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REVIEW

Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review

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Abstract
Agriculture is a pivotal player in the climate change narrative, contributing to greenhouse gas (GHG) emissions while offering potential mitigation solutions. This study delved into agriculture's climate impact. It comprehensively analysed emissions from diverse agricultural sources, carbon sequestration possibilities, and the repercussions of agricultural emissions on climate and ecosystems. The study began by contextualising the historical and societal importance of agricultural GHG emissions within the broader climate change discourse. It then discussed into GHG emitted from agricultural activities, examining carbon dioxide, methane, and nitrous oxide emissions individually, including their sources and mitigation strategies. This research extended beyond emissions, scrutinising their effects on climate change and potential feedback loops in agricultural systems. It underscored the importance of considering both the positive and negative implications of emissions reduction policies in agriculture. In addition, the review explored various avenues for mitigating agricultural emissions and categorised them as sustainable agricultural practices, improved livestock management, and precision agriculture. Within each category, different subsections explain innovative methods and technologies that promise emissions reduction while enhancing agricultural sustainability. Furthermore, the study addressed carbon sequestration and removal in agriculture, focussing on soil carbon sequestration, afforestation, and reforestation. It highlighted agriculture's potential not only to reduce emissions, but also to serve as a carbon reservoir, lowering overall GHG impact. The research also scrutinised the multifaceted nature of agriculture, examining the obstacles hindering mitigation strategies, including socioeconomic constraints and

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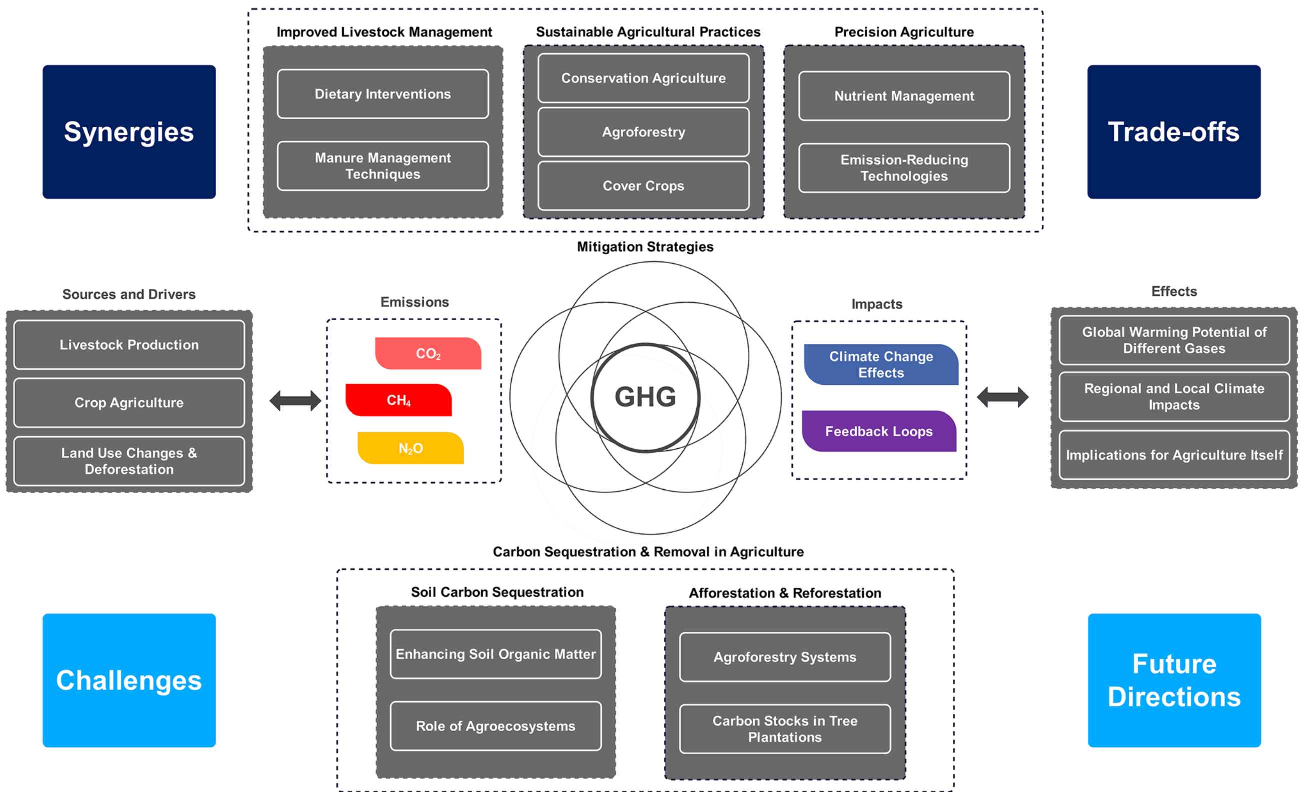
regulatory hurdles. This study emphasises the need for equitable and accessible solutions, especially for smallholder farmers. It envisioned the future of agricultural emissions reduction, emphasising the advancements in measurement, climate-smart agricultural technologies, and cross-sectoral collaboration. It highlighted agriculture's role in achieving sustainability and resilience amid a warming world, advocating collective efforts and innovative approaches. In summary, this comprehensive analysis recognised agriculture's capacity to mitigate emissions while safeguarding food security, biodiversity, and sustainable development. It presents a compelling vision of agriculture as a driver of a sustainable and resilient future.

Graphical abstract



Keywords Greenhouse gas emission · Removal · Agriculture · Carbon pollutants

1 Introduction

As a fundamental pillar of human civilisation, agriculture has evolved continuously to satisfy the needs of a growing global population. Nevertheless, this evolution has not unfolded in a vacuum. This relationship is characterised by a complex interplay of greenhouse gas (GHG) emissions and carbon removal mechanisms [1]. The modern agricultural landscape is inextricably linked to the Earth's changing climate. As the world confronts the incontrovertible challenge of climate change, it becomes imperative to comprehend the role of agriculture in both contributing to and mitigating GHG emissions.

Owing to technological advancements, intensification of production, and globalisation of food systems, agriculture has undergone remarkable changes over the past century. These changes have not only revolutionised food production, but also increased the sector's environmental footprint, which has contributed substantially to global GHG emissions. Agriculture's complexity results in the emission of several GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These emissions originate from a variety of agricultural sources, such as enteric fermentation in livestock, manure management, soil management practices, energy consumption, and land use alterations for cereal cultivation and pastureland expansion.

Agriculture substantially contributes to GHG emissions. According to the Inter-governmental Panel on Climate Change (IPCC) [2], in 2019, approximately 34% (20 $GtCO_2$-eq) of the total net anthropogenic GHG emissions originated from the energy supply sector; 24% (14 $GtCO_2$-eq) from industry; 22% (13 $GtCO_2$-eq) from agriculture, forestry, and other land use (AFOLU); 15% (8.7 $GtCO_2$-eq) from transport; and 5% (3.3 $GtCO_2$-eq) from buildings (see Fig. 1). These statistics demonstrate the undeniable contribution of the agriculture sector to climate change.

Agriculture is a source of GHG emissions, but it also has the potential to mitigate climate change through carbon removal mechanisms. CO_2 can be removed from the atmosphere through agricultural practices such as afforestation, reforestation, agroforestry, and soil carbon sequestration [3]. This dual position as both a contributor to and a mitigator of GHG emissions presents a unique and complex challenge for the agricultural sector in addressing climate change.

1.1 Background and importance of agriculture-related GHG emissions

Agriculture plays a crucial role in the global economy, providing billions of people with food, income, and economic opportunities [4]. Nonetheless, it is a significant contributor to GHG emissions, thereby exerting a substantial influence on the climate system of the Earth. Understanding the dynamics of GHG emissions in the agricultural sector is crucial because of the significant implications for mitigating climate change.

In agriculture, CH_4 emitted from enteric fermentation in ruminant animals and manure management practices are two significant sources of GHG emissions [5]. In the short term, enteric fermentation, a natural digestive process in livestock, generates CH_4, a potent GHG with a substantially higher global warming potential than CO_2. Manure management practices, such as storage and application to cropland, can also result in significant emissions of CH_4 and N_2O.

The majority of N_2O emissions result from soil management practices such as using synthetic fertilisers and performing ineffective nutrient management [6]. N_2O is a potent GHG with long-lasting climate effects. In addition, CO_2 emitted from agriculture is predominantly attributable to land use changes such as deforestation for agricultural expansion and energy consumption associated with farm operations, including mechanised cultivation and transportation [7].

The contribution of the agricultural sector to GHG emissions has significant implications for global climate change. Climate change, in turn, poses significant threats to agriculture, including altered precipitation patterns, higher temperatures, and increased frequency of extreme weather events, which can disrupt food production and reduce crop yields [8]. On the other hand, agriculture contributes to climate change by exacerbating these risks through GHG emissions, thereby creating a feedback cycle that aggravates climate-related difficulties. Agriculture is a significant source of GHG emissions, but it also provides opportunities for carbon sequestration and emission reduction. Agricultural practices such as afforestation, reforestation, agroforestry, and soil carbon sequestration have the potential to mitigate climate change by removing CO_2 from the atmosphere [9]. Given agriculture's dual role in both contributing to and mitigating GHG emissions, a thorough comprehension of the sources, trends, and mitigation strategies related to agricultural emissions is essential. This comprehensive review seeks to assess the current state of knowledge in this field by synthesising existing research to cast light on the complex relationship between agriculture and climate change. The findings of this study can introduce strategies and policies that promote sustainable agricultural practices while mitigating the sector's contribution to climate change by addressing this complex interaction [10].

In short, recognising the significance of agriculture-related GHG emissions and their effects on climate change emphasises the need for a comprehensive review to

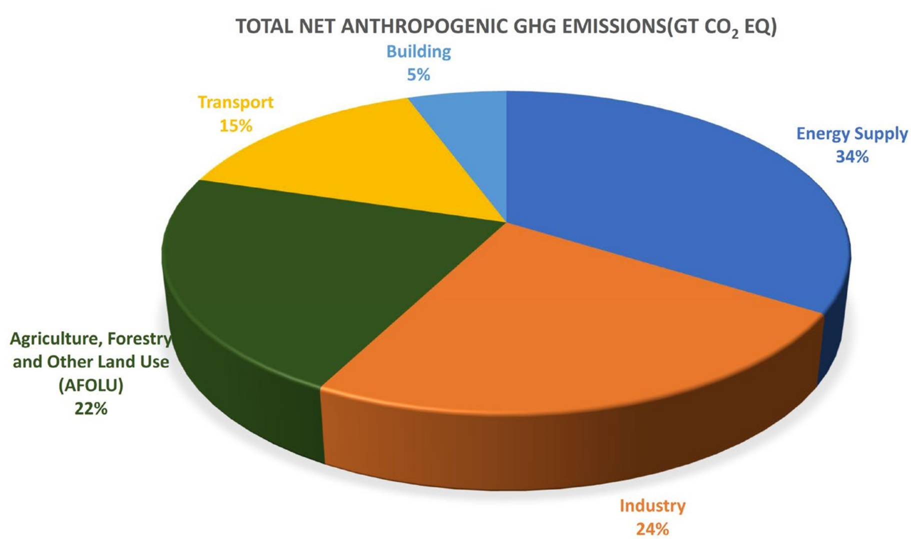


Fig. 1 Total net anthropogenic GHG emissions based on sectors (according to the report issued by the Inter-governmental Panel on Climate Change (IPCC) [2] (Climate Change 2022))

consolidate existing knowledge, identify research gaps, and inform strategies for achieving sustainable agriculture in a changing climate. This paper contributes to this effort by providing policymakers, researchers, and other stakeholders with insights and recommendations for addressing the challenges and opportunities presented by agriculture in the context of climate change adaptation and mitigation.

