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Contributing Factors to Greenhouse Gas Emissions in Agriculture for Supporting Sustainable Development Goals (SDGs): Insights from a Systematic Literature Review Completed by Computational Bibliometric Analysis

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ABSTRACT

Agricultural production contributes significantly to greenhouse gas (GHG) emissions and global climate change. This study conducts a systematic literature review to examine the evolution and drivers of agricultural GHG emissions. We analyzed Web of Science, Scopus, and Google Scholar data using bibliometric and thematic methods. Our analysis identified emission sources such as energy use, soil management, fertilizer application, and livestock management. It also discussed mitigation measures such as sustainable practices, precision agriculture, and renewable energy. The findings showed that crop cultivation, livestock activities, and land-use change remained key sources of emissions. Technological innovations and policy-driven strategies are reshaping the research landscape. This study provides a framework for understanding agricultural GHG emissions and supporting interventions to reduce the sector's carbon footprint as well as Sustainable Development Goals (SDGs).

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1. INTRODUCTION

Agriculture feeds people. That is the reason many reports regarding agriculture [1-12]. However, it also emits about 24 % of human-caused greenhouse gases. Most emissions come from livestock management and crop cultivation. Land-use practices and soil also add substantial emissions [13-15]. These activities release carbon dioxide, nitrous oxide, and methane [16, 17]. Livestock operations account for over 44 % of methane emissions. Fertilizer use and soil degradation drive most nitrous oxide emissions [18-20]. Rising food demand and intensification have increased emissions [21]. Precision agriculture and renewable energy can cut emissions [22-27]. Agroforestry, minimum tillage, and crop rotation can also reduce emissions [28, 29]. Carbon pricing and subsidies for low-emission technologies support reduction efforts [30, 31]. Agricultural systems vary by region. Local policies must reflect social, economic, climatic, and ecological contexts [32-34]. For example, Sub-Saharan Africa and Southeast Asia require frameworks different from those of Europe and North America [35, 36].

Several literature reviews have examined sources of agricultural greenhouse gas (GHG) emissions and corresponding mitigation strategies. One study explored emission-reduction strategies in crop production and livestock management [37]. Another integrated climate-smart agriculture practice to reduce emissions while enhancing system resilience [38]. Global contributions of agricultural subsectors to GHG emissions have been mapped in detail [13]. Fertilizer use and soil management have been identified as major drivers of N_2O emissions [39]. The impact of precision agriculture technologies on both productivity and emissions has also been investigated [22]. A systematic review of farm-level mitigation policies in the UK offered additional insights [40]. Carbon shadow prices along the Belt and Road Initiative have been analyzed to assess emission costs [41]. A comprehensive review of carbon farming practices within the EU provided policy-relevant perspectives, though limited in generalizability beyond the European context [42]. Life cycle assessments on primary pig production have been synthesized, albeit with limited applicability to integrated agricultural systems [43]. Mechanisms for soil carbon sequestration via biochar have been explored, yet socio-economic and policy barriers remain underexamined [44]. While these studies offer valuable insights, they often lack interdisciplinary integration, comparative evaluation of regional mitigation practices, and analyses of policies that support the adoption of new technologies. This research aims to address these gaps by developing a holistic theoretical framework and empirically evaluating mitigation strategies across diverse regional contexts.

This study develops a theoretical framework through a systematic literature review and bibliometric and thematic analyses. It identifies the primary sources and pathways of greenhouse gas emissions in agriculture, traces their evolution, and evaluates current mitigation strategies. It focuses on key production functions such as fertilizer use, enteric fermentation, and soil management. This analysis examines how technological innovations and policies affect emission patterns. It identifies four primary emission sources. These sources are enteric fermentation, fertilizer-driven nitrous oxide, carbon dioxide from tillage and machinery, and indirect energy inputs. It highlights a shift from quantifying emissions to solution-oriented research. Key approaches include carbon sequestration, precision agriculture, and renewable energy. The findings offer insights for designing sustainable agricultural practices that balance economic and environmental goals and support climate change mitigation. This study supports current issues in the sustainable development goals (SDGs).

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2. METHODS

The study followed PRISMA 2020 guidelines for reproducibility [45-47]. The methodology had seven sequential stages. The first stage defined eligibility criteria. The second stage identified information sources and set the search strategy. The third stage defines research questions. The fourth stage carried out the selection process. The fifth stage handled data collection and management. The sixth stage involved data cleaning and refining. The seventh stage involved conducting data analysis and visualization.

2.1. Eligibility Criteria

We included only English-language; peer-reviewed articles published by 31 July 2024. We required each article to address greenhouse gas emissions in agricultural production. We excluded conference proceedings, technical reports, non-peer-reviewed materials, and articles without full-text access [46, 48].

2.2. Information Sources and Search Strategy

We searched Scopus and Web of Science between August 1 and 7, 2024. We also ran queries in Google Scholar to collect all relevant peer-reviewed studies [50, 51]. We applied the Boolean string ("greenhouse gas emissions" OR "GHG emissions") AND ("agricultural production" OR "farming" OR "crop production" OR "livestock emissions") to titles, abstracts, and keywords. This search returned 504 unique records. **Figure 1** shows the Python script we used to build and verify the query.

```
# Define main and secondary terms for the Boolean search

main_terms = ["greenhouse gas emissions", "GHG emissions"]

secondary_terms = ["agricultural production", "farming", "crop production", "livestock
emissions"]

# Construct the Boolean search string

main_query = " OR ".join([f"({term})" for term in main_terms])

secondary_query = " OR ".join([f"({term})" for term in secondary_terms])

boolean_search_string = f"({main_query}) AND ({secondary_query})"

# Display the final search query

print("Boolean Search String:")

print(boolean_search_string)
```

Figure 1. Python code for constructing the Boolean search string for agricultural GHG emissions literature.

2.3. Defining Research Questions

We posed three guiding questions: (RQ1) What are the prevailing research themes in agricultural GHG emissions? (RQ2) How have these themes evolved? (RQ3) What roles do different production processes play in generating emissions? **Figure 2** shows the conceptual framework for RQ1. **Figure 3** shows the temporal framework for RQ2.

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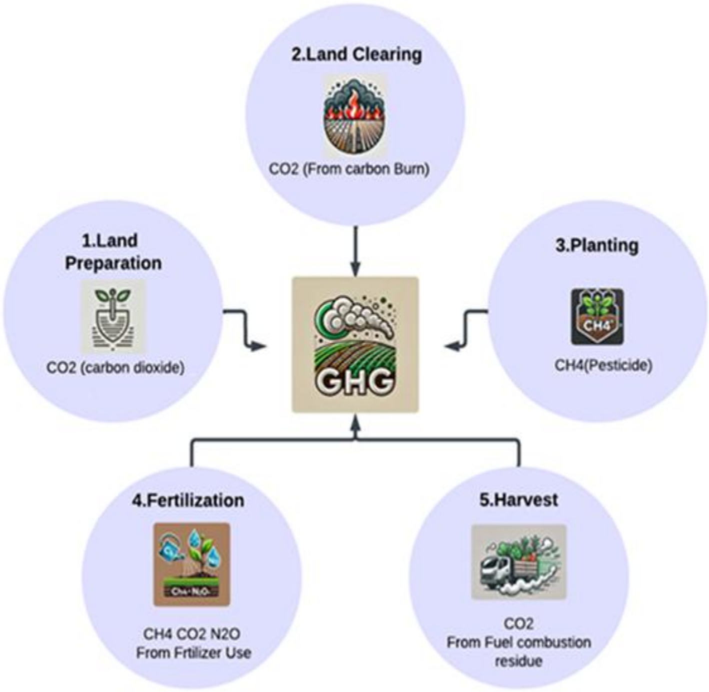

Figure 2. Agricultural GHG emissions schematic.

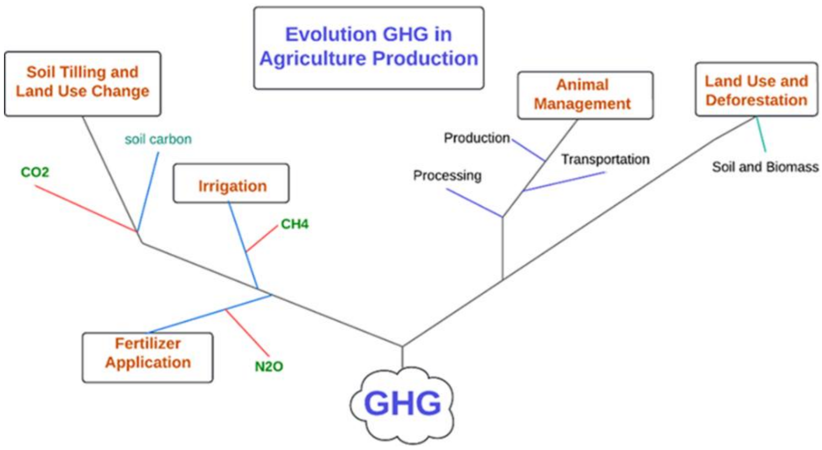

Figure 3. Schematic diagram illustrating the yearly evolution of research topics in GHG emissions in agricultural production.

2.4. Selection Process

Out of 150 full-text articles that met the initial inclusion criteria, 41 did not report quantitative GHG data and were excluded. This left 109 articles for the final analysis. Figure 4 shows the PRISMA 2020 flow diagram of records identified, screened, and included in the review of greenhouse gas emissions in agriculture [52].

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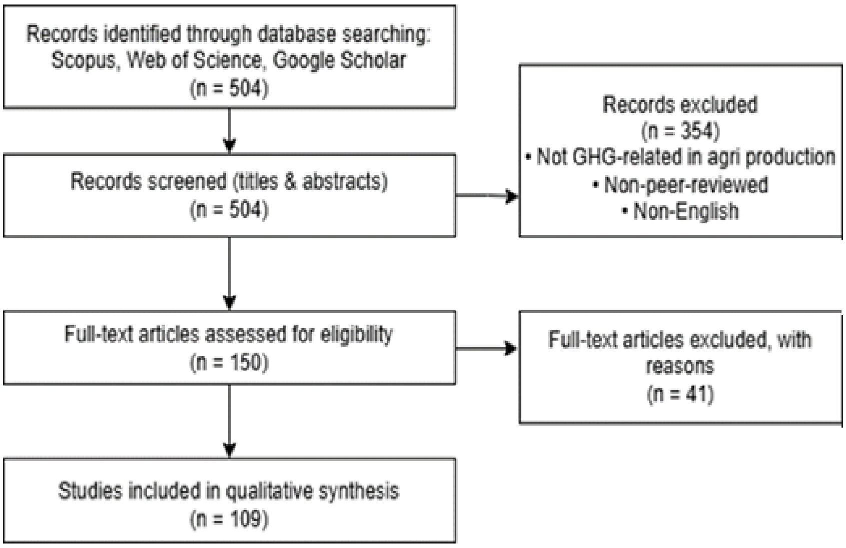

Figure 4. PRISMA 2020 diagram of agricultural GHG review.

2.5. Data Collection and Management

Metadata for the 150 included articles was exported from Mendeley Desktop in BibTeX format, encompassing title, abstract, authors, journal, year, citation count, DOI, and keywords. We manually verified and corrected all entries against Crossref and publisher websites to ensure accuracy [53, 54].

2.6. Data Cleaning and Refining

We imported the cleaned BibTeX data into Biblioshiny (Bibliometrix v4.1 in R 4.2.1) to create a structured data frame [55]. The metadata of each document, including title, authors, journal, year, DOI, keywords, and citations, was standardized. We resolved missing entries via Crossref, removed duplicates by DOI and title, and harmonized author names and keyword variants [56, 57]. Full texts were then analyzed in Leximancer 4.5 using a customized stop-word list and sensitivity of 0.8 to generate robust thematic datasets [58].

2.7. Data Analysis and Visualization

We applied three platforms for comprehensive insight: Biblioshiny for co-citation analysis, keyword co-occurrence mapping (threshold ≥ 5), Louvain clustering, and temporal trend charts; Leximancer for tf-idf-weighted concept maps across thirty themes; and VOSviewer for co-authorship network visualization [59-61]. Outputs include the PRISMA flow diagram, network graphs, thematic evolution charts, concept maps, and author-network diagrams, together offering a multi-angled perspective on agricultural GHG emissions research.

3. RESULTS AND DISCUSSION

This chapter shows our bibliometric and thematic analysis results. We validated the data by cross-checking with standard literature indicators. The chapter addresses the three research questions from Chapter I. First, we examine research themes and publication trends. Second, we analyze annual shifts in those themes. Third, we assess the impact of production processes on GHG emissions. Each section presents concise, data-driven results. Each section ends with a brief discussion that compares our findings to those of previous studies.

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3.1. Research Themes and Publication Trends in Agricultural GHG Emissions

Figure 5 shows that from 1997 to July 2024, 109 articles addressed GHG emissions in agriculture. Annual counts were low and variable before 2009 (e.g., two articles in 1997, under 1 per year in the late 1990s, and 1-2 articles annually through 2009). After 2009, publications increased steadily, with 3 in 2010, peaking at 10 in 2013, then dipping to 4 and 3 in 2014-2015 before stabilizing at 5-9 per year from 2016 to 2022. By July 2024, three articles had been published. The average annual growth since 2010 was about 8%, reflecting growing research interest in agricultural GHG emissions.

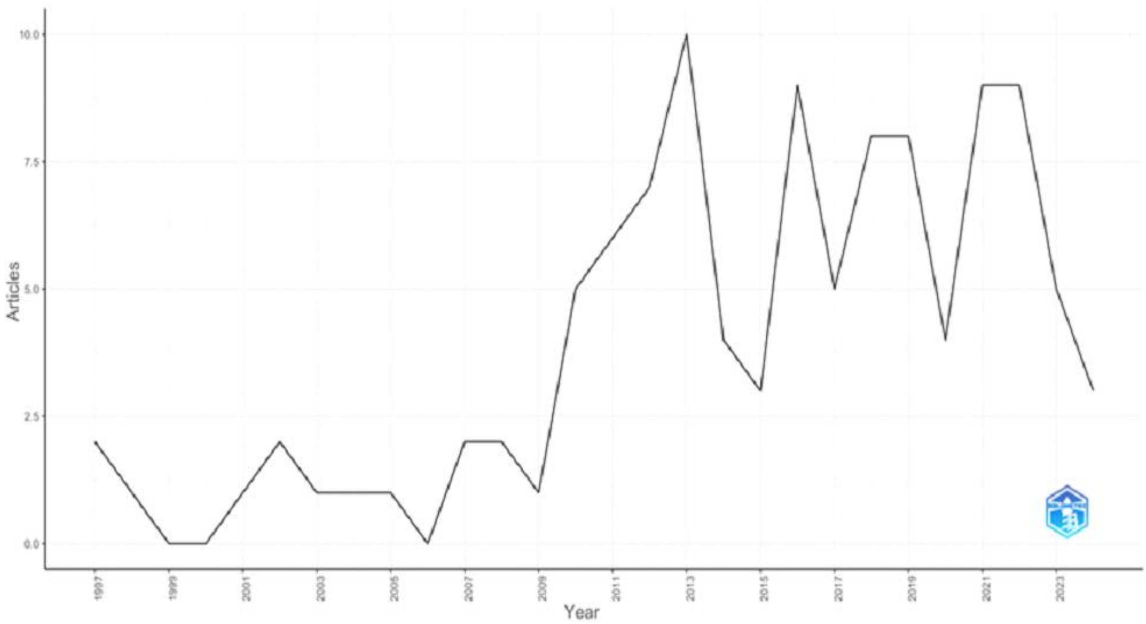

Figure 5. Annual scientific production trend on GHG emissions in agricultural production.

The increase in publications around 2013 likely reflects intensified research funding and policy focus following the IPCC's Fifth Assessment Report and the Paris Agreement [62-64]. The slight dip in 2014-2015 may indicate a transitional lag as scholars shifted from quantification to mitigation studies [65, 66]. From 2017 onward, there has been more work on precision agriculture, using soil sensors and drones for targeted fertilizer and irrigation [67-70]. Recent studies suggest that this approach can reduce N_2O emissions by 15-20% through optimized inputs [71, 72].

The thematic map in **Figure 6** identifies four quadrants. Motor themes (high development and relevance) include climate change mitigation, soil organic carbon, and carbon sequestration. Niche themes (high development, low relevance) cover sustainability, energy use, and urban agriculture. Basic themes (high relevance, low development) split into two clusters: measurement and evaluation ("global warming potential," "life cycle assessment," "greenhouse gas emissions") and core emission terms ("greenhouse gases," "methane," "mitigation"). Emerging/declining themes (low development and relevance) feature agroforestry, GHG emission, reduced tillage, and biochar.

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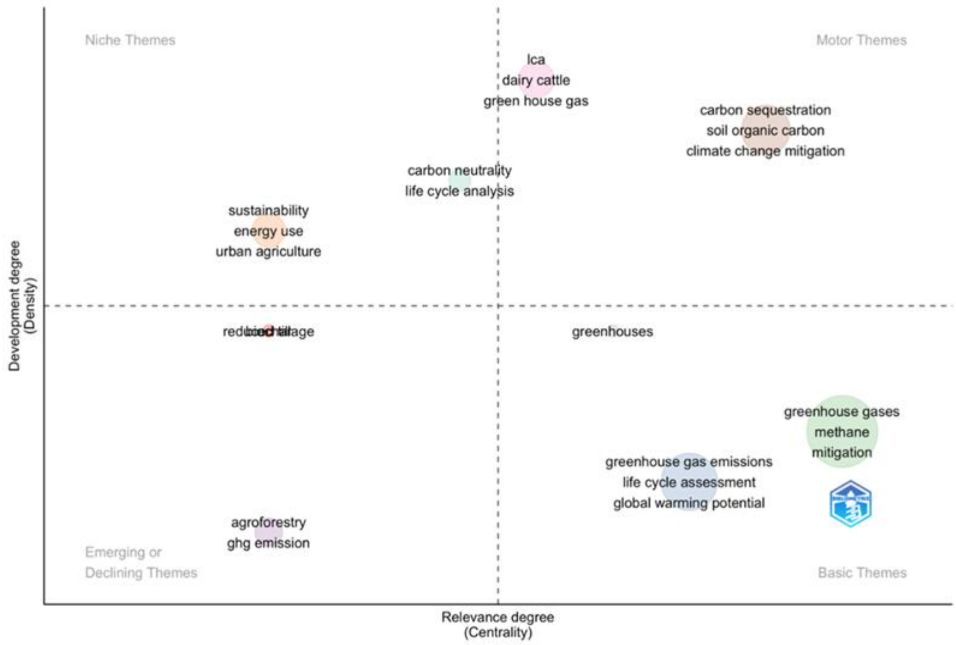

Figure 6. Thematic map.

Motor themes shift from measuring emissions to focusing on solutions [73, 74]. Niche themes show a growing interest in specific sustainable practices [75, 76]. Basic themes show the continued importance of standard metrics [77, 78]. The emerging and declining cluster points to future study areas such as biochar and reduced tillage techniques [79, 80].

The treemap in **Figure 7** shows keyword frequencies. “Greenhouse gas emissions” appears in 7% of records. “Greenhouse gases” and “methane” each account for 6%. “Mitigation” appears in 5% of records. “Carbon footprint” appears in 4%. The keywords “carbon dioxide,” “nitrous oxide,” and “climate change” each appear in 4%. “Life cycle assessment,” “carbon sequestration,” and “global warming potential” each appear in 3%. Lesser-used terms like “renewable energy,” “IoT,” and “biochar” account for 1-2%. These lesser-used terms indicate emerging technological and policy trends.

The keyword distribution shows that the field is evolving. Early studies focused on quantification. Recent studies pair measurement with mitigation strategies and new technologies [81, 82]. This trend suggests that future research must explore under-represented topics. These topics include precision technologies and policy integration [83-85].

3.2. Annual Evolution of Research Topics in Agricultural GHG Emissions

Figure 8 shows that research on agricultural GHG emissions evolved through distinct periods. From 1997 to 2011, studies focused on carbon dioxide, mitigation, and greenhouse gas emissions. From 2012 to 2014, researchers explored agriculture, methane, global warming potential, life cycle assessment, and greenhouse gas emissions. From 2015 to 2018, they studied greenhouse gas emissions, carbon footprint, carbon sequestration, and sustainability in life cycle assessment. From 2019 to 2021, they focused on carbon footprint, carbon sequestration, and greenhouse gases. From 2022 to mid-2024, they focused mainly on their carbon footprint.

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Figure 7. Tree map of the theme.

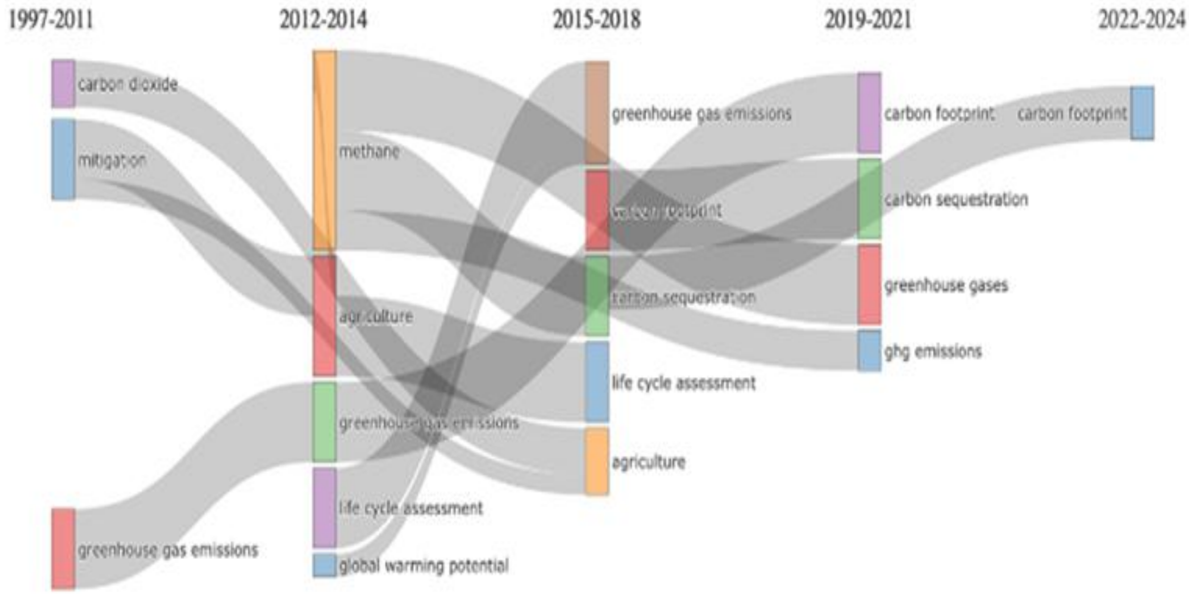

Figure 8. Thematic evolution.

Figure 9 shows a conceptual map with three clusters. The biochar cluster focuses on biochar as a carbon-mitigation technology. The mitigation solutions and technology cluster include greenhouses, renewable energy, IoT, carbon neutrality, and life cycle analysis. The basic topics cluster covers greenhouse gas emissions, plant production, soybean, policy, and global warming potential. **Figure 10** tracks keyword emergence over time. Carbon dioxide first appeared around 2006. Nitrous oxide emerged around 2010-2011. Methane and mitigation spiked in 2011-2012. “Greenhouse gas emissions” peaked in 2013, and “GHG emissions” in 2016. “Carbon sequestration” appeared and peaked around 2015-2016. “Carbon footprint” rose sharply around 2018.

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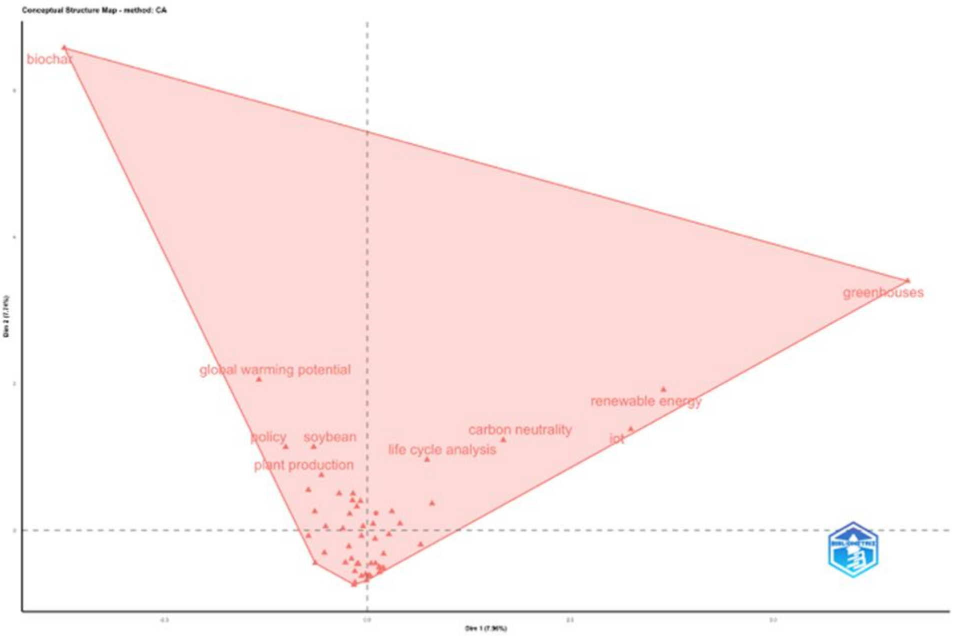

Figure 9. Conceptual map and keywords' cluster.

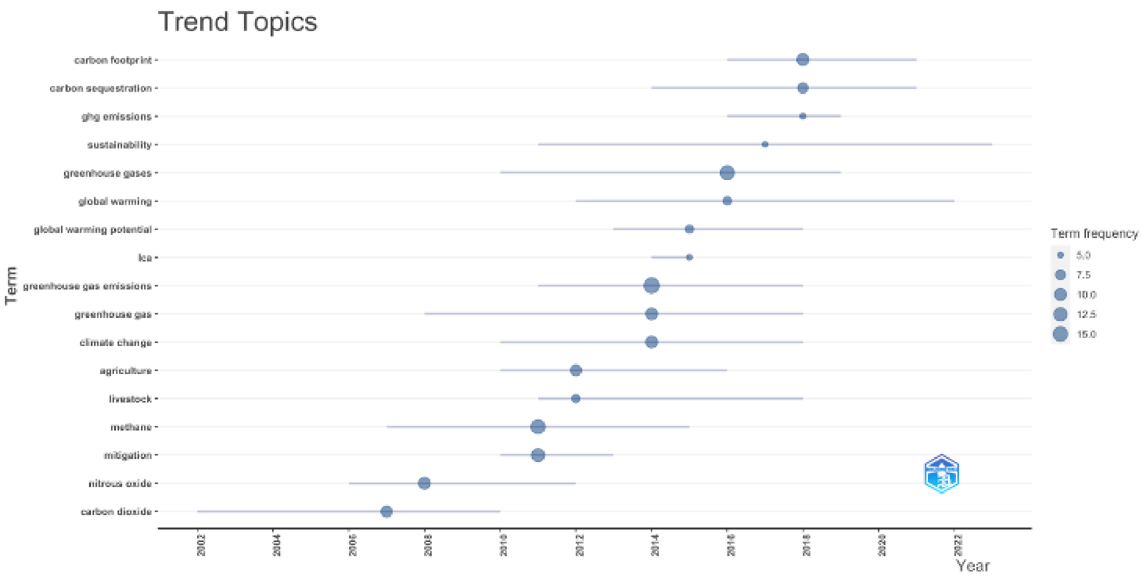

Figure 10. Yearly trend of greenhouse gas emissions in agriculture

These patterns show a progression from early quantification (1997-2011) to methodological and impact assessment (2012-2014) and finally to solution-oriented research (2015-2024). A strong focus on life cycle assessment during 2012-2018 reflects the emphasis in literature [86, 87]. The rise of carbon sequestration after 2015 matches post-Paris Agreement priorities. The dominance of carbon footprint since 2022 highlights a growing emphasis on emission accountability. The biochar cluster supports several data points [44, 88, 89] on biochar's role in soil carbon storage. The mitigation solutions and technology cluster confirm previous data [24, 90, 91] on integrating IoT and renewable energy into low-emission agriculture. The basic topics cluster underlines an enduring focus on emission metrics and policy frameworks.

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3.3. Influence of Agricultural Production Processes on GHG Emissions

Figure 11 shows that "Production" appears in 18,686 co-occurrences. It covers all stages, from planting and harvesting to processing and waste management. It captures direct emissions (e.g., enteric CH_4 from livestock) and indirect CO_2 from machinery. "Emissions" appears in 17,091 records. It highlights CH_4, N_2O, and CO_2 and follows IPCC quantification standards. The "Soil" theme appears in 11,635 hits. It links tillage and fertilization practices to N_2O emissions and carbon sequestration potential. The "Crop" theme appears in 10,001 hits. It covers crop-specific impacts, such as anaerobic rice paddies, and mitigation via rotation. "Energy" appears in 8,821 hits. It covers fossil-fuel use in machinery, transport, and fertilizer production. The "Climate" cluster appears in 6,060 hits. It links agricultural emissions to carbon pricing and resilience policies. "IPCC" appears in 976 hits. It underscores the role of standardized GHG accounting for transparency and cross-country comparison. Minor themes include data availability, oil, review, and the USA. They point to gaps in data access, fossil-fuel influence, the importance of review syntheses, and a U.S. policy emphasis.

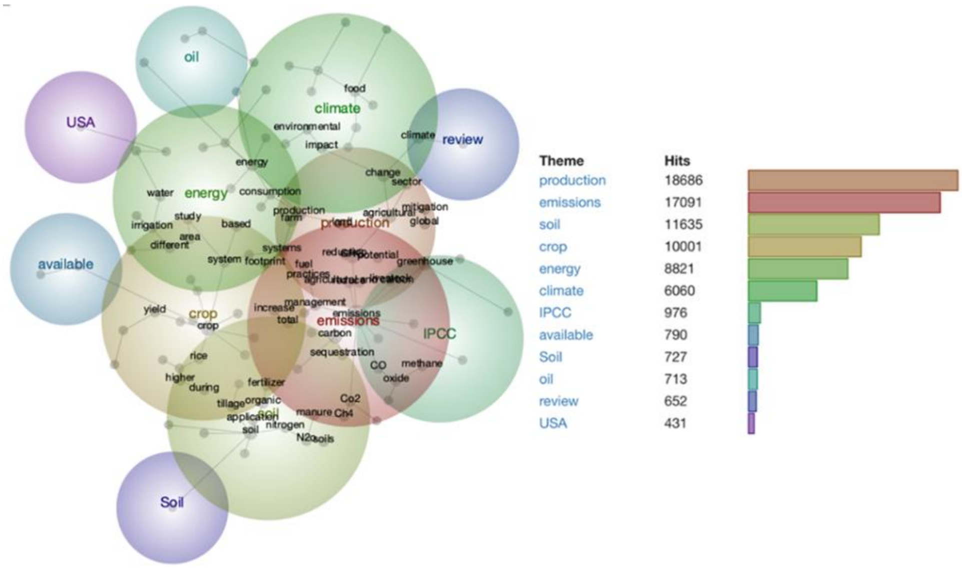

Figure 11. Cloud words of interconnected concepts of GHG.

These patterns confirm a holistic supply-chain perspective on emissions [92-94] and emphasize livestock management's role in enteric CH_4 and manure emissions. Soil conservation measures such as reduced tillage and cover crops emerge as key to lowering N_2O, while crop choices and rotations [95-97], such as alternative rice varieties with managed irrigation, offer CH_4 reductions [98-100]. The energy cluster highlights the urgency of shifting to low-emission machinery and renewable energy [101-103]. Precision agriculture techniques, including sensor-based fertilization, targeted pesticide application, and precision irrigation, show 10-15% reductions in N_2O and CO_2 [104-106]. Finally, the prominence of climate policy and IPCC standards underscores their necessity for guiding low-carbon agricultural practices [107, 108].

3.4. Greenhouse Gas Emissions Factors in Agriculture

Greenhouse gas (GHG) emissions from the agricultural sector are one of the main contributors to global climate change [109]. These emissions arise from various activities related to crop cultivation, livestock farming, and land management. In general, the main sources of greenhouse gas emissions in agriculture involve methane (CH_4), nitrous oxide

(N_2O), and carbon dioxide (CO_2), which are released through biological, chemical, and mechanical processes that occur in agricultural production activities [110].

Methane is a greenhouse gas that has a global warming potential of about 28-36 times greater than CO_2 (depending on whether various indirect climate effects are included) over 100 years [111]. In the agricultural sector, methane is mainly produced through anaerobic fermentation or the decomposition of organic matter without oxygen. Anaerobic fermentation is a biological process carried out by microorganisms (especially methanogenic bacteria) to decompose organic matter in an oxygen-free (anaerobic) environment [112]. This process produces various gases, with methane (CH_4) as one of the main products, besides CO_2 and H_2. In the agricultural context, anaerobic conditions are often created due to stagnant water, accumulation of organic waste, or closed or unaerated waste management. Anaerobic fermentation involves four main stages [113], including:

(i) Hydrolysis. Hydrolysis is the process of breaking down large organic polymers such as cellulose, proteins, and fats into smaller, water-soluble molecules such as glucose, amino acids, and fatty acids. This stage relies on the enzymatic activity of microorganisms such as Clostridium and Bacillus, which secrete cellulase, protease, and lipase enzymes. However, hydrolysis is often the main limiting step, especially for high-fiber wastes such as straw. The general macromolecular reactions that occur in this stage are: Carbohydrates → Glucose; Protein → amino acids; Fat → glycerol + fatty acids.
(ii) Acidogenesis. The products of hydrolysis then enter the acidogenesis stage, where acidogenic bacteria such as Lactobacillus and Peptostreptococcus ferment them into organic acids (especially acetate, propionate, and butyrate), alcohol, and H_2 and CO_2 gases.
(iii) Acetogenesis. The products of the acidogenesis stage become important substrates for the acetogenesis stage, where compounds such as propionate and butyrate, which cannot be directly used by methanogens, are converted into acetic acid, H_2, and CO_2 by acetogenic bacteria such as Syntrophomonas in a syntrophic relationship with methanogens. This stage is very dependent on a low partial pressure of H_2 so that the reaction remains thermodynamically favorable.
(iv) Methanogenesis. Finally, in the methanogenesis stage, methanogenic archaea such as Methanosarcina and Methanobacterium convert acetic acid and hydrogen into methane (CH_4) and carbon dioxide. This process can take place via the acetoclastic pathway (using acetate) or the hydrogenotrophic pathway (using H_2 and CO_2).

The main sources of methane include [114]:

(i) Flooded rice fields. Flooded rice fields create an anaerobic environment in the soil, which supports the activity of methanogenic microbes. These microbes break down organic matter such as straw, compost, and crop residues into CH_4.
(ii) Enteric fermentation from ruminant livestock. Microorganisms in the rumen digest fiber through fermentation, producing methane, which is then released through belching and respiration of the livestock.
(iii) Livestock manure management. Livestock waste stored under anaerobic conditions (e.g., in ponds or tanks without aeration) will undergo fermentation, producing significant amounts of CH_4.

N_2O is a greenhouse gas with a GWP of about 298–300 times greater than CO_2, and is the most potent gas from the agricultural sector in terms of impacts on climate change and ozone depletion [115]. N_2O emissions from agricultural land occur mainly through the process of nitrogen transformation in the soil, which is mediated by the activity of soil microorganisms under certain environmental conditions [116]. The two main biological processes responsible

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are nitrification and denitrification [117]. In the nitrification stage, nitrogen in the form of ammonium (NH_4^+), resulting from the decomposition of organic matter or synthetic fertilizers, is converted into nitrate (NO_3^-) by nitrifying bacteria such as Nitrosomonas and Nitrobacter under aerobic conditions. In contrast, under anaerobic conditions, denitrification occurs when denitrifying bacteria such as Pseudomonas and Clostridium reduce nitrate (NO_3^-) to nitrogen gas (N_2), with N_2O as an intermediate product that can be released into the atmosphere. An imbalance in soil oxygen levels can cause N_2O accumulation due to incomplete denitrification.

Furthermore, N_2O emissions are greatly influenced by the amount and type of nitrogen applied, as well as the method and timing of fertilization. Over-application of nitrogen fertilizers, whether from synthetic sources such as urea or organic sources such as manure, can cause a surplus of nitrogen in the soil that cannot be absorbed by plants. This excess nitrogen then becomes a substrate for microorganisms that produce N_2O. Not only that, but irrigation systems and soil moisture play an important role. Soil that is saturated with water or frequently irrigated, such as in rice fields or fields that are not properly irrigated, creates an anaerobic environment that accelerates the rate of denitrification. This condition increases the possibility of N_2O formation [115]. Therefore, to reduce N_2O emissions from agriculture, efficient nitrogen management practices are needed, including the use of balanced fertilizers, controlled irrigation, and the selection of the right planting and fertilization times. Carbon dioxide (CO_2) is one of the main greenhouse gases released from the agricultural sector, both through natural processes and due to human intervention. In the context of agriculture, the sources of CO_2 emissions are very varied and interrelated. One of the main contributors is soil respiration and organic matter decomposition, in which soil microorganisms and plant roots use oxygen and release CO_2 as a by-product. This process is part of the natural carbon cycle, but can be greatly increased when there is a lot of rapidly decomposing organic matter, especially in soils that are frequently disturbed by plowing or intensive cultivation [116].

In addition, the burning of agricultural biomass, such as rice straw, corn stalks, or other crop residues used to clear land, is a significant contributor to the release of CO_2 directly into the atmosphere. This practice, which is still common in many rural areas, not only releases carbon but also removes the potential for organic matter to be returned to the soil as natural fertilizer. CO_2 emissions are also greatly influenced by the use of fossil fuels in agricultural mechanization activities, such as tractors, tillage machines, irrigation pumps, and other heavy equipment that use diesel or gasoline. The combustion of these fuels directly produces large amounts of CO_2, especially in modern and intensive agricultural systems. No less important is the impact of land use changes, especially the conversion of forests, shrubs, or peatlands to agricultural land. This deforestation process causes the release of massive amounts of carbon that were previously stored in vegetative biomass and soil. When trees are cut down, roots die, and soils are turned or drained, carbon stored for hundreds of years can be quickly released as CO_2. Overall, although some CO_2 comes from natural processes, human intervention in agricultural intensification, biomass burning, use of fossil fuel engines, and land conversion makes this sector one of the important contributors to increasing CO_2 concentrations in the atmosphere and accelerating the rate of climate change [117].

Based on the previous explanation, the detailed discussion of the biological, chemical, and mechanical processes or activities that occur in agricultural production activities that contribute to the production of greenhouse gas emissions is explained as follows.

(i) Use of synthetic nitrogen fertilizers

The use of synthetic nitrogen fertilizers in modern agricultural activities has an important role in increasing crop productivity, but is also one of the main sources of greenhouse gas

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emissions, especially nitrous oxide (N_2O) [118]. Fertilizers such as urea [$CO(NH_2)_2$], ammonium nitrate (NH_4NO_3), ammonium sulfate [$(NH_4)_2SO_4$], and other forms of nitrogen are absorbed by plants in the form of nitrate ions (NO_3^-) and ammonium ions (NH_4^+). However, only some of this nitrogen can be absorbed efficiently by plants. The remaining unabsorbed nitrogen will remain in the soil and trigger microbiological processes that can produce N_2O gas emissions into the atmosphere [119, 120]. The main processes that cause N_2O emissions from nitrogen fertilizers are nitrification and denitrification, which are part of the soil nitrogen cycle and are carried out by microorganisms such as Nitrosomonas, Nitrobacter, and Pseudomonas. Nitrification occurs under aerobic (oxygenated) conditions, where ammonium (NH_4^+) is gradually converted to nitrite (NO_2^-) and then to nitrate (NO_3^-). At this stage, a small amount of N_2O can be produced as a by-product, especially if oxygen is limited or soil conditions change to semi-aerobic. Meanwhile, denitrification is an anaerobic (oxygen-deficient) process, in which nitrate (NO_3^-) is reduced to nitrogen gas (N_2) through a series of stepwise reductions: $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ [121, 122]. In flooded, compacted, or organic-rich soil conditions (so that microbial respiration rates are high and oxygen is quickly depleted), this process becomes dominant and produces nitrous oxide (N_2O) as an intermediate product. If the reduction is incomplete due to a lack of donor electrons or microbial interference, N_2O will be released into the atmosphere before it has time to become harmless N_2 [123].

The level of N_2O emissions from soil are highly dependent on several factors [124, 125], including:

(a) Soil moisture: The more saturated the soil is with water, the more likely denitrification and N_2O emissions are.
(b) Temperature: Microbial activity increases at warm temperatures (25–35°C), accelerating nitrogen conversion and gas emissions.
(c) Soil pH: The optimal pH for nitrification activity is in the neutral range (6.5–7.5), while denitrification is more likely to occur at slightly lower pH.
(d) Organic matter content: High soil organic carbon content provides an energy source for denitrifying microorganisms, leading to more N_2O formation.
(e) Fertilizer type and dosage: Nitrate-based fertilizers are more direct in causing emissions than ammonium fertilizers, which still need to undergo nitrification.

In addition to biological and chemical aspects, the method of fertilizer application also has a major impact on the potential for N_2O emissions. Applying large amounts of fertilizer at once (broadcasting) increases the possibility of excess nitrogen that is not absorbed by plants. This is exacerbated by high rainfall or excessive irrigation, which can cause leaching (nitrate washing) and increased soil moisture, ideal conditions for denitrification. Meanwhile, fertilizer application with precision farming techniques, such as split application (division of fertilization time), deep placement (placement in the soil), or the use of nitrification inhibitors, has been shown to significantly reduce N_2O emissions [126].

Overall, N_2O produced from the use of synthetic nitrogen fertilizers has a global warming potential (GWP) almost 300 times greater than CO_2 over 100 years. This means that even though its concentration is lower than CO_2 in the atmosphere, the climate impact of each N_2O molecule is much greater. In addition to being a GHG, N_2O also acts as a stratospheric ozone-depleting gas, making it a dangerous pollutant in two environmental aspects at once. Therefore, efforts to manage nitrogen fertilization more efficiently and environmentally friendly manner are very important to reduce GHG emissions from the agricultural sector [118].

(ii) Enteric fermentation in livestock

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Enteric fermentation in ruminant livestock is one of the main sources of greenhouse gas emissions from the agricultural sector, especially in the form of methane gas (CH_4), which contributes significantly to global warming. This process naturally occurs in the rumen, which is the first part of the digestive system of ruminant animals such as cows, goats, and sheep, which is designed to digest feed materials rich in crude fiber, especially cellulose and hemicellulose, which cannot be digested directly by animal enzymes [127]. In the rumen, feed materials are fermented by a complex community of microorganisms, including cellulolytic bacteria, protozoa, and especially methanogenic archaea (methanogens). This fermentation produces volatile fatty acids (such as acetate, propionate, and butyrate), which are used by animals as an energy source, as well as by-products in the form of gases such as carbon dioxide (CO_2) and hydrogen (H_2). The hydrogen gas formed cannot accumulate in large quantities because it will disrupt the fermentation balance [127]. To maintain the stability of the rumen environment, the hydrogen is used by methanogenic microorganisms in the reduction reaction of CO_2 to methane (CH_4), through the process in reaction (1):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

The methane gas produced is not absorbed by the animal's body, but is released into the atmosphere mainly through eructation (belching), and in small amounts through respiration and excretion [128]. This emission is chronic and occurs every day throughout the life of the ruminant animal. The level of methane emission from enteric fermentation is greatly influenced by several factors [129]:

(a) Type and quality of feed: Feed with high crude fiber content (such as hay or straw) tends to increase methane production because fermentation produces more H_2. Conversely, high-quality feed (such as grain, corn silage) that is more easily digested tends to reduce CH_4 emissions.
(b) Type of animal and breed: Dairy cattle usually produce more methane than goats or sheep because of their larger body size and feed consumption.
(c) Physiological status and age: Pregnant, lactating, or fast-growing cattle have a higher metabolism and different digestion.
(d) Keeping system: Intensive farming with concentrate feed and proper nutrition.
(e) Management can reduce emissions compared to extensive farming with natural pastures.

Strategies to mitigate methane emissions from enteric fermentation include:

(a) Improved feed management: Providing feed with high digestibility, feed additives such as fat, tannins, or essential oils that can inhibit methanogenesis.
(b) Microbial vaccines or additives: Efforts to reduce the population of methanogens in the rumen biologically.
(c) Genetic selection of livestock: Selecting animals with high feed efficiency and lower gas production.
(d) Changes in livestock systems: Integration with agroforestry systems or sustainably managed pastures.

(iii) Ineffective livestock waste management

Ineffective livestock waste management is a major source of greenhouse gas emissions from the livestock sector, occurring when animal waste, either in solid (feces) or liquid (urine or a mixture of the two), is not properly treated. In such conditions, waste is often left to accumulate in open areas, holding ponds, or in uncovered storage tanks, creating an anaerobic (oxygen-poor) environment. These conditions are ideal for the growth of methanogenic microorganisms, a group of microbes that naturally degrade organic matter and produce methane gas (CH_4) as an end product [130].

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This anaerobic decomposition process involves complex biochemical stages, starting from hydrolysis (the breakdown of complex compounds into simple compounds), acidogenesis (the formation of organic acids), acetogenesis (the conversion of organic acids to acetate, hydrogen, and CO_2), to methanogenesis, which is the production of methane by special microorganisms using hydrogen and carbon dioxide or acetate. The general chemical reactions in this stage are shown in reactions (2) and (3) [131].

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (3)$$

In addition to methane, nitrous oxide (N_2O) can also be released, especially from waste management systems that undergo partial nitrification-denitrification processes, especially when there is fluctuation between aerobic and anaerobic conditions, for example, on the surface of open waste ponds [118]. Factors that influence GHG emissions from livestock waste include [132]:

(a) Animal type and waste volume: Cattle and pigs produce large volumes of waste with a high organic content, so emissions tend to be higher than poultry.
(b) Environmental temperature and humidity: High temperatures accelerate the activity of methanogenic microbes, thereby increasing gas production, especially in tropical areas.
(c) Storage systems: Open ponds are more prone to producing methane than closed or semi-closed systems.
(d) Storage time: Waste stored longer under anaerobic conditions produces more methane gas.
(e) A mixture of feces and urine: This combination increases the nitrogen and carbon content, which increases the potential for the formation of N_2O and CH_4.

If livestock waste is dumped directly onto land without processing (land spreading), in addition to polluting the soil and groundwater due to excessive nutrient content, it also contributes to the release of ammonia (NH_3) and N_2O from microbiological processes in the soil, depending on soil moisture and aeration conditions [131].

(iv) Intensive land management and cultivation practices

Intensive soil management and cultivation practices are an essential part of modern agricultural systems aimed at increasing productivity, but on the other hand, they also have a significant impact on greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These contributions come from various biological, chemical, and mechanical processes that occur due to human intervention in soils and agroecosystems [133].

First, intensive tillage such as plowing and hoeing carried out repeatedly using heavy equipment or tractors, increases soil aeration and accelerates the oxidation of organic matter in it. Under normal conditions, organic matter in the soil acts as a carbon sink, but when the soil is physically disturbed, organic carbon is converted to CO_2 and released into the atmosphere. This process accelerates the mineralization of organic matter and reduces long-term soil carbon stocks. In addition, the use of heavy equipment produces direct CO_2 emissions from the combustion of fossil fuels, thereby increasing the carbon footprint of the cultivation process [126].

Second, minimal crop rotation or monoculture systems (planting the same type of crop continuously) cause degradation of soil structure and a decrease in soil microbial diversity. Monoculture triggers an increase in the use of chemical inputs such as fertilizers, pesticides, and herbicides, which not only produce GHG emissions in the production process but also disrupt the nitrogen and microbial carbon cycles in the soil. This imbalance leads to increased

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N_2O emissions through the nitrification and denitrification processes by microorganisms, especially when nitrogen fertilizers are applied excessively [134].

Third, the practice of burning crop residues, such as rice straw or corn stalks, is still widely used to accelerate land clearing. This burning process results in the direct release of CO_2 into the atmosphere, as well as black carbon, a particulate component that has a very high global warming effect due to its ability to absorb solar heat. Black carbon also worsens air quality and has impacts on public health. In addition to CO_2 and black carbon, open burning also releases significant amounts of CH_4 and N_2O, depending on combustion conditions (whether perfect or not) [135].

Fourth, the use of synthetic pesticides and herbicides does not directly produce GHG when applied, but the production process based on industrial chemicals contributes to CO_2 emissions from fossil fuels. Once applied to the soil, these compounds also affect microbial activity, suppressing the population of microorganisms that play a role in natural nitrogen fixation and decomposition of organic matter, which in turn changes the dynamics of nutrient cycles and GHG emissions [136].

Fifth, soil compaction due to excessive heavy equipment or livestock traffic causes a decrease in porosity and water infiltration. Compacted soil is more susceptible to anaerobic conditions, especially in the rainy season or on irrigated land, potentially increasing methane and N_2O production from anaerobic microbial activity. These anaerobic conditions change the microbial respiration pathway from aerobic to fermentative, which is generally more efficient in producing GHG gases [137].

Sixth, intensification practices often ignore soil conservation-based approaches such as mulching, cover cropping, or agroforestry conservation, which play an important role in stabilizing soil organic carbon and reducing emissions [138].

Overall, intensive farming practices contribute to accelerated soil carbon loss, increased demand for synthetic inputs, and GHG releases from both soil, heavy equipment, and agricultural input production processes. Therefore, a transformation towards conservation and regenerative farming practices is essential to reduce GHG emissions [139]. Some recommended approaches include:

(a) Minimum tillage or no-tillage to maintain soil structure and carbon stocks.
(b) Crop rotation and cover crops to improve soil fertility and biological diversity.
(c) Utilization of crop residues for compost or mulch, not burning.
(d) Agroecological farming and reduction of excess chemical inputs.
(e) Flooded rice cultivation and its impact on methane emissions.

One agricultural practice known to produce high methane emissions is flooded rice cultivation. The waterlogged conditions of rice fields create an ideal anaerobic environment for methanogenic microbial activity, which degrades organic matter in the soil and produces CH_4 [140]. This process is influenced by temperature, soil type, rice variety, and organic inputs (e.g., manure or straw). Flooded rice cultivation contributes around 15–20% of global methane emissions from the agricultural sector [141]. Innovations such as alternate wetting and drying (AWD) have been shown to significantly reduce emissions without reducing crop yields [142].

The process of methane formation in rice field soil that remembers rice fields occurs when the rice field soil is flooded, and microorganisms in the soil adapt to anaerobic conditions, where oxygen is not available [112]. Under these conditions, methanogenic microbes, which are a type of anaerobic microbe, break down degraded organic matter (such as straw, rice plant roots, and manure) into methane (CH_4) as the final product [143]. This process generally occurs in several stages, namely:

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(a) Organic Acid Fermentation: Organic matter in the soil is broken down into organic acids by fermentative microbes (e.g., acidogenic bacteria) [144]

(b) Reduction of Organic Acids to Acetate: Some microbes then convert these organic acids to acetate (CH_3COO^-) [145]

(c) Methanogenesis: Methanogenic microbes, especially from the genera Methanobacterium and Methanosarcina, convert acetate to methane (CH_4) and carbon dioxide (CO_2). This process is part of the carbon cycle in flooded rice fields [146]. Reaction (4) shows the process of methane formation in rice field soil as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (4)$$

In this reaction, acetate (CH_3COOH), which is produced from the decomposition of organic matter, is converted by methanogenic microbes into methane (CH_4) and carbon dioxide (CO_2). This process shows how the activity of microorganisms in rice field soil can produce methane as a by-product [112, 140, 147].

(v) Land use changes, especially deforestation to open agricultural land

The largest contribution to climate change from the agricultural sector comes from land use changes, especially deforestation for the expansion of agricultural land and plantations. When forests are cut down, especially carbon-rich tropical forests, the carbon stored in biomass (stems, leaves, roots) is released as carbon dioxide (CO_2) into the atmosphere [148]. This process not only eliminates the forest's ability to absorb carbon (function as a carbon sink), but also releases previously stable soil carbon stocks. Land clearing by burning exacerbates GHG release and causes permanent soil degradation [149].

The process of carbon release due to deforestation and burning causes significant carbon release into the atmosphere [150]. Tropical forests, which store carbon in plant biomass such as stems, leaves, and roots, release carbon dioxide (CO_2) when burned or degraded. This burning process oxidizes carbon (C) in biomass to CO_2, as described in reaction (5) [151]:

$$C + O2 \rightarrow CO_2 \quad (5)$$

In addition, land clearing also disturbs the carbon stored in the soil. Tropical forest soil is rich in organic matter containing carbon, which is released into the atmosphere when the soil is disturbed. The process of decomposition of organic matter by microorganisms converts glucose ($C_6H_{12}O_6$) into CO_2 and water (H_2O) as shown in reaction (6) [149]:

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O \quad (6)$$

This release of carbon from biomass and soil contributes greatly to increasing greenhouse gas emissions and global warming.

(vi) Fossil fuel use in agriculture

Fossil fuel use in agriculture is a source of GHG emissions from mechanical processes. Tractors, harvesters, irrigation pumps, and soil processing equipment generally use diesel or gasoline fuel. The combustion process of fossil fuels produces CO_2 directly. In developing countries, irrigation using fossil fuel pumps is very common, especially during the dry season. In addition, the use of coal-based electricity in the process of drying crops or cooling agricultural products adds to indirect emissions from this sector.

(vii) Production and distribution of agricultural inputs

The production and distribution of agricultural inputs is one of the sources of indirect greenhouse gas (GHG) emissions from the agricultural sector that is often overlooked, but has a significant impact on the overall carbon footprint of the food system. The production of various agricultural inputs—such as chemical fertilizers (especially nitrogen), pesticides, herbicides, and hybrid or transgenic seeds—requires large amounts of energy, much of it from fossil fuels [126]. For example, the production of nitrogen fertilizers through the Haber-Bosch process is very energy-intensive because it involves high pressure and temperature to

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combine nitrogen from the air with hydrogen (usually from natural gas) to form ammonia. This process produces large amounts of carbon dioxide (CO_2) emissions, and for every ton of nitrogen fertilizer produced, up to 7 tons of CO_2 equivalent can be produced, depending on the energy efficiency and type of fuel used in the industrial process [118].

In addition, the production of synthetic pesticides and herbicides involves complex chemical reactions that also use organic solvents, heating, and cooling systems, all of which add to the energy consumption and potential GHG emissions of the chemical industry sector. Not only limited to the manufacturing process, the carbon footprint also comes from the packaging and storage of agricultural inputs, which generally use plastic or metal materials, and require controlled temperatures to maintain product stability, especially for seeds and pesticides [121].

The distribution of agricultural inputs from factories to farmers also contributes additional emissions. This process usually involves land transportation modes such as diesel trucks, or even ships and trains, in large-scale distribution systems. The longer the distance between the production site and the end use on the farm, the higher the emissions, especially when logistics are inefficient and vehicles do not use low-carbon fuels. In addition, the practice of transporting small quantities at high frequencies also increases the carbon intensity per unit of input used.

On the other hand, farmers' dependence on cheaply produced external inputs also increases their vulnerability to energy price shocks and supply crises, which indirectly encourages excessive use of inputs to achieve maximum yields in a short time, which increases environmental impacts and cumulative GHG emissions. Therefore, a sustainable agricultural approach that relies on local, organic, and renewable resource-based inputs is highly recommended [136]. For example, the use of compost or biofertilizers, botanical pesticides, and local seeds that are resistant to extreme climates not only reduces dependence on industrial inputs but also reduces the carbon footprint of the farming system as a whole. Finally, this study adds new information regarding SDGs, as reported elsewhere [152-161].

4. CONCLUSION

This study identifies four main emission pathways in agriculture: enteric fermentation, fertilizer-driven soil nitrous oxide emissions, carbon dioxide from machinery and tillage, and indirect energy inputs, and show that optimized manure management, precision fertilization, reduced tillage practices, and renewable energy integration can enable low GHG agriculture. These findings align with the abstract's objectives by pinpointing key emission sources, tracing their evolution, and examining the roles of technological innovations and policy measures in mitigation. The evidence highlights that precision agriculture tools such as soil sensors and drone monitoring can significantly shrink the sector's carbon footprint through targeted resource use. The shift from basic emission quantification to solution-oriented research underscores the importance of supportive policies and interdisciplinary collaboration in advancing sustainable farming. This integrated framework offers policymakers, researchers, and practitioners' actionable insights to align agricultural productivity with global climate change mitigation goals.

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6. AUTHORS' NOTE

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