [122]	Legacy phosphorus use	Proposed sustainable nutrient management strategies	Limited large-scale application evidence

3.4. Socio-Economic and Policy Dimensions of Adoption

While technical interventions for reducing GHG emissions in agriculture are well established, their large-scale adoption is often constrained by socio-economic realities.

Farmers face barriers such as limited access to credit, insecure land tenure, and inadequate extension services, all of which reduce their willingness or ability to invest in sustainable practices [123]. Studies show that adoption rates of conservation tillage, precision nutrient management, and agroforestry remain low in developing regions despite their proven benefits, largely due to upfront costs and perceived risks [124]. Knowledge gaps and lack of training further hinder uptake, especially among smallholder farmers, who form the backbone of global food production [125]. Gender and social inequalities also influence adoption, as women farmers often have less access to resources, technologies, and decision-making platforms [126].

Policy frameworks play a decisive role in shaping adoption outcomes. Well-designed incentives, including subsidies for biochar, carbon credits for agroforestry, and payments for ecosystem services, can accelerate the uptake of mitigation practices [127]. However, the effectiveness of such policies depends on transparent monitoring, verification, and enforcement mechanisms [128]. Market-based approaches, such as carbon trading, are gaining prominence, but they often overlook small-scale farmers and risk exacerbating inequalities [129]. Integrated CSA policies that combine financial support, capacity building, and technology dissemination are essential to overcome these limitations [129]. Strengthening institutional support, aligning national climate commitments with local agricultural strategies, and promoting participatory approaches to policy design can further enhance adoption [130,131]. Table 6 synthesizes socio-economic and policy dimensions affecting the adoption of agricultural GHG mitigation practices, highlighting barriers, incentives, and institutional mechanisms.

Table 6. Socio-economic and Policy Dimensions of Adoption.

Study	Focus Area	Key Findings	Limitations / Challenges
Mahapatra and Lenka [123]	Credit access	Identified barriers in agri-business financing	Limited rural credit availability restricts adoption
Tranchina, Reubens [124]	Agroforestry adoption	High upfront costs and risk perception reduce uptake	Adoption low despite proven benefits
Duffy, Toth [125]	Smallholder agroforestry	Contributes to food security and resilience	Lack of training and extension support
Shahbaz, Ul Haq [126]	Gender and CSA practices	Women’s involvement enhances adoption of climate-smart agriculture	Women face unequal access to resources and decisions

Mayr, Pokorny [127]	Payments for ecosystem services	Incentives can accelerate agroforestry adoption	Effectiveness depends on long-term monitoring
Zhelyazkova [128]	Policy transparency	Transparent enforcement supports adoption	Weak compliance undermines effectiveness
Olabanji and Chitakira [129]	CSA scaling in South Africa	Market and institutional frameworks drive adoption	Smallholders excluded from benefits in some contexts
Dinesh, Zougmore [130]	Science-policy engagement	Strengthens CSA adoption pathways	Requires multi-level collaboration
Baker, Nye [131]	Participatory agri-environment design	Aligns schemes with farmer needs and nature recovery	Implementation challenges persist

3.5. Integrated Approaches and Future Pathways

The complexity of GHG emissions in agriculture highlights the need for integrated approaches that combine technical, ecological, and socio-economic dimensions.

Studies increasingly point to the effectiveness of multi-practice systems, such as combining conservation tillage with biochar application and precision nutrient management, which generate cumulative benefits for carbon sequestration, yield stability, and emission reduction [132]. Integrated crop–livestock systems offer another pathway, recycling organic residues and manure to enhance soil fertility while lowering N₂O and CH₄ emissions [133]. Similarly, CSA frameworks emphasize regenerative practices, diversification, and resilience-building measures that address both mitigation and adaptation needs [134]. The use of digital tools, including remote sensing, artificial intelligence, and decision-support systems, has further strengthened the potential of integrated strategies by enabling more accurate monitoring and site-specific interventions [135].

Looking forward, the future of agricultural GHG mitigation depends on scaling these integrated approaches through supportive policies and international cooperation. Long-term field experiments and region-specific trials are essential to validate the durability and effectiveness of proposed strategies [136]. Emerging innovations such as microbial amendments, carbon farming markets, and recoupled energy–agriculture systems offer promising new avenues but require careful socio-economic and environmental assessment [137]. Bridging the gap between smallholder realities and global climate goals remains a critical challenge, calling for inclusive financing mechanisms, equitable access to technologies, and participatory governance [138]. By uniting scientific advances with farmer-driven practices and robust institutional frameworks, integrated approaches provide a pathway for achieving sustainable and verifiable emission reductions in line with international climate targets [139–141]. Table 7 compiles key studies on integrated approaches and future pathways, emphasizing technological, ecological, financial, and policy innovations for agricultural GHG mitigation.

Table 7. Integrated Approaches and Future Pathways.

Study	Focus Area	Key Findings	Limitations / Challenges
Srivastava [132]	Conservation tillage	Improved soil health and reduced GHG emissions	Benefits vary by soil and climate conditions
Swarnam, Velmurugan [133]	Crop–livestock integration	Reduced N ₂ O and CH ₄ emissions, enhanced fertility	Requires resource availability and management capacity

Vidadala [134]	Regenerative agroforestry	Promotes climate-resilient landscapes	Long adoption timelines and land-use trade-offs
Karada, Khan [135]	Digital & AI tools	Internet of Things (IoT) and Artificial intelligence (AI) improve site-specific nutrient and water use	High cost and infrastructure needs
Udomkun, Rupngam [136]	Regenerative soil management	Novel scoring system for SOC and GHG monitoring	Limited regional validation
Musa and Ariff Lim [137]	Smart technologies	Systematic review shows climate mitigation potential	Requires socio-economic feasibility studies
Adegbite and Machethe [138]	Financial inclusion	Access to finance enhances adoption of CSA	Gender gaps persist in smallholder agriculture
Doukas, Nikas [139]	Policy integration	Stresses integrative approaches to Paris goals	Requires alignment of global and local policies
Schneider and La Hoz Theuer [140]	Carbon markets	Analyzed integrity of Paris mechanisms	Risk of inequitable benefit distribution
Paipa-Sanabria, González-Montoya [141]	Green technologies	Novel mitigation for air/water impact in shipping	Lessons need adaptation to agriculture context

The application of ICEMF in practice requires addressing key barriers such as financial limitations, technology adoption, and socio-economic contexts. Case studies from regions where mitigation strategies have been implemented (e.g., agroforestry in Sub-Saharan Africa) could help validate the framework and refine its predictions. Future research should prioritize long-term field experiments and integrate more localized data to test ICEMF's scalability. Moreover, exploring socio-economic barriers to adoption, such as access to capital and knowledge gaps, will be crucial in improving the practical applicability of the ICEMF framework in different agricultural systems.

3.6. Expanded Policy Implications:

Agricultural policy frameworks need to be tailored to support the adoption of mitigation practices at different scales. For example, the introduction of carbon credits for sustainable practices, such as agroforestry, can incentivise farmers to adopt climate-smart practices. Additionally, policies should include technical support such as training programs and access to low-cost technologies. The ICEMF framework can guide policymakers in designing region-specific policies that combine technical, financial, and socio-economic aspects, ensuring that interventions are both effective and equitable.

4. Addressing Gaps in ICEMF

While the ICEMF presents a novel approach to connecting farm-level agricultural practices with GHG reduction targets, several key gaps must be addressed to enhance its applicability, scalability, and long-term effectiveness. These gaps are outlined in the following areas: long-term validation, improved socio-economic adoption data, region-specific case studies, and methodological inconsistencies.

4.1. Long-Term Validation

ICEMF's current theoretical stage requires long-term field validation to assess the sustained impact of the proposed mitigation strategies. Although empirical data support the potential for

emission reductions through practices such as agroforestry, reduced tillage, and biochar application, significant uncertainty remains about the long-term effectiveness of these strategies. For example, how do soil health improvements and GHG reductions evolve over multiple growing seasons or decades? Long-term studies will be essential to capture seasonal variability, the impacts of climate change, and the effects of soil regeneration, ensuring that mitigation practices are both reliable and adaptive over time. Moreover, there is a need for field trials that compare ICEMF-driven practices with conventional farming systems to confirm the real-world benefits across diverse agricultural systems.

4.2. Improved Socio-Economic Adoption Data

One of the significant challenges facing the ICEMF framework is the adoption of mitigation strategies by farmers, particularly in low-resource and smallholder contexts. The integration of socio-economic data into ICEMF is crucial for understanding the barriers to adoption and how socio-economic conditions influence farmers' decision-making. These conditions include access to capital, knowledge, technology, and secure land tenure. For instance, the upfront costs of implementing ICEMF-based practices such as biochar application or precision fertilization may deter farmers from adopting them. Studies show that farmers in developing regions face substantial barriers, including limited access to credit, perceived risks, and a lack of market incentives [12]. To address these barriers, more data is needed on farmer behavior, the effectiveness of financial incentives (e.g., carbon credits), and how government policies can support adoption. Integrating socio-economic modelling into ICEMF will provide better insights into how policies, subsidies, and training programs can be structured to encourage widespread adoption of GHG mitigation practices.

5.3. Region-Specific Case Studies

While ICEMF offers a global framework for agricultural GHG mitigation, its effectiveness will vary significantly across regions due to differences in climatic conditions, soil types, and farming systems. There is a lack of region-specific case studies that demonstrate how ICEMF can be tailored to local conditions. For example, while agroforestry may be a highly effective practice in tropical regions, its applicability in temperate regions may be more limited due to differences in crop types and climate conditions. Likewise, practices like no-till farming may have varying degrees of effectiveness depending on soil texture, precipitation patterns, and crop rotation systems. Region-specific case studies are critical for testing the framework's adaptability and for refining ICEMF to meet the unique needs of different agricultural systems. In particular, there is a need for cross-regional comparisons that evaluate how the same practice may result in different outcomes in terms of GHG reductions, productivity, and economic viability. These studies will help policymakers and farmers understand how to adapt mitigation strategies to suit local contexts and increase the scalability of ICEMF.

5.4. Methodological Inconsistencies and Standardization

Another critical gap is the lack of standardized methodologies for measuring the impact of ICEMF on GHG emissions. Currently, there is a wide variation in how emission reductions are quantified across studies, with differing methods, emission factors, and LCA boundaries. This inconsistency makes it challenging to compare results across regions and systems. To strengthen ICEMF, there is a need for harmonized metrics for emission measurement that can be applied consistently across diverse agricultural practices and environmental contexts. Furthermore, the integration of advanced technologies, such as remote sensing, artificial intelligence, and machine learning, can enhance the accuracy and scalability of emission modelling, ensuring that ICEMF can be applied to a variety of farming systems globally. Standardizing monitoring, reporting, and verification (MRV) systems will also be crucial for tracking the progress of mitigation strategies and ensuring that they meet global GHG reduction targets.

6. Bridging the Gaps with Case Studies

To demonstrate the practicality and applicability of the ICEMF, several real-world case studies offer valuable insights into the framework's potential to reduce agricultural GHG emissions while maintaining productivity. The following case studies showcase how agricultural practices integrated into the ICEMF framework contribute to global emission reduction targets and regional sustainability goals. For examples: 1) Agroforestry in Southeast Asia. In Indonesia, agroforestry systems have been employed to mitigate carbon emissions and enhance biodiversity. Studies in West Java have shown agroforestry carbon stocks ranging from 74 to 320 Mg ha⁻¹, depending on system age and tree diversity, with mixed-tree systems demonstrating the highest sequestration potential [142]. While agroforestry can contribute to greenhouse gas mitigation, effects on CH₄ and N₂O emissions vary by system type, with soils under agroforestry oxidizing 1.6 kg CH₄ ha⁻¹ yr⁻¹ and emitting 7.7 kg N₂O ha⁻¹ yr⁻¹ on average [143]. However, high rainfall and fluctuations in moisture can lead to challenges in nitrogen cycling and N₂O emissions, affecting the long-term sustainability of these practices. ICEMF's spatial emission modelling would predict the effectiveness of agroforestry in such regions, accounting for local soil types and moisture levels to optimize GHG reductions. Additionally, socio-economic adoption pathways would ensure that policies and incentives are tailored to the specific needs of farmers in these regions, facilitating widespread adoption. 2) No-Till and reduced tillage practices in the United States. The United States has promoted no-till farming as a conservation practice to reduce soil erosion and potentially sequester carbon. Long-term research from the Kellogg Biological Station over 30 years shows that no-till fields accumulated more soil carbon and had lower global warming impact than conventionally tilled fields, primarily due to greater soil carbon accumulation rather than direct CO₂ emission reductions [144]. However, soil moisture and temperature variability in tropical climates may limit the effectiveness of no-till in regions such as Southeast Asia, where soil compaction and high rainfall can impact the long-term success of this practice. ICEMF's approach would evaluate the effectiveness of no-till in temperate regions using region-specific models that factor in soil moisture and crop type. The framework would also recommend adaptive techniques for temperate zones, ensuring that no-till is integrated with socio-economic support systems for farmers to implement the practice successfully. 3) In Germany and other temperate European regions, biochar application has demonstrated potential for reducing soil N₂O emissions. A meta-analysis indicates overall N₂O reductions of 16.2% across diverse agricultural systems [86]. Long-term field studies in temperate regions confirm biochar maintains its N₂O reduction efficiency even after 4-6 years of ageing, contributing to sustained climate mitigation and improved soil quality [91]. Biochar's effectiveness is particularly pronounced in temperate zones, where seasonal fluctuations have less influence on soil microbial activity. In contrast, its effectiveness in tropical climates may be reduced due to high moisture levels and rapid decomposition of organic matter, which could limit its long-term carbon sequestration potential. ICEMF would model the long-term effectiveness of biochar in different climates, ensuring that its application is prioritized in temperate regions and adapted to tropical systems based on local soil and moisture conditions. The framework's spatially explicit models would provide specific recommendations on how biochar can best be applied to maximize GHG mitigation, depending on the region and soil type. 4) Precision Fertilization in India. In the Indo-Gangetic Plains of India, including Punjab, site-specific nutrient management using the Nutrient Expert (NE) tool has shown potential for mitigating greenhouse gases. Field trials across 1,594 comparison plots showed that NE-based fertilizer recommendations reduced global warming potential by 2.5% in rice and 12-20% in wheat compared to farmers' conventional fertilization practices [145]. While precision nitrogen management tools such as Leaf Color Charts developed by Punjab Agricultural University can reduce N fertilizer application by 51 kg N/ha in rice and 29 kg N/ha in wheat [146], Punjab remains challenged by chronic over-fertilization, with regions applying N higher than recommended doses on a long-term basis, leading to soil health deterioration [147]. ICEMF can integrate precision fertilization practices into its spatial emission models by assessing soil types, crop management practices, and regional climate conditions. The framework could optimize the use of fertilizers while accounting for regional variability in soil

health, moisture, and temperature. Additionally, by incorporating socio-economic adoption pathways, ICEMF can ensure that these practices are accessible to farmers in low-resource regions by providing financial incentives, subsidies, and knowledge-sharing programs. 5) Crop Rotation and Legume Integration in Europe. In southwestern France, low-input cropping systems incorporating grain legumes (33 kg N ha⁻¹ year⁻¹) showed reduced reliance on synthetic fertilizers compared to conventional cereal-based systems (96 kg N ha⁻¹ year⁻¹), though N₂O emissions were slightly higher in the legume-based system (1.12 vs. 0.78 kg N₂O-N ha⁻¹ year⁻¹) due to increased nitrogen cycling from biological nitrogen fixation. Nevertheless, these systems enhanced nitrogen efficiency and offered environmental benefits, including reduced nitrate leaching and pesticide use [148]. Crop rotation, especially legume integration, is a valuable strategy in ICEMF's toolkit for enhancing soil health and mitigating GHGs. ICEMF can integrate legume-based crop rotations into its regional emission models, using spatially explicit data to assess how soil types, climate conditions, and crop management systems influence GHG reductions and carbon sequestration. The framework can assess the carbon sequestration potential of different crop rotations across various regions, helping tailor mitigation strategies based on local soil and climate conditions.

7. Conclusion

This review highlights the central role of agricultural crop systems in global GHG emissions and the diverse strategies available for mitigation. Practices such as conservation tillage, biochar application, precision nutrient management, crop diversification, and integrated crop-livestock systems show strong potential to reduce emissions while enhancing soil health and productivity. However, significant gaps remain in the literature. One major issue is the lack of long-term validation of these strategies across diverse regions and environmental conditions. Additionally, while much focus has been placed on the technical potential of these interventions, socio-economic barriers, such as land tenure issues and financial limitations, have not been sufficiently addressed.

Thematic analysis reveals that soil-based, crop-based, nutrient-oriented, and policy-driven measures are interconnected, yielding cumulative benefits when implemented in conjunction. However, their effectiveness remains context-dependent, shaped by regional conditions, socio-economic constraints, and policy frameworks. The importance of addressing these gaps is evident: without consideration of socio-economic factors, the scalability of these practices is limited, particularly in developing regions. Moreover, without proper long-term validation, the actual impact of mitigation strategies on GHG emissions remains uncertain.

The proposed ICEMF provides a novel pathway for linking practice-level interventions with global mitigation goals, offering both scientific and practical insights. To achieve meaningful emission reductions, strategies must be adapted to local realities, supported by enabling policies, and scaled through inclusive, farmer-centered approaches that align agricultural development with climate objectives. To move forward, future research should prioritize region-specific field trials and the development of integrated decision-support tools that combine technical, environmental, and socio-economic data. These tools will ensure that mitigation strategies are not only practical but also equitable and scalable, enabling policymakers to design inclusive and sustainable solutions to combat climate change.

Limitation and future work: Broader long-term field validation and socio-economic integration are needed to strengthen evidence and scalability.

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Abbreviations

The following abbreviations are used in this manuscript:

alternate wetting and drying	AWD
artificial intelligence and machine learning	AI-ML
carbon dioxide	CO ₂
climate-smart agriculture	CSA
Greenhouse gas	GHG
greenhouse gases	GHGs
Integrated Assessment Models	IAMs
Integrated Crop Emission Mitigation Framework	ICEMF
Internet of Things	IoT
life cycle assessment	LCA
Low-Emission Development Strategies	LEDS
methane	CH ₄
monitoring, reporting, and verification	MRV
nitrous oxide	N ₂ O
Nutrient Use Efficiency	NUE
Nutrient Expert	NE
Soil Organic Carbon	SOC

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