1.2 The need for a comprehensive analysis

Understanding the complex relationship between agriculture and GHG emissions is essential to the development of effective strategies for mitigating and adapting to climate change. A comprehensive review of the extant corpus of research in this field is necessary to identify trends and knowledge gaps and make informed decisions.

This paper investigates and synthesises the data on GHG emissions and removals in the context of agriculture. This comprehensive review aims to attain the following goals:

- To identify and quantify various sources of GHG emissions in agriculture, including regional and sectoral variations.
- To evaluate the efficacy and practicability of existing and emergent mitigation strategies used in agriculture to reduce GHG emissions.
- To examine the potential and limitations of carbon removal mechanisms in agriculture, such as soil carbon sequestration, afforestation, and innovative technologies.
- To investigate the intricate synergies and trade-offs between emission reduction strategies and carbon removal mechanisms in the agricultural sector.
- To identify areas where additional research is required to further clarify the role of agriculture in mitigating climate change.

By pursuing these objectives, this exhaustive study seeks to provide a thorough and current understanding of the role of agriculture in the global dynamics of GHG emissions. It will be a valuable resource for policymakers, researchers, and other stakeholders, who seek to navigate the complex challenges and opportunities presented by agriculture in the context of climate change adaptation and mitigation.

2 GHG emissions in agricultural production

Agriculture is a key contributor to global GHG emissions, encompassing a spectrum of emission sources that have significant impacts on global climate. In this multifaceted domain, three primary GHG, i.e. CO_2 (CO_2), CH_4 (CH_4), and N_2O (N_2O), are at the forefront, each originating from distinct agricultural practices and activities (see Fig. 2). Individually and collectively, these emissions exert a significant impact on the Earth's climate system, highlighting the urgent need for a comprehensive understanding of their origins, magnitudes, and effects. This section delves into the complex dynamics of GHG emissions in the agricultural sector, providing an in-depth analysis of CO_2, CH_4, and N_2O emissions. By analysing the nuances of each GHG type and their agricultural origins, this section lays the groundwork for understanding the sector's climate change implications, challenges, and opportunities. The following subsections will present the unique characteristics of these emissions, casting light on their origins, variability, and contribution to the larger climate change landscape.

The following subsections offer insights into the fundamental emission sources that influence the agricultural climate footprint [11]. Through an in-depth analysis of CO_2, CH_4, and N_2O emissions, this study could contribute to a more nuanced understanding of the agricultural sector's role

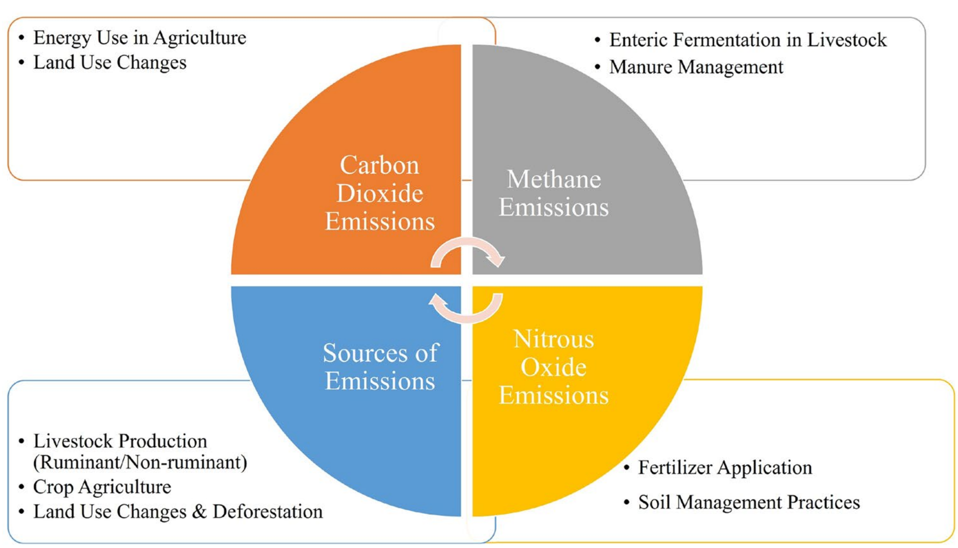


Fig. 2 Three primary GHG:CO_2, CH_4, and N_2O, and their sources

in global climate dynamics, ultimately guiding the efforts made towards environmentally friendly and climate-resilient agricultural practices [12].

2.1 CO_2 emissions

CO_2 (CO_2) emissions have been manifested as a multidimensional component of the GHG landscape in the realm of agricultural production [13]. These emissions are primarily caused by two distinct, yet interconnected, aspects of agriculture: energy consumption and land use changes. This section discusses the complexities of CO_2 emissions, shedding light on their underlying mechanisms, regional variations, and implications for strategies of climate change mitigation [14].

2.1.1 Energy use in agriculture

Energy use in agriculture is a major contributor to CO_2 emissions. Modern agricultural practices are increasingly dependent on energy-intensive technologies such as mechanised machinery, irrigation systems, and transport networks [15]. These technologies, which are primarily propelled by fossil fuels, have substantially increased the energy requirement of the agricultural sector. As a result, the combustion of fossil fuels in tractors, harvesters, and transportation fleets produces substantial CO_2 emissions [15]. The extent of CO_2 emissions from energy use varies by region and is influenced by variables such as the size of agricultural operations, the availability of renewable energy sources, and the efficacy of energy use. Industrialised agricultural systems typically have greater energy consumption and CO_2 emissions than small-scale sustainable farming practices that prioritise energy efficiency and employ renewable energy sources [16].

2.1.2 Land use changes

Land use changes, including deforestation, afforestation, and adjustments in land allocation for agricultural purposes, represent another significant source of CO_2 emissions in the agricultural context [17]. Carbon contained in trees and vegetation is released into the atmosphere as CO_2 as a result of deforestation, which is often caused by the expansion of agricultural frontiers. In contrast, initiatives to convert agricultural land into forests or reforest previously deforested areas can act as carbon sinks, sequestering atmospheric CO_2.

The magnitude of CO_2 emissions resulting from changes in land use depends on the extent and rate of deforestation, land conversion practices, and the likelihood of forest regrowth. Regional disparities in land use change dynamics further confound the assessment of CO_2 emissions, as some areas experience more extensive deforestation for agricultural expansion while others witness reforestation efforts to mitigate these emissions.

Understanding the nuances of CO_2 emissions resulting from energy use and land use changes is crucial to developing effective strategies for mitigating agriculture-attributed climate change. The following sections will examine other GHG emissions such as CH_4 and N_2O in order to provide a comprehensive overview of agriculture's multifaceted function in the global GHG landscape.

2.2 CH_4 emissions

CH_4 emissions are an important and distinctive component of GHG emissions in agricultural production. CH_4 emissions are characterised by their potent warming potential and complex sources, which are primarily derived from livestock-related activities [18]. This section examines the complexities of CH_4 emissions, concentrating on two important subcategories: enteric fermentation in livestock and manure management practices.

2.2.1 Enteric fermentation in livestock

Enteric fermentation within the digestive systems of ruminant animals, such as cattle, sheep, and goats, is one of the primary sources of CH_4 emitted from agriculture. During digestion, these animals have a distinct microbial ecosystem in their stomachs, where microorganisms decompose fibrous plant materials and produce CH_4 as a metabolic byproduct. Although this process is essential for the animals' metabolism, it results in the emission of CH_4 into the atmosphere through belching [19].

As a type of GHG, CH_4 has a greater global warming potential on a shorter timescale than CO_2. As a result, the large population of ruminant livestock throughout the globe contributes significantly to CH_4 emissions from enteric fermentation. Diet, livestock management practices, and animal genetics can affect the intensity of emissions, making this source of CH_4 emissions the subject of ongoing research to devise effective mitigation strategies.

2.2.2 Manure management

Manure management practices in the agriculture sector are a significant source of CH_4 emissions. Rich in organic material, manure produces CH_4 under anaerobic conditions during storage and treatment. This CH_4 production is a consequence of microbial activity that breaks down organic compounds within manure [20]. The magnitude of CH_4 emissions can be affected by manure management practices, such as storage in lagoons, landfills, or mounds. In addition, the management and application of manure to cropland can result in the emission of CH_4 and N_2O, two potent GHGs. In addition to temperature and humidity, manure management practices have a significant impact on the amount of CH_4 released from this source [21].

CH_4 emitted from enteric fermentation and manure management in agriculture present unique reduction and mitigation challenges and opportunities. Understanding the underlying mechanisms, quantifying emissions, and investigating innovative management practices are essential stages in developing strategies to reduce CH_4 emissions from livestock production systems while maintaining their viability. In the following, the intricate dynamics of N_2O emissions and their contributions to the larger agricultural GHG emissions landscape are discussed.

2.3 N_2O emissions

N_2O, a very powerful GHG that possesses considerable global warming potential over extended periods, exhibits extensive interconnections with diverse agricultural practices. The primary sources of N_2O emissions in the agricultural sector are attributed to two main factors: the use of fertilisers and the implementation of soil management practices [22]. This section aims to elucidate the intricacies of N_2O emissions, exploring the unique attributes of various sources and their ramifications for sustainable agricultural methodologies.

2.3.1 Fertiliser application

The use of both synthetic and organic fertilisers is a significant factor contributing to N_2O emitted from the agriculture sector. The application of nitrogen, an essential nutrient for the growth of plants, is a common practice in agricultural settings with the aim of improving crop productivity. Nevertheless, the presence of nitrogen within the soil might result in the generation of N_2O through the mechanisms of nitrification and denitrification [23].

Nitrification refers to the biochemical process by which ammonium (NH_4+) is converted into nitrate (NO_3-), an oxidised form of nitrogen that may be easily assimilated by plants. N_2O may be generated as a byproduct during this particular process, particularly in soils characterised by heightened nitrogen levels or those exposed to excessive wetness be generated as a byproduct during this particular process, particularly in soils characterised by heightened nitrogen levels or those exposed to excessive wetness [24].

In contrast, denitrification takes place in oxygen-deprived environments inside the soil, where the process involves the conversion of nitrate into nitrogen gas (N_2) through a sequence of intermediary reactions. Notably, one of the intermediate products released during this process is N_2O. The aforementioned process is subject to the effect of several elements, including soil moisture, temperature, and the presence of organic matter.

The use of efficient strategies in nitrogen management, such as precise application techniques and optimal timing, has the potential to mitigate the release of N_2O emissions linked to the utilisation of fertilisers. Furthermore, the implementation of alternate nitrogen sources and the adoption of organic agricultural practices have the potential to mitigate the effects by modifying the dynamics of the nitrogen cycle [25].

2.3.2 Soil management practices

The emissions of N_2O resulting from soil management practices in the agriculture sector span a diverse range of activities and approaches. The emissions in question are a result of the modification of soils for diverse objectives, such as agricultural cultivation, irrigation, and alterations in land use [26].

The introduction of oxygen into the soil by tillage practices, such as ploughing and cultivation, can have an impact on the equilibrium between aerobic and anaerobic conditions. Consequently, this phenomenon affects the likelihood of N_2O emissions occurring during denitrification processes in soils saturated with water [27]. The use of conservation tillage and reduced tillage practices has been recognised as an effective solution in mitigating N_2O emissions that are linked to soil management. These practices are specifically geared to minimise soil disturbance [28]. Furthermore, alterations in land use such as the conversion of forested areas into arable land or the transformation of wetlands into agricultural fields have the capacity to modify soil characteristics and nitrogen processes, which may result in heightened emissions of N_2O.

It is of utmost importance to comprehend the variables that dictate the release of N_2O emissions resulting from the application of fertilisers and the implementation of soil management practices. This understanding is crucial in order to devise precise and effective tactics for mitigating these emissions. The use of sustainable agricultural practices that involve the optimisation of nutrient management, reduction of tillage intensity, and protection of ecosystems can effectively mitigate N_2O emissions without compromising agricultural production. The following sections examine the complex network of interactions and compromises among different initiatives aimed at reducing GHG emissions and removing carbon in the agriculture sector.

3 Sources and drivers of agricultural emissions

The complicated and intricate connection between agriculture and GHG emissions is characterised by a multifaceted interplay of many sources and factors that shape the emission patterns in the agricultural sector. This section undertakes an analysis to grasp the fundamental sources and underlying processes driving GHG emissions from the agriculture sector. The present investigation is structured around three fundamental subcategories: Livestock Production, Crop Agriculture, and Land Use Changes and Deforestation [29]. Each of the aforementioned subsections explores a separate aspect of agricultural emissions, elucidating the complex nature of emission sources and the underlying variables that contribute to them. This study delves into the intricacies of agricultural emissions, acknowledging the distinct obstacles and prospects associated with each individual source. Gaining an understanding of the sources and factors that contribute to these emissions can facilitate well-informed decision-making and implement efficient methods for reducing emissions, which are specifically designed to address many components of the agricultural environment.

3.1 Livestock production

Livestock production is a significant contributor to GHG emissions in the agriculture sector [30]. This subsection examines the intricacies of livestock production, investigating the crucial differences between ruminant and non-ruminant emissions and analysing the numerous elements that impact these emissions.

3.1.1 Ruminant vs. non-ruminant emissions

The classification of livestock may be generally divided into two main categories: ruminants, which encompass cattle, sheep, and goats, and non-ruminants comprising poultry and pigs. The categorisation of emissions is crucial for comprehending their nature, as ruminant animals possess a distinct digestive system that produces CH_4 through enteric fermentation, which notably contributes to emissions. In contrast, non-ruminant animals have lower levels of CH_4 emissions as a result of their distinct digestive mechanisms. This distinction emphasises the significance of taking into account emission differences in the cattle industry [31].

3.1.2 Factors influencing emissions

Numerous elements affect GHGs emitted from the production of cattle. In this regard, the most important factors are the composition of the diet, feeding practices, animal genetics, and management strategies. CH_4 emitted by ruminants is notably influenced by the kind and nutritional value of the forage or feed consumed. Livestock management practices, including the management of waste and the provision of suitable living conditions, are additional factors that contribute to the reduction of emissions. Furthermore, the implementation of feed additives and dietary modifications have the potential to reduce CH_4 emissions originating from ruminant animals [32].

Gaining a comprehensive understanding of the intricate aspects of livestock emissions is crucial to devising precise methods that effectively enhance livestock production and simultaneously mitigate its carbon footprint. By differentiating between emissions from ruminant and non-ruminant sources and taking into account various elements that influence emissions, efforts can be made to promote livestock production systems that are more sustainable and capable of moderating climate change impacts.

3.2 Crop agriculture

Crop agriculture plays a crucial role in the worldwide production of food; although, it is a substantial source of GHG emissions [33]. This subsection examines the complex dynamics of crop agriculture, specifically addressing two key factors: the effects of different types of fertilisers and techniques of application, and the influence of tillage practices on emissions.

3.2.1 Fertiliser types and application methods

Fertilisers play a crucial role in augmenting agricultural output; yet, their use can result in the release of N_2O, a highly powerful GHG. The emission consequences of different types of fertilisers and application techniques vary. Nitrogen-based fertilisers, specifically, exhibit a correlation with the release of N_2O, whereby the emission levels are subject to several parameters such as the timing and rate of application [34].

Opportunities to mitigate emissions can be found through advancements in fertiliser formulations and application technologies. One example of a technology that can improve nutrient utilisation efficiency and reduce N_2O emissions is the use of controlled-release fertilisers. Moreover, the use of precision agricultural techniques enables the utilisation of more accurate and effective methods for the application of fertilisers, hence mitigating wastage and minimising the release of related emissions.

3.2.2 Tillage practices

The act of tillage, which involves the mechanical manipulation of soil to facilitate crop production, has the potential to influence GHG emissions through altering the dynamics of soil carbon and nitrogen. The use of traditional tillage methods, which include regular disturbance of the soil, has been seen to expedite the depletion of carbon from soils and promote the release of N_2O through heightened microbial activities [35].

In contrast, conservation tillage practices aim to minimise soil disturbance, thereby maintaining soil carbon content and mitigating N_2O emissions. No-till and reduced-till practices exemplify conservation tillage approaches that foster soil health and mitigate emissions. Achieving a harmonious equilibrium between the imperative for crop production and the imperative for emissions reduction within the realm of crop agriculture necessitates the adoption of a sophisticated and multifaceted strategy. Emissions are greatly influenced by the fertiliser types and application techniques, together with tillage practices. Through the use of sustainable and appropriate agriculture methodologies, it is possible to enhance agricultural productivity while simultaneously reducing the ecological repercussions associated with crop cultivation.

3.3 Land use changes and deforestation

Land use changes and deforestation are significant components of agricultural emissions, exerting a profound influence on the environmental and climatic consequences of agricultural activities. This article discusses the complex dynamics of land use changes and deforestation, specifically examining two crucial subtopics: the conversion of forests into agricultural land and the impacts of peatland draining on emissions.

3.3.1 Conversion of forests to agricultural land

The process of transforming forests, especially the tropical ones, into agricultural land is a significant catalyst for the release of GHGs [36]. The aforementioned procedure results in the release of substantial amounts of CO_2 that are held inside trees and soil; this makes a large contribution to global emissions. Furthermore, deforestation has a detrimental impact on the equilibrium of carbon in the Earth's atmosphere, which intensifies the effects of climate change. Forest conversion is primarily influenced by several reasons, including the extension of agricultural frontiers. This expansion is mostly driven by factors such as population increase and the worldwide demand for agricultural goods. Policies and economic incentives that promote deforestation for agricultural purposes also expedite the process of forest conversion.

3.3.2 Peatland drainage and emissions

Peatlands, renowned for their significant carbon storage capacity, have a high susceptibility to draining activities undertaken for agricultural purposes. Peatlands, upon drainage, liberate carbon sequestered inside them in the form of CO_2 and CH_4, hence adding to GHG emissions. The drainage of peatlands is a matter of significant concern because of the dual impact of carbon release and consequences such as soil subsidence, heightened flood vulnerabilities, and soil degradation [37].

The motivation behind the frequent drainage of peatlands is the intention to transform these regions into agricultural terrain, with a specific emphasis on rice farming and palm oil manufacturing. In some geographical areas, there have been historical instances where legislation and economic incentives have fostered the promotion of this particular practice. The mitigation of emissions resulting from land use changes and deforestation necessitates the implementation of a comprehensive and multidimensional strategy. Efforts aimed at mitigating forest conversion encompass the promotion of sustainable land use practices, enforcement of anti-deforestation legislation, and encouragement of reforestation and afforestation activities. Likewise, the act of restoring and conserving peatlands can both cut emissions and safeguard these crucial ecosystems. Achieving a harmonious equilibrium between the expansion of agricultural activities and the preservation of forests and peatlands is of utmost importance in mitigating emissions linked to alterations in land use.

4 Impacts of agricultural emissions

The emissions resulting from agricultural operations have significant and wide-ranging implications, which extend beyond the immediate areas where they are produced. This section discusses numerous and diverse consequences of agricultural emissions. The primary attention lies on two crucial aspects: the direct consequences of these emissions on climate change and the complex feedback mechanisms that exacerbate the difficulties presented by a shifting climate [38].

The agricultural sector, which is indispensable for the production of food and the sustenance of global lives, exhibits an inherent interconnection with the Earth's climatic system. Agricultural practices are responsible for the emission of CO_2, CH_4, and N_2O, which make a substantial contribution to the overall accumulation of GHGs in the Earth's atmosphere. Consequently, the industry has a significant impact on the climate change.

4.1 Climate change effects

The emissions resulting from agricultural operations have substantial implications for the Earth's climate system, leading to various impacts that have both global and local repercussions [39]. This section investigates the impacts of agricultural emissions, with a particular focus on two crucial aspects: the varying global warming effects of different GHGs and the regional and local climate impacts that these emissions engender.

4.1.1 Global warming potential of different gases

Agricultural emissions comprise a range of GHGs, each with unique Global Warming Potentials (GWPs) and atmospheric lifespans. The GWPs of these gases are indicators of their comparative capacities to trap heat over certain time periods in relation to CO_2. CH_4 and N_2O, which are commonly found in agricultural emissions, have much larger GWPs compared to CO_2 when considering shorter time periods [40].

CH_4 is predominantly generated by enteric fermentation in cattle and manure management and is distinguished by its significant capacity for inducing short-term global warming. Although CH_4 has a relatively short air lifetime, its GWPs over a 20-year period is estimated to be around 84–87 times higher than that of CO_2. This particular attribute highlights the substantial impact it has on the acceleration of climate change in the immediate future.

N_2O, which is largely emitted as a result of fertiliser application and soil management practices, is a very powerful GHG with a GWP exceeding 20 times that of CO_2. The extended atmospheric residence of N_2O contributes to its impact on climate over varying temporal scales, exerting effect on the Earth's energy balance through its total radiative forcing.

4.1.2 Regional and local climate impacts

The regional and local impacts of agricultural emissions on climate lead to significant impacts on agriculture, ecosystems, and people. These emissions significantly influence regional climate patterns, which results in alterations in temperature and precipitation distributions. These alterations have the potential to result in modified growing seasons, heightened heat stress on agricultural crops and livestock, and fluctuations in water supply [41]. Regions that heavily depend on rain-fed agriculture are especially susceptible to the impacts of shifting precipitation patterns. These changes can lead to the occurrence of droughts or floods, hence causing significant disruptions to both food production and the overall lives of the affected population.

Regarding the climate impacts, the effects of agricultural emissions are more noticeable at the local level. The impact of elevated temperatures and modified precipitation patterns on agricultural productivity encompasses changes in crop yields and crop quality and the incidence of pests and diseases. The health of livestock can be impaired as a result of heat stress and the shifting dynamics of diseases. Furthermore, alterations in climatic circumstances have the potential to disturb the intricate equilibrium of ecosystems, hence affecting biodiversity and the various ecosystem services they offer [42].

It is crucial to comprehend the diverse GWPs shown by different gases and the regional and local climatic consequences resulting from agricultural emissions in order to develop precise and effective mitigation and adaptation measures. Through a comprehensive understanding of the intricacies associated with these impacts, policymakers, researchers, and stakeholders could formulate climate-resilient agricultural practices and policies that effectively address the challenges posed by GHG emissions and, at the same time, ensure the preservation of food security and the environment. The next part will examine the complex feedback loops that magnify the difficulties presented by agricultural emissions within a dynamic environment.

4.2 Feedback loops

The emissions generated by agricultural activities have the potential to create feedback loops that exacerbate the difficulties associated with a shifting climate because of their complex interactions with the climate system. The following subsection analyses a crucial facet of these feedback loops: their consequences for the agricultural sector.

4.2.1 Implications for agriculture itself

The agriculture sector both contributes to GHG emissions and experiences substantial effects from the resulting climate change. In the agriculture domain, the presence of feedback loops gives rise to an intricate interplay of causal relationships, resulting in possible consequences for the production of food, livelihoods, and the provision of ecosystem services [43].

The phenomenon of soil degradation and fertility loss can be intensified by increasing temperatures and changes in precipitation patterns, resulting in reduced capacity for moisture retention. The process of deterioration has the potential to result in diminished agricultural productivity and heightened vulnerability to erosion, hence compromising the resilience of agricultural systems. As a reaction, farmers may choose for more rigorous strategies of land management, such as heightened irrigation or fertiliser application, which have the potential to augment emissions and intensify the feedback loop.

Moreover, the alteration of climate conditions has the potential to disturb the geographical spread of pests, illnesses, and invasive species, thereby presenting health difficulties for agricultural crops and animals. For example, elevated temperatures have the potential to facilitate the spread of pests, resulting in detrimental effects on agricultural crops and subsequent reductions in output. In response to these issues, farmers may opt to augment their pesticide usage, which can further intensify GHG emissions while simultaneously resolving pressing agricultural concerns.

Furthermore, water scarcity and quality are significant concerns that arise from changes in precipitation patterns, such as the heightened occurrence and intensity of droughts and floods [44]. These alterations can have adverse effects on the availability of water for agricultural use. The shortage of water has the potential to impose limitations on the irrigation of crops, which adversely influences agricultural production. In addition, alterations in water quality can have an impact on the overall health of animals. The adaptation techniques, such as the development of irrigation infrastructure or alterations in crop choices, might potentially affect energy consumption and GHG emissions.

In addition, alterations to temperature and the duration of growing seasons might affect the appropriateness of certain crops in different places. Farmers may require to make adjustments by modifying the types of crops cultivated and the timing of planting. These modifications can affect land use patterns and contribute to emissions, particularly if they entail activities such as deforestation or alterations in land management strategies. The interplay between climate change and feedback loops might result in economic and social vulnerabilities within agricultural communities. The potential decline in agricultural yields and animal production has the potential to significantly impact both food security and the financial well-being of farmers. In light of this situation, populations may endeavour to pursue alternative means of sustenance or undertake relocation, which might possibly result in alterations in land utilisation and environmental consequences.

Therefore, it is crucial to comprehend the intricacies of these feedback loops and their impacts on the agricultural sector in order to formulate effective approaches to the alleviation of and adjustment to the issues presented by agricultural emissions and climate change. Efforts made to mitigate these loops should prioritise the promotion of sustainable farming practices, the enhancement of resilience, and the minimisation of adverse effects on both food production and the environment.

5 Mitigation strategies for agricultural emissions

In light of the pressing imperative to confront climate change, the agricultural industry finds itself at a pivotal juncture. Agriculture has a crucial role in assuring global food security and livelihoods; nevertheless, it also constitutes a substantial source of GHG emissions [45]. This complex situation requires a collaborative endeavour to formulate and execute measures aimed at both decreasing emissions and promoting the establishment of agricultural systems that are sustainable and resilient.

This part of the article discusses a wide range of mitigation measures specifically designed to reduce GHGs emitted from agricultural operations. These methods comprise a range of approaches, spanning from sustainable agricultural practices to novel technologies and managerial techniques. With a mutual dedication to tackling the issues presented by agricultural emissions, these policies possess the capacity to revolutionise the sector into an active participant in the battle against climate change (see Fig. 3).

5.1 Sustainable agricultural practices

Sustainable agricultural practices are considered a fundamental component of mitigating strategies in the agriculture industry [46]. These practices not only promote the long-term health and resilience of agricultural ecosystems, but also have a significant impact on the reduction of GHG emissions. The following subsections discuss three significant sustainable agricultural practices: conservation agriculture, agroforestry, and cover Crops.

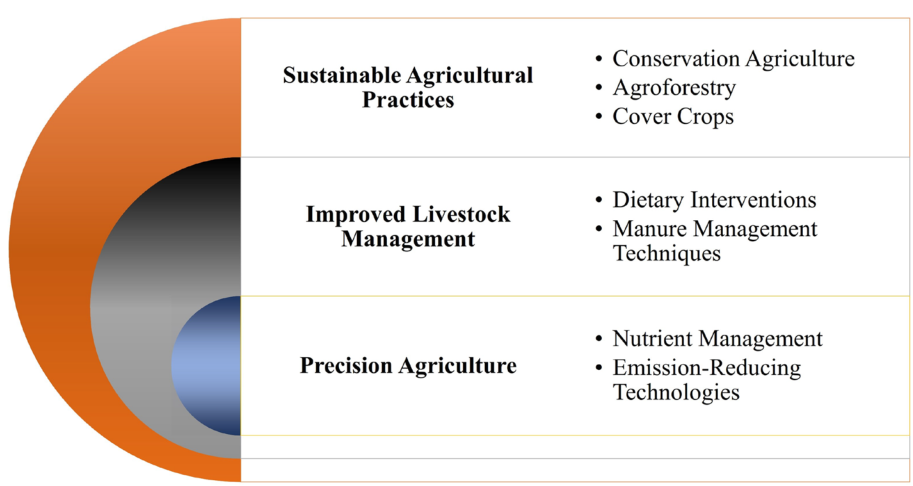


Fig. 3 Mitigation strategies for agricultural emissions summary

5.1.1 Conservation agriculture

Conservation agriculture is an innovative methodology that seeks to revolutionise conventional agricultural techniques through its focus on minimising soil disturbance, adopting reduced or zero tillage practices, and ensuring the continuous presence of permanent soil cover [47]. Through the practice of minimising soil disturbance, several benefits may be observed. One of such benefits is the reduction of carbon loss from soils. In addition, this practice facilitates the sequestration of carbon by promoting increased organic matter content in the soil. Moreover, it has been found to boost overall soil health. Furthermore, conservation agriculture enhances the capacity of soil to retain water, hence diminishing the necessity for irrigation and alleviating emissions linked to energy-intensive irrigation methods. The aforementioned methodology serves as evidence of how the reconsideration of agricultural practices might result in favourable outcomes for both the environment and the climate.

5.1.2 Agroforestry

Agroforestry is a comprehensive methodology that combines the cultivation of trees and woody plants inside agricultural environments. This practice provides a variety of benefits such as the storage of carbon, the enhancement of soil quality, and the promotion of biodiversity. Agroforestry systems encompass trees that effectively store carbon from the atmosphere; that way, they aid in the reduction of GHG emissions [48]. In addition, these trees offer vital ecosystem services. Agroforestry serves as a comprehensive and sustainable approach to land management, showcasing the integration of agricultural or livestock cultivation alongside strategically positioned trees. This practice embodies a holistic perspective and offers extensive environmental advantages.

5.1.3 Cover crops

Cover crops (sometimes known as green manure) play a crucial role in the implementation of sustainable agriculture systems. Intermediary crops are strategically cultivated during the intervals between primary crop seasons in order to mitigate soil erosion, optimise nutrient preservation, and facilitate the buildup of organic matter within the soil. Cover crops provide the additional benefit of carbon sequestration, which occurs throughout their development and subsequent breakdown; this augments the overall carbon stores in the soil [49]. By assuming the role of a living cover over agricultural fields, they serve the purpose of safeguarding against soil erosion, enhancing the structure of the soil, and suppressing the growth of unwanted vegetation. Consequently, this facilitates the development of farming practices that are resilient and contribute to the reduction of emissions [50].

Performing sustainable agricultural practices highlights the capacity of agriculture to function as a viable solution, rather than a contributing factor, in the ongoing efforts to combat climate change. Through the conservation agriculture, agroforestry, and cover cropping practices, farmers have the potential to effectively address several objectives, including the reduction of emissions, improvement of soil health, and enhancement of the overall sustainability of food production systems. These practices serve as a prime example of the successful integration of agricultural and environmental stewardship, presenting a model for a more sustainable and climate-resilient future in the field of farming.

5.2 Improved livestock management

The livestock sector, an essential element of the agricultural sector, also serves as a substantial source of GHG emissions, mostly owing to the production of CH_4. The mitigation of emissions stemming from animal agriculture necessitates the implementation of a comprehensive strategy that covers the enhancement of livestock management practices [51]. In the following subsections, two fundamental aspects of enhanced livestock management: dietary interventions and manure management techniques.

5.2.1 Dietary interventions

Dietary modifications have a crucial role in mitigating CH_4 emitted from livestock and preserving animal output. CH_4 is predominantly produced within the gastrointestinal tracts of ruminant animals through a naturally occurring phenomenon known as enteric fermentation [52]. Dietary interventions have the potential to alter the composition of animal diets in order to minimise CH_4 emissions as following:

1. Scholars have successfully devised CH_4 inhibitors, such as feed additives or supplements, which have exhibited the capacity to mitigate CH_4 emissions originating from livestock. Inhibitors operate by modifying the microbial makeup inside the gastrointestinal tract, resulting in a decrease in CH_4 generation. This strategy presents a potentially effective method for reducing emissions and, simultaneously, maintaining animal feed integrity.
2. The mitigation of CH_4 emissions can be achieved by the improvement of livestock nutrition, which involves enhancing forage quality and ensuring balanced diets. Enhancing the nutritional composition of livestock diets by including high-quality forage and optimising nutrient ratios has the potential to enhance feed efficiency, which results in reducing the amount of CH_4 generated per unit of feed ingested.
3. Selective breeding programmes focussed on the production of livestock with decreased CH_4 emissions are con-

sidered a viable and enduring approach to sustainability. Through the strategic selection of animals with reduced CH_4 production rates, the livestock business may effectively mitigate emissions over time, all the while safeguarding valuable genetic features.

5.2.2 Manure management techniques

Efficient management strategies for manure are crucial not only in mitigating CH_4 emissions, but also in using the rich byproducts derived from animal farming which mentioned below: anaerobic digestion: the process of anaerobic digestion involves the conversion of animal dung into biogas, which serves as a sustainable energy source. This technology also contributes to the reduction of CH_4 emissions that occur during the storage of manure. This procedure provides a dual advantage by both reducing emissions and offering an energy source that can be utilised either on-farm or off-farm [53].

Composting is a very beneficial method of managing manure that serves to stabilise the nutrients present in the manure, mitigate the release of odorous emissions, and inhibit the production of CH_4 gas. Composting procedures managed efficiently yield a soil amendment abundant in nutrients and mitigate emissions resulting from the decomposition of manure. The manner in which manure is administered to agricultural areas has a substantial impact on the emission of CH_4. Precision manure application techniques, such as the injection or integration of manure into the soil, have been found to result in decreased CH_4 emissions when compared to the conventional practice of surface spreading. Furthermore, these practices serve to improve nutrient utilisation efficiency, which makes them harmonised with the objectives of sustainable agriculture.

Enhanced livestock management practices not only decrease emissions, but also improve animal welfare, increase farm output, and enhance resource efficiency. The utilisation of dietary treatments and waste management strategies serves as a notable illustration of the possibilities inherent in sustainable and environmentally conscious practices in the realm of animal agriculture. By incorporating these practices into livestock production systems, the agriculture industry may achieve substantial progress in mitigating its environmental impact and simultaneously satisfying the worldwide need for animal-derived commodities.

5.3 Precision agriculture

Precision agriculture is an advanced technology domain that aims to mitigate GHG emissions originating from agricultural practices and concurrently improve the efficiency of resource utilisation and crop productivity [54]. This subsection examines two fundamental components of precision agriculture, namely nutrient management and emission-reducing technologies.

5.3.1 Nutrient management

A fundamental aspect of precision agriculture is the optimisation of fertiliser and nutrient delivery to save waste and emissions while maximising crop output; this process is known as nutrient management. The implementation of precision techniques in nutrition management is contingent upon the use of data-driven decision-making processes and the adoption of customised application methods [55].

The use of precision agriculture involves the utilisation of global positioning systems (GPS) and geographic information systems (GIS) to enable farmers to accurately target fertiliser treatments. By employing this approach, the occurrence of excessive application is minimised, hence mitigating the potential consequences of nutrient runoff, such as the emission of N_2O and the degradation of water quality.

Variable rate technology (VRT) is a technological approach that enables the administration of fertilisers at varying rates, taking into account the specific needs of the soil and crop. Through the examination of soil nutrient levels and the assessment of crop circumstances, VRT systems effectively allocate nutrients in specific locations and at specific times, hence enhancing resource utilisation and minimising emissions.

The implementation of controlled-release fertilisers, which exhibit a steady release of nutrients over a longer duration, serves to improve the efficiency of nutrient utilisation. These fertilisers have the ability to decrease the likelihood of N_2O emissions, which is a powerful GHG linked to an excessive amount of nitrogen in soils.

5.3.2 Emission-reducing technologies

The use of emission-reducing technologies in precision agriculture plays a crucial role in mitigating GHG emissions and, at the same time, ensures the preservation or enhancement of crop yields. These technologies comprise a range of inventions specifically developed to mitigate and minimise emissions originating from diverse agricultural operations. Advancements in agricultural technology have facilitated the emergence of low-emission equipment, shown by the integration of cleaner engines in tractors and harvesters. It significantly helps mitigate emissions throughout various field operations, encompassing activities such as ploughing and harvesting [56].

Precision irrigation methods, including drip and micro-irrigation, are utilised in the agriculture sector to enhance water utilisation efficiency. These devices effectively mitigate energy-intensive irrigation practices and related emissions by providing water directly to the root zone of crops. The use of sensor technologies, including drones and ground-based sensors, enables the acquisition of instantaneous data pertaining to the well-being of crops, soil conditions, and nutrient demands. Data-driven methodologies empower farmers to make well-informed decisions, hence optimising the allocation of resources and mitigating emissions [57].

Precision agriculture serves as a prime illustration of the amalgamation of technology and data-driven decision-making in order to augment sustainability and mitigate emissions in the agriculture sector. By implementing enhanced strategies of nutrient management and embracing emission-reducing technologies, this strategy presents a viable pathway for harmonising agricultural practices with climate objectives, all the while ensuring the sustainability of global food production.

6 Carbon sequestration and removal in agriculture

As mentioned earlier, the agriculture sector not only contributes to GHG emissions, but also addresses climate change through carbon storage and removal. This section examines the significant role that agriculture plays in the process of absorbing and sequestering CO_2 from the Earth's atmosphere. This part is divided into two subsections: soil carbon sequestration and afforestation and reforestation. It highlights the measures taken by the agriculture sector in order to transition into a net carbon sink [58].

The process of carbon sequestration in agriculture encompasses more than just emission reduction; it involves the active removal of CO_2 from the atmosphere, thereby contributing to the overarching objective of attaining carbon neutrality. These initiatives utilise the potential of natural processes and agricultural methodologies to sequester and retain carbon, which offers a hopeful trajectory towards a more environmentally sustainable and climate-resilient agricultural future.

The next subsections examine the mechanisms, difficulties, and possibilities pertaining to soil carbon sequestration and afforestation/reforestation in the agriculture domain. Collectively, these methods provide a potent array of measures in the battle against climate change; they provide a viable path for the agriculture sector to shift from being a source of CO_2 emissions to a means of actively removing it.

6.1 Soil carbon sequestration

The process of soil carbon sequestration harnesses the potential of soils to act as a significant storage facility for atmospheric CO_2. This subsection discusses the possibilities and processes of soil carbon sequestration, which can be categorised into two essential aspects: the augmentation of soil organic matter and the significance of agroecosystems.

6.1.1 Enhancing soil organic matter

Improving soil organic matter is a key approach to the sequestration of carbon in agricultural systems. Soil organic matter, which consists of the products decomposed from plant and animal leftovers, serves the dual purpose of carbon storage and enhancement of soil structure, fertility, and water retention capacity. The use of cover crops and green manure into farming systems serves to improve the content of soil organic matter. These agricultural practices involve the intercropping of designated crops during intervals between cash crop seasons, the integration of crop leftovers into the soil, and the facilitation of the proliferation of advantageous microbes [59].

The implementation of reduced tillage practices, including reduced or no-tillage methods, serves to minimise soil disturbance. This approach effectively safeguards soil organic matter by mitigating its exposure to breakdown. This methodology effectively increases the capacity for carbon sequestration and also preserves the integrity and fertility of the soil. Crop rotation is a well-recognised agricultural practice that involves the systematic alteration of plant species in order to boost the content of soil organic matter. This is achieved by introducing a variety of organic leftovers into the soil, thereby diversifying the types of nutrients supplied. These rotational practices mitigate the potential for soil depletion and enhance carbon sequestration on a broader scale.

6.1.2 Role of agroecosystems

The contribution of agroecosystems to the sequestration of soil carbon extends beyond the scope of specific farming practices, encompassing the wider ecological environment in which agricultural activities are performed. The promotion of biodiversity and enhancement of ecosystem services are facilitated by the presence of diverse agroecosystems, which encompass various agricultural practices such as mixed cropping and agroforestry. These systems not only enhance the process of carbon sequestration, but also contribute to the improvement of soil health, pest control, and overall agricultural resilience [60].

In addition to their capacity for carbon absorption, conservation tillage methods offer advantages such as less soil erosion and enhanced water quality. The aforementioned benefits at the agroecosystem level highlight the diverse advantages associated with farming practices that prioritise carbon. Agroecosystems that are specifically constructed for the purpose of soil carbon sequestration generally demonstrate enhanced resilience to adverse climatic conditions.

The improvement of soil organic matter has been found to have a positive impact on the water-holding capacity of soil, hence providing a protective mechanism for crops during periods of drought and floods. This aligns with the objectives of climate adaptation, as it contributes to the resilience of agricultural systems in the face of changing climatic conditions. The process of soil carbon sequestration has the dual purpose of mitigating climate change and bolstering soil production and resilience. Through the implementation of strategies aimed at increasing soil organic matter and promoting diversified agroecosystems, the agricultural sector has the capacity to function as a carbon sink, thereby making significant contributions to both climate mitigation efforts and the achievement of sustainable food production goals. The following subsection focuses on another crucial element of carbon sequestration, namely afforestation and reforestation within agricultural landscapes.

6.2 Afforestation and reforestation

The implementation of afforestation and reforestation practices in agricultural landscapes is considered a strategic method for carbon sequestration [61]. These practices utilise the inherent ability of trees and forests to trap and store CO_2. This subsection examines the complexities of afforestation and reforestation initiatives, specifically emphasising two key aspects: agroforestry systems and carbon stocks in tree plantations.

6.2.1 Agroforestry systems

Agroforestry systems involve the deliberate integration of trees and woody plants into agricultural landscapes, which can result in a mutually beneficial cohabitation of food production and carbon sequestration. These systems generate a wide range of environmental, social, and economic advantages. Carbon sequestration refers to the process by which trees within agroforestry systems effectively collect and retain carbon within their biomass and the soil [62]. The integration of agricultural and forestry components amplifies the total potential for carbon sequestration in comparison with conventional monoculture farming practices. Agroforestry landscapes play a crucial role in promoting biodiversity as they serve as habitats and sources of sustenance for a wide array of plant and animal species. The presence of various ecological resources contributes to the overall resilience of ecosystems and provides essential support for pollinator populations, ultimately leading to positive impacts on crop output.

Taking erosion-control measures, such as cultivating trees and woody plants, can effectively mitigate soil erosion through the stabilisation of soil particles facilitated by their intricate root systems [63]. The use of erosion-control measures safeguards the integrity of precious topsoil and mitigates the occurrence of sedimentation in aquatic environments. The inclusion of trees in agroforestry systems has been found to provide microclimates that effectively alleviate temperature fluctuations and, consequently, bring about advantageous conditions for the growth of crops and the well-being of animals. The provision of shade by trees has the potential to mitigate heat stress experienced by animals, and the presence of protected circumstances can prolong the growing seasons of specific crops.

6.2.2 Carbon stocks in tree plantations

The cultivation of trees with the primary objective of carbon storage, as shown by tree plantations, provides a focussed strategy for the mitigation of carbon emissions. One of the objectives of tree planting is to optimise the process of carbon sequestration in a compressed time period. Rapidly expanding tree species has the capacity to amass considerable biomass, which enables the sequestration of enormous quantities of CO_2 [64].

Tree plantation can provide lucrative wood and biomass resources through sustainable harvesting practices [65]. The incorporation of harvested wood products has the potential to mitigate emissions by serving as a substitute to resources that have a high carbon footprint. Silvopasture, a practice that involves the integration of tree plantations with livestock grazing, is a synergistic approach that combines the benefits of carbon sequestration with livestock productivity. In this system, trees play a significant role in providing shade and food for cattle. It presents a land use alternative that is both economically feasible and environmentally advantageous [66].

Long-term carbon storage is facilitated by the retention of a significant part of carbon inside wood products over extended periods, spanning decades, or even centuries. The potential for agriculture to contribute to mitigating climate change is exemplified by afforestation, reforestation, and agroforestry systems. These solutions provide a dual advantage as they improve the process of carbon sequestration and also encourage sustainable land use. This alignment with the wider objectives of climate mitigation and agricultural sustainability is noteworthy. The following section examines the incorporation of various solutions for mitigating and removing carbon in the framework of agricultural policies and practices.

7 Challenges and barriers to mitigation

The endeavour to mitigate GHG emissions in the agriculture sector is not devoid of intricacies and challenges. The agriculture sector has considerable potential for mitigating emissions, adopting carbon sequestration practices, and improving sustainability. However, it also faces many obstacles that hinder its advancement [67]. In this regard, the present section discusses the intricate and diverse terrain of barriers to mitigation. The section is separated into two separate, yet interrelated, subsections, namely socioeconomic constraints and policy and regulatory challenges.

The aforementioned problems highlight the need for adopting a comprehensive and nuanced strategy to address agricultural emissions reduction and carbon sequestration. Overcoming these obstacles necessitates the collective effort of many stakeholders, the implementation of inventive agricultural methodologies, and the establishment of efficient policy and regulatory structures. By acknowledging the obstacles that the agriculture sector encounters in the framework of climate change mitigation, better-informed, fair, and efficient strategies could be formulated, which effectively negotiate the intricacies of this crucial industry.

7.1 Socioeconomic constraints

The adoption of mitigation techniques in agriculture is significantly hindered by socioeconomic restrictions. The aforementioned limitations, which are frequently interconnected with specific circumstances at the local and regional levels, have an impact on the ability of farmers and communities to actively participate in initiatives aimed at reducing emissions and sequestering carbon [66]. This section covers two significant aspects of these limitations: smallholder farmers and the accessibility of technology.

7.1.1 Smallholder farmers

Smallholder farmers, who constitute a substantial proportion of the worldwide agricultural labour force, encounter distinctive obstacles when it comes to the implementation of mitigation practices. Smallholder farmers frequently have constraints in regard to their access to financial capital, land, and technology, resulting in restricted resources at their disposal. This limitation hampers their capacity to allocate resources towards the development and implementation of technology aimed at lowering emissions, embracing sustainable practices, and engaging in afforestation and reforestation initiatives. A large number of smallholder farmers face a dearth of resources and opportunities to acquire information and expertise pertaining to climate-smart farming practices. The implementation of mitigation and carbon sequestration measures may be impeded because of smallholders' poor awareness of their advantages and methodologies [68].

Risk aversion is a characteristic that may be observed in smallholders as a result of their dependence on agriculture as a means of sustenance and ensuring food security. The act of engaging in novel practices or technology may be seen as inherently precarious, particularly in the absence of safeguards or support systems. Market access is a significant challenge for small-scale farmers in regard to gaining entry into markets and obtaining equitable prices for their sustainably produced agricultural goods. This phenomenon has the potential to deter investments in mitigation strategies that have the capacity to raise production expenses.

7.1.2 Access to technology

The availability of technology considerably facilitates mitigation measures in the agriculture sector. However, differences in access to technology might further amplify existing inequities. The use of advanced emission-reducing technology and precision agricultural instruments may pose a significant financial burden for a considerable number of farmers because of their high costs. The expenses associated with adoption might serve as a hindrance, especially for farmers with limited resources. Rural regions, characterised by a dominant agricultural sector, frequently have deficiencies in infrastructure, such as limited internet connectivity and unreliable electrical provision. The presence of infrastructural gaps is a significant obstacle to the widespread use of digital technology and data-driven practices [69].

Capacity building is essential for farmers to acquire the necessary skills and knowledge to properly utilise emerging technologies. The lack of educational and extension services may impede the adoption of practices aimed at lowering emissions. Disparities in technology innovation and adaptability might give rise to a digital divide, resulting in differential access to cutting-edge solutions among farmers.

To effectively tackle socioeconomic restrictions, it is imperative to adopt customised strategies that take into account the unique obstacles encountered by small-scale farmers and the inequalities in technology accessibility. The use of strategies that foster inclusion, facilitate knowledge-sharing, and encourage capacity development can effectively empower agricultural communities to surmount these challenges and actively engage in endeavours related to climate mitigation and adaptation.

7.2 Policy and regulatory challenges

The implementation of an enabling policy and regulatory framework is crucial for the reduction of GHG emissions in the agriculture sector [70]. However, successfully navigating the intricate landscape of laws and regulations poses a unique set of challenges. This article examines two key components of policy and regulatory challenges, i.e. land use planning and incentive mechanisms.

7.2.1 Land use planning

Land use planning is an iterative and comprehensive process that entails the methodical evaluation and administration of land resources with the ultimate aim of attaining sustainable development. The process includes the discovery, analysis, and allocation of land resources. The function of land use planning is of paramount importance in shaping the structure of agricultural landscapes and their potential to reduce emissions and absorb carbon.

Agricultural regions may face conflicts arising from competing land uses such as urbanisation, industrialisation, and infrastructure development. The potential limitations on the allocation of land for carbon sequestration endeavours, such as afforestation and reforestation, may arise owing to land use conflicts. The absence of adequate zoning and land use regulations might possibly impede the advancement and execution of carbon sequestration practices, which shows that they lack the essential incentives and facilitation. The implementation of clear and well-structured policies is crucial to promoting sustainable practices of land management and establishing designated areas for afforestation, reforestation, and conservation [71].

Insecure land tenure systems can discourage enduring investments in afforestation and sustainable practices of land management. Farmers may demonstrate hesitancy in embracing carbon sequestration practices in the absence of land ownership or secure land rights.

7.2.2 Incentive mechanisms

Incentive mechanisms include a variety of tactics and systems employed to stimulate individuals or groups to adopt desired behaviours or attain certain outcomes. The implementation of effective incentive frameworks is essential to encouraging the engagement of farmers and landowners in climate mitigation initiatives. Financial incentives, such as subsidies, grants, and carbon credit programmes, can encourage the adoption of emission-reducing technologies and practices that facilitate carbon sequestration. However, significant disparities may exist in the structure and inclusivity of these incentives [72].

Policy coherence is a concept that pertains to the lack of incongruities or contradictions across agricultural, environmental, and climatic policies. These inconsistencies might impede the effectiveness of mitigation measures. The achievement of improved mitigation measures can be facilitated by aligning policies to provide a comprehensive framework. Monitoring and verification are essential components that ensure the mitigation activities comply with set criteria and standards. The aforementioned systems exhibit a tendency to use a substantial quantity of resources and require careful planning and execution in their design and implementation [73]. The efficacy of incentive schemes is augmented when they are complemented with public awareness campaigns that underscore the benefits of embracing environmentally sustainable practices. The development of mindfulness can function as a catalyst for the voluntary participation of farmers and landowners in efforts to mitigate environmental impacts.

The successful settlement of policy and regulatory challenges requires a collaborative effort including governmental entities, policymakers, and other stakeholders. Efficient land use planning, thorough regulatory frameworks, and suitably designed incentive systems have the potential to provide the necessary support for agriculture to become a substantial contribution to climate change mitigation. By overcoming these challenges, it is possible to fully harness the potential of agriculture as a method of mitigating climate change and also ensure the long-term sustainability and resilience of food production systems.

8 Synergies and trade-offs in agricultural emissions reduction

In the agriculture sector, the endeavour to reduce emissions and sequester carbon is a multifaceted undertaking characterised by the convergence of several possibilities, difficulties, and repercussions. In light of climate change, it is imperative to study the interconnections and trade-offs associated with reducing agricultural emissions while agricultural systems undergo adaptation. This section examines the complex interaction of several elements that contribute to emissions reduction techniques. It is organised into three key parts: food security and emissions reduction, alignment with sustainable development goals, and conservation of biodiversity.

Agriculture is not an independent industry, but rather a fundamental component of worldwide food systems, economies, and ecosystems. The implementation of measures aimed at reducing emissions and fostering sustainability in the agriculture sector can result in positive outcomes not only for the environment, but also for society and the economy. Therefore, it is essential to investigate the potential synergies that exist between the reduction of agricultural emissions and larger social objectives and also to recognise the potential trade-offs that may arise. Through a comprehensive analysis of these characteristics, it is possible to strategically plan a trajectory that optimises the beneficial effects of mitigating agricultural emissions on a global scale, particularly in relation to sustainability, food security, and biodiversity preservation.

8.1 Food security and emissions reductions

The complex interconnection between food security and emissions reduction in the agriculture sector highlights the necessity for a well-balanced strategy that addresses climate change and simultaneously guarantees universal access to safe, nutritious, and enough food. Tables 1 and 2 show, respectively, the synergies and trade-offs in the food security and emission reductions. Achieving a harmonious equilibrium between food security and carbon reductions necessitates a comprehensive and contextually tailored methodology. Through the identification of synergies and the mitigation of trade-offs, policymakers and stakeholders can devise solutions that not only address the challenges posed by climate change, but also enhance the resilience of food systems, decrease vulnerabilities, and foster equal access to food. The adherence to principles of sustainability and social fairness is crucial in ensuring the long-term effectiveness of efforts to reduce emissions in the agricultural sector, leading to beneficial and enduring effects for the environment and society.

8.2 Sustainable development goals alignment

The sustainable development goals (SDGs) established by the United Nations provide a comprehensive framework for addressing a range of global concerns such as climate change and sustainable agriculture. This subsection examines the correlation between SDGs and agricultural emissions reduction, emphasising the potential synergies and trade-offs that emerge in this complex framework. Tables 3 and 4 show the synergies and trade-offs in SDGs, respectively.

The convergence of emissions reduction in the agriculture sector with the SDGs is a viable avenue for achieving comprehensive and sustainable development. The achievement of optimal synergies while minimising trade-offs necessitates meticulous strategic planning, active engagement and cooperation among relevant parties, and a steadfast dedication to the ideals of fairness and inclusiveness. Through acknowledging the interdependence of global development objectives, it is possible to construct a prospective scenario wherein the reduction of agricultural emissions plays a role

Table 1 Synergies in food security and emissions reductions

Field	Description
Sustainable practices	Numerous solutions aimed at reducing emissions, such as conservation agriculture and agroforestry, have the potential to improve soil health and fertility. These practises not only facilitate the sequestration of carbon but also enhance crop yields, therefore, making a valuable contribution to food security
Reduced food loss and waste	The mitigation of post-harvest losses and food waste can provide substantial reductions in emissions linked to the production and disposal of unconsumed food. The implementation of strategies aimed at enhancing food distribution and storage systems is in line with the objective of reducing emissions
Diversified diets	The promotion of diverse and balanced diets that integrate a greater proportion of plant-based meals has the potential to mitigate emissions linked to cattle agriculture. The implementation of dietary changes has the potential to provide favourable health effects, while also mitigating the environmental impact associated with agricultural practises

Table 2 Trade-offs in food security and emissions reductions

Field	Description
Yield variability	Certain emissions reduction practises, such as the implementation of decreased tillage or adoption of organic farming methods, have the potential to result in fluctuations in crop yields. Although the aforementioned practises have the potential to be environmentally sustainable over an extended period, it is important to acknowledge that short-term variations in crop yields may provide obstacles to ensuring food security, particularly in areas that are already susceptible to vulnerabilities
Resource competition	Resource rivalry can arise when there is a conflict for land and water resources between endeavours focussed on food production and those aimed at carbon sequestration, such as afforestation. Achieving a balance between these conflicting objectives is crucial in order to safeguard food production without compromising emissions reduction efforts
Cost implications	The implementation of emissions reduction practises might entail some expenses, which can be either absorbed by farmers or transferred to consumers. It is of utmost importance to ensure that the impact of these expenses on food accessibility is not disproportionately borne
Livelihoods	Impacts on Livelihoods: The move away from high-emission agricultural practises, such as animal farming, might potentially have consequences for livelihoods in some circumstances. One potential approach to tackle this situation involves the implementation of strategies aimed at offering other sources of income and opportunity for communities that are impacted

Table 3 Synergies in sustainable development goals alignment

Field	Description
SDG 2	SDG 2, often known as Zero Hunger, may be effectively advanced through the reduction of agricultural emissions. This can be achieved by advocating for the adoption of sustainable agricultural practises that not only contribute to food security but also improve nutritional outcomes. The implementation of several strategies aimed at enhancing soil health, mitigating food loss and waste, and promoting the cultivation of crop types tolerant to climate change significantly contribute to the attainment of the Zero Hunger goal
SDG 13	SDG 13, also known as Climate Action, is advanced by the reduction of emissions in the agricultural sector. This endeavour aligns with the urgent urgency to address climate change and its associated consequences as outlined in SDG 13. The objectives of climate mitigation and adaptation are congruent with sustainable agricultural practises, afforestation, and reforestation endeavours
SDG 15	SDG 15 (Life on Land) encompasses endeavours focussed on the preservation of biodiversity, frequently interconnected with initiatives aimed at mitigating emissions. These conservation efforts are in line with the objectives of SDG 15, which seeks to safeguard, rehabilitate, and foster sustainable terrestrial ecosystems. The use of agroecological practises and afforestation has been found to have a positive impact on the overall health of terrestrial ecosystems
SDG 1 & SDG 8	The promotion of sustainable agriculture has the potential to generate job opportunities and mitigate poverty, so harmonising with the objectives outlined in SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth). The promotion of rural livelihoods and provision of support to smallholder farmers can serve as effective emissions reduction initiatives that have the potential to contribute to equitable economic growth

Table 4 Trade-offs in sustainable development goals alignment

Field	Description
SDG 9	SDG 9, which focuses on Industry, Innovation, and Infrastructure, highlights that the implementation of emissions reduction technologies and practises may necessitate significant expenditures in innovation and infrastructure. This allocation of resources towards emissions reduction initiatives has the potential to divert funds from other development objectives. The act of maintaining equilibrium between these investments and other competing goals is of utmost importance
SDG 7	SDG 7, which focuses on inexpensive and clean energy, highlights the potential implications on the accessibility of inexpensive and clean energy due to the energy demands associated with certain emissions reduction technologies, such as bioenergy production or the use of electric farm gear. Thorough strategic planning is necessary in order to achieve energy equity
SDG 6	SDG 6, which pertains to clean water and sanitation, posits that the implementation of sustainable agriculture practises has the potential to influence both water use and the overall quality of water resources. Ensuring a harmonious equilibrium between the reduction of emissions and the protection of water resources is of utmost importance in order to prevent inadvertent repercussions on the accessibility of clean water
SDG 10	SDG 10, often known as "Reduced Inequalities," underscores the crucial need of ensuring that activities aimed at reducing emissions do not further worsen pre-existing disparities. When formulating strategies, it is crucial to take into account the possible effects on vulnerable and marginalised populations, and to actively strive towards reducing any existing gaps

in fostering a society characterised by fairness, adaptability, and environmental sustainability.

8.3 Biodiversity conservation

The preservation of biodiversity in agricultural systems is a crucial factor to be taken into account in efforts made to achieve emissions reduction. This subsection examines the complex connection between biodiversity conservation and agricultural emissions reduction, highlighting the synergies and trade-offs that exist in this dynamic interaction. Tables 5 and 6 show the synergies and trade-offs in the biodiversity conservation, respectively.

The interdependence of biodiversity protection and emissions reduction is evident since their respective results hold significant consequences for global sustainability. Achieving a harmonious equilibrium among these goals requires the implementation of a holistic strategy that takes into account the ecological, social, and economic aspects of agriculture. Including biodiversity protection into emissions reduction plans may lead to a future in which agricultural practices are both climate-smart and conducive to the flourishing and varied ecosystems that underpin food systems.

9 Future outlook and research directions

The review of the literature on mitigating agricultural emissions and enhancing carbon sequestration reveals that it is still difficult to achieve a certain conclusion in this regard. The future trajectory of sustainable agriculture hinges upon our capacity to engage in innovative practices, adapt to changing circumstances, and foster successful collaboration. This section focuses on future

Table 5 Synergies in biodiversity conservation

Field	Description
Ecosystem services	The provision of ecosystem services is heavily reliant on biodiversity, since it plays a pivotal role in supporting agricultural activities. These services encompass essential functions like as pollination, natural pest control, and the maintenance of soil fertility. The implementation of conservation initiatives aimed at preserving biodiversity has the potential to not only improve agricultural output but also effectively reduce emissions
Carbon sequestration	The implementation of emissions reduction measures, such as afforestation and agroforestry, demonstrates a congruence with the objectives of biodiversity conservation. Forested regions and diversified agroecosystems function as ecological niches for a broad spectrum of organisms, so playing a crucial role in the conservation and maintenance of biodiversity
Resilience to climate change	The resilience of ecosystems to climate change is typically enhanced by their biodiversity, which enables them to better withstand and adapt to the consequences of climate change, including extreme weather events and insect outbreaks. The use of biodiversity-enhancing practises has the potential to mitigate the negative impacts of climate change on agriculture
Genetic diversity	The preservation of genetic variety in agricultural and animal species is of utmost importance for ensuring food security and for adaptability to evolving environmental circumstances. Biodiversity conservation endeavours have the potential to save the wild counterparts of cultivated plants and domesticated animals, so ensuring the preservation of valuable genetic reservoirs

Table 6 Trade-offs in biodiversity conservation

Field	Description
Land use changes	Land use changes can occur as a result of emissions reduction initiatives, such as afforestation, which may have implications for current agricultural areas and ecosystems. It is imperative to achieve a harmonious equilibrium between these alterations and endeavours in biodiversity conservation in order to prevent the loss of habitats
Pesticide use	The utilisation of pesticides in intensive agricultural practises has the potential to have adverse impacts on biodiversity. The task of minimising dependence on pesticides while still sustaining agricultural output is a complex undertaking that needs meticulous oversight and strategic planning
Invasive species	The implementation of some mitigation measures has the potential to unintentionally introduce invasive species or pests, hence causing detrimental effects on local ecosystems. In order to mitigate these unexpected outcomes, it is imperative to employ vigilance and conduct comprehensive risk assessments
Habitat fragmentation	Habitat fragmentation is a consequence of land use changes that are often implemented to achieve emissions reductions. This phenomenon poses a significant risk to many species as it might result in their isolation and vulnerability. The implementation of landscape design is of utmost importance in order to effectively manage this danger

outlook and research directions for mitigating agricultural emissions, developing a scenario where progress is driven by improvements, innovations, and multidisciplinary collaboration.

Under this overall subject, this section discusses three crucial subsections: progress in emission measurement and monitoring, innovations in climate-smart agriculture, and collaborative efforts across sectors. Collectively, these domains offer a look into the dynamic field of agricultural emissions research and application, elucidating the promising opportunities and obstacles that lie on the horizon.

The efficacy of agriculture as a climate mitigation strategy relies on the successful incorporation of advanced scientific knowledge, technological advancements, and policy frameworks into agricultural practices, alongside the cultivation of collaborative alliances that surpass conventional limitations. In this sense, the present section establishes the groundwork for a sustainable and resilient agricultural trajectory in light of the challenges posed by climate change.

9.1 Advancements in emission measurement and monitoring

The successful pursuit of mitigating agricultural emissions and improving carbon sequestration relies heavily on the capacity to precisely measure, monitor, and evaluate the effectiveness of these efforts. This subsection looks into the dynamic terrain of advancements in emission measurement and monitoring in order to provide insights into the cutting-edge equipment and procedures that can significantly transform our comprehension of agricultural emissions. These advancements are illustrated in Fig. 4 and summarised as follows:

- Remote Sensing and Satellite Technology: The progress made in remote sensing and satellite technologies has provided unparalleled opportunities for the surveillance of agricultural emissions on a regional and global level. Satellite-derived sensors have the capability to identify alterations in land utilisation, crop vitality, and vegetation coverage; therefore, they can offer significant scholarly perspectives into sources of emissions, patterns, and prospective avenues for mitigation. These technologies provide the monitoring of events in near real-time, allowing for a swift reaction to emergent difficulties.

- IoT and Sensor Networks: The advent of the Internet of Things (IoT) has facilitated the emergence of a novel epoch in precision agriculture, as it facilitates the implementation of sensor networks throughout agricultural fields. The sensors are responsible for gathering data pertaining to several aspects, including soil conditions, concentrations of GHGs, patterns of weather, and the development of crops. When combined with data analytics and artificial intelligence, IoT-based monitoring systems enable farmers to make decisions based on data, leading to a reduction in emissions and an increase in production [74–76].
- Data Integration and Modelling: The progress in data integration and modelling techniques has augmented the capacity of simulating and forecasting the consequences of measures taken to reduce agricultural emissions. The use of integrated models that incorporate many elements such as climate, land use, and socioeconomic variables allows for a more complete evaluation of mitigation strategies. These models facilitate the identification of optimal techniques for reducing emissions and sequestering carbon. This aids policymakers and researchers in their decision-making processes [77, 78].
- Blockchain Technology and Transparency: The utilisation of blockchain technology is increasingly being recognised as a means to augment transparency and traceability in agricultural supply chains. Through the systematic recording of emission data at every step of production and distribution, blockchain technology plays a crucial role in promoting accountability and facilitating emissions reduction across the whole value chain. Being provided with access to verifiable information, consumers and stakeholders can make educated decisions that align with sustainable practices [79].
- Advancements in Measurement Techniques for Future Applications: In contemporary laboratory settings, novel measuring methodologies are progressively enhancing our capacity to accurately estimate agricultural emissions. The advent of novel technologies such as laser-based spectroscopy and portable gas analysers has facilitated the acquisition of real-time, on-site data pertaining to GHGs. These approaches offer significant insights into areas with high emissions and facilitate the implementation of focussed measures for reducing them.

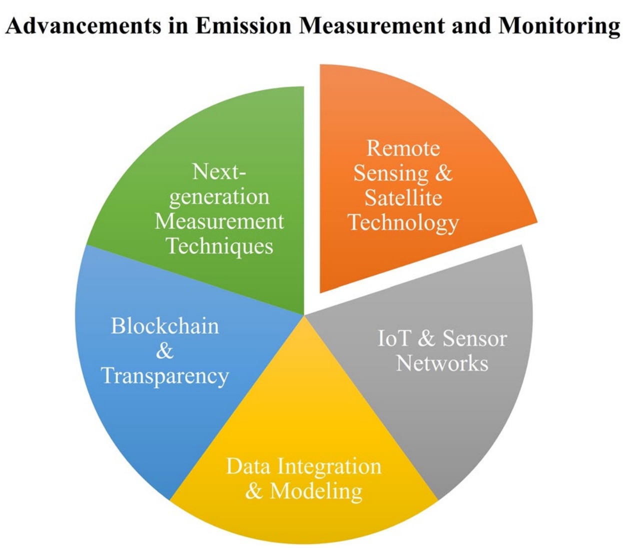


Fig. 4 Main advancements in emission measurement and monitoring

The key to making informed decisions, tracking progress, adapting tactics, and refining regulations lies in the advancements made in emission measurement and monitoring. By adopting these advanced technologies and practices, a more sustainable and resilient agricultural sector could be developed, which assumes a crucial role in the mitigation of climate change and the guarantee of food security for an expanding global population.

9.2 Climate-smart agriculture innovations

Given the dynamic nature of climate change, it is imperative for the agriculture sector to undergo a transformation that prioritises resilience, sustainability, and adaptability. This subsection concentrates on the innovations in the domain of Climate-Smart Agriculture, whereby revolutionary methodologies and technologies are reshaping the trajectory of agricultural practices. The development of climate-resilient crop varieties shows potential through the use of advanced crop breeding techniques, including precision breeding and gene editing. The primary objective of these improvements is to augment the capacity of crops to withstand severe temperatures, drought, and pests, hence facilitating their growth and development in the face of shifting climatic circumstances. Climate-resilient cultivars provide a vital means of safeguarding food security.

Precision agriculture utilises data-driven technologies, e.g. GPS, remote sensing, and artificial intelligence, in order to optimise farming practices. From the implementation of precise irrigation management to the use of variable rate fertilisation, these technological advancements contribute to the enhancement of resource efficiency, the mitigation of emissions, and the augmentation of agricultural yields. Digital farming platforms help farmers make informed decisions with considering data-driven insights.

Agroecological practices, including organic farming, permaculture, and regenerative agriculture, enhance biodiversity, soil health, and carbon sequestration. These methodologies highly emphasise promoting sustainability and resilience, demonstrating a strong alignment with objectives aimed at reducing emissions. Agroecological technologies are playing a transformative role in the restructuring of agricultural systems, fostering a heightened level of alignment with the natural environment [80].

Carbon farming practices, such as the use of cover cropping, conservation tillage, and the application of organic soil amendments, are primarily centred on enhancing the accumulation of soil organic carbon. In addition to carbon sequestration, healthy soils also enhance nutrient cycling and water retention. The use of novel strategies for soil health management has been shown to effectively enhance both the emissions reduction capacity and the productivity of agricultural systems.

Livestock management has witnessed notable advancements, encompassing the implementation of feed additives aimed at mitigating CH_4 emissions, the adoption of enhanced breeding tactics, and the use of precision nutrition techniques. These developments both reduce emissions associated with livestock and improve animal health and production. Integrated agricultural methods involve the integration of crop and animal production, resulting in the reduction of waste and the optimisation of resource use. These systems imitate natural ecosystems, promoting the development of resilience and biodiversity. The implementation of integration and diversification strategies in agriculture contributes to the long-term viability and environmental soundness of agricultural practices. The technologies related to Climate-Smart Agriculture provide a viable approach to effectively tackle the challenges of reducing emissions, ensuring food security, and enhancing resistance to the impacts of climate change. As society grapples with the implications of global warming, it becomes more evident that innovative strategies and technologies will be important in determining the trajectory of agriculture. These transformational methods have significant potential in promoting the long-term viability of the agricultural sector and preserving the welfare of both farmers and consumers.

9.3 Cross-sectoral collaboration

The reduction of GHG emissions and the storage of carbon in the agriculture sector are complex issues that are interconnected with other sectors, including energy, transportation, forestry, and conservation. This subsection examines the significance of cross-sectoral collaboration in tackling the intricate array of difficulties linked to the influence of agriculture on climate change and summarises the results in Fig. 5.

The promotion of cross-sectoral collaboration facilitates the development of interdisciplinary research that surpasses conventional limitations. The synergy of agricultural scientists, climate specialists, ecologists, and social scientists facilitates a comprehensive understanding of the many dimensions pertaining to the mitigation of emissions and the sequestration of carbon. The act of sharing knowledge expedites the advancement of comprehensive plans in this regard.

To formulate effective policies, it is imperative to incorporate agriculture in comprehensive climate and sustainability frameworks. The establishment of collaborative partnerships among agriculture ministries, environmental agencies, and climate policy authorities aids in taking coherent and coordinated initiatives. To effectively address climate change, it is imperative that policies promoting emissions reduction and carbon sequestration be in accordance with both domestic and global climate objectives.

Public–private partnerships are of great significance in expediting the implementation of emissions reduction technology and practices. The mobilisation of resources, sharing of best practices, and promotion of innovation may be achieved through the collaboration of governments, industry, and civil society. These collaborations play a crucial role in expanding the scope of climate-smart agriculture activities.

In addition, the establishment of collaborative efforts within agricultural supply chains is crucial in mitigating emissions across the whole production-to-consumption process. Retailers, processors, and consumers are integral stakeholders in the promotion and endorsement of sustainable and environmentally friendly farming practices. Efforts such as the implementation of sustainable sourcing practices and the establishment of certification programmes facilitate the reduction of emissions.

Furthermore, the establishment of a collaborative relationship between the agricultural and conservation sectors is of utmost importance in order to effectively safeguard

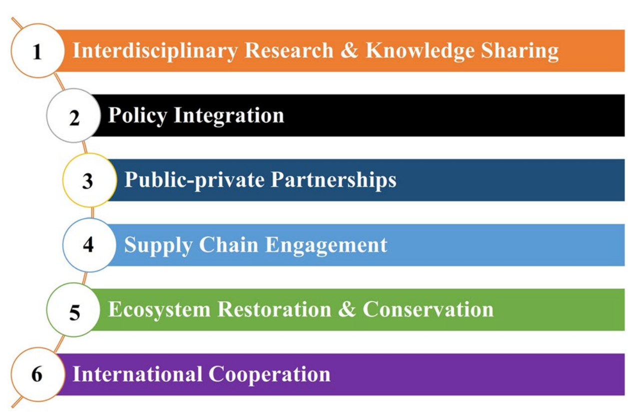


Fig. 5 Cross-sectoral collaboration

biodiversity and carbon-rich ecosystems. The integration of agroforestry, reforestation, and conservation initiatives that incorporate agricultural practices has the potential to yield simultaneous advantages in regard to mitigating emissions and safeguarding habitats.

Climate change is also a significant global challenge that highlights the need for international cooperation. It is imperative for nations to collaborate in order to synchronise emissions accounting systems, facilitate the exchange of technology and experience, and provide assistance to poorer countries in the adoption of climate-smart agriculture practices. International collaboration is a crucial component in the pursuit of global objectives of emissions reduction. Cross-sectoral collaboration beyond the boundaries of conventional disciplines and sectors acknowledges that the intricate issues associated with reducing agricultural emissions necessitate solutions that incorporate several perspectives and approaches.

By cultivating collaborations that connect agriculture with climate action, sustainability, and conservation, a revolutionary and resilient agricultural sector can significantly contribute to global efforts made to reduce emissions.

10 Conclusions

Given the increasing climate-related difficulties, the agricultural sector occupies a pivotal position since it is intricately linked to both the underlying issue and the potential resolution. The present study examined the GHG emissions and removals in the agricultural sector, which provided insights into the complex nature of this sector's contribution to climate change mitigation. During this investigation, a substantial amount of information was discovered, highlighting the capacity of agriculture to serve as a viable solution to climate-related challenges. Considering aspects such as the origins of GHG emissions in agricultural production, the complexities of carbon sequestration, and the intricate interplay of synergies and trade-offs, the significance of agriculture in mitigating global climate change is evident.

The future of the agriculture sector is on a terrain characterised by the presence of novelty, cooperation, and flexibility. This industry is on the verge of a transformation by advancements in emission measuring and monitoring, innovations in climate-smart agriculture, and more cross-sectoral collaborations. These advancements present a promising outlook for a future in which the goals of reducing emissions and ensuring food security are not conflicting, but rather interconnected aims. Nevertheless, the path of this transformation is not devoid of obstacles. The progression of smallholder farmers and the welfare of vulnerable populations might be hindered by socioeconomic limitations and legislative obstacles. The need for cautious navigation arises from the possible trade-offs that may exist between emissions reduction and other important objectives such as food security, biodiversity protection, and sustainability. However, when confronted with these obstacles, the shared dedication of individuals and groups involved worldwide provides motivation for progress. The impetus for change is evident, including various stakeholders such as farmers who embrace sustainable practices, governments that formulate enabling legislation, academics who advance the frontiers of knowledge, and consumers who advocate sustainability. In summary, the extensive examination of GHG emissions and removals for agriculture presents a multifaceted depiction of an industry on the verge of a significant change. This statement urges us to acknowledge agriculture not only as a contributor to GHG emissions, but also as a significant source of creative and inventive solutions. This statement calls upon individuals to acknowledge and accept the intricate nature, unpredictability, and potential advantages that characterise the agricultural environment in a global climate that is getting progressively warmer.

By leveraging the potential of information, technology, and collaborative efforts, it is possible to guide the agriculture sector towards a future characterised by sustainability and resilience. This future involves not only the provision of food for the global population, but also the promotion of environmental well-being and the preservation of the climate for future generations.

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Data availability All data generated or analyzed during the study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Badji A, Benseddik A, Bensaha H, Boukhelifa A, Hasrane I (2022) Design, technology, and management of greenhouse: a review. J Clean Prod 373:133753. https://doi.org/10.1016/j.jclepro.2022.133753
2. Shukla P, Skea J, Slade R, Khourdajie AA, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (2022) In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK and New York, NY, USA). https://doi.org/10.1017/9781009157926.001

3. Gregory RP (2022) The effect of atmospheric greenhouse gases on firm value and firm size distribution. J Clean Prod 358:131751. https://doi.org/10.1016/j.jclepro.2022.131751
4. Stewart K, Balmford A, Scheelbeek P, Doherty A, Garnett EE (2023) Changes in greenhouse gas emissions from food supply in the united kingdom. J Clean Prod 410:137273. https://doi.org/10.1016/j.jclepro.2023.137273
5. Jiang O, Li Y, Zheng Y, Gustave W, Tang X, Xu J (2023) Cadmium reduced CH_4 emissions by stimulating CH_4 oxidation in paddy soils. Environ Res. https://doi.org/10.1016/j.envres.2023.117096
6. Khan MN, Huang J, shah A, Li D, Daba NA, Han T, Du J, Qaswar M, Anthonio CK, Sial TA, Haseeb A, Zhang L, Xu Y, He Z, Zhang H, Núñez-Delgado A (2022) Mitigation of greenhouse gas emissions from a red acidic soil by using magnesium-modified wheat straw biochar. Environ Res 203:111879. https://doi.org/10.1016/j.envres.2021.111879
7. Yang X, Liu D, Fu Q, Li T, Hou R, Li Q, Li M, Meng F (2022) Characteristics of greenhouse gas emissions from farmland soils based on a structural equation model: regulation mechanism of biochar. Environ Res 206:112303. https://doi.org/10.1016/j.envres.2021.112303
8. Gaines AM, Davies T, Shahid M, Taylor F, Wu JH, Hadjikakou M, Pettigrew S, Seferidi P, Neal B (2023) A novel approach to estimate product-specific greenhouse gas emissions for 23,550 australian packaged foods and beverages. J Clean Prod. https://doi.org/10.1016/j.jclepro.2023.138816
9. Khan MN, Li D, Shah A, Huang J, Zhang L, Núñez-Delgado A, Han T, Du J, Ali S, Sial TA, Lan Z, Hayat S, Song Y, Bai Y, Zhang H (2022) The impact of pristine and modified rice straw biochar on the emission of greenhouse gases from a red acidic soil. Environ Res 208:112676. https://doi.org/10.1016/j.envres.2022.112676
10. Li F, Anjarsari Y, Wang J, Azzahiidah R, Jiang J, Zou J, Xiang K, Ma H (2022) Arramel, Modulation of the lattice structure of 2d carbon-based materials for improving photo/electric properties. Carbon Lett 1–11
11. Song K, Baiocchi G, Feng K, Hubacek K, Sun L (2022) Unequal household carbon footprints in the peak-and-decline pattern of U.S. greenhouse gas emissions. J Clean Prod 368:132650. https://doi.org/10.1016/j.jclepro.2022.132650
12. Sivaranjanee R, Kumar PS, Rangasamy G (2023) A critical review on biochar for environmental applications. Carbon Lett 1–26
13. Kamyab H, Chelliapan S, Tavakkoli O, Mesbah M, Bhutto JK, Khademi T, Kirpichnikova I, Ahmad A, ALJohani AA (2022) A review on carbon-based molecularly-imprinted polymers (cbmip) for detection of hazardous pollutants in aqueous solutions. Chemosphere 308:136471. https://doi.org/10.1016/j.chemosphere.2022.136471
14. Tahir MA, Hamza A, Hussain S, Xie Z, Brestic M, Rastogi A, Allakhverdiev SI, Sarwar G (2022) Carbon sequestrating fertilizers as a tool for carbon sequestration in agriculture under aridisols. Carbon Lett 32(7):1631–1644
15. Mehryar M, Hafezalkotob A, Azizi A, Sobhani FM (2021) Cooperative reliability allocation in network flow problems considering greenhouse gas emissions: optical fiber networks structure. J Clean Prod 326:129315. https://doi.org/10.1016/j.jclepro.2021.129315
16. Cruz OF Jr, Campello-Gómez I, Casco ME, Serafin J, Silvestre-Albero J, Martínez-Escandell M, Hotza D, Rambo CR (2023) Enhanced CO_2 capture by cupuassu shell-derived activated carbon with high microporous volume. Carbon Lett 33(3):727–735
17. Ribeiro-Kumara C, Köster E, Aaltonen H, Köster K (2020) How do forest fires affect soil greenhouse gas emissions in upland boreal forests? A review. Environ Res 184:109328. https://doi.org/10.1016/j.envres.2020.109328
18. Hu Y, Thomsen TP, Fenton O, Sommer SG, Shi W, Cui W (2023) Effects of dairy processing sludge and derived biochar on greenhouse gas emissions from Danish and Irish soils. Environ Res 216:114543. https://doi.org/10.1016/j.envres.2022.114543
19. Li L, Zhao C, Wang X, Tan Y, Wang X, Liu X, Guo B (2023) Effects of nitrification and urease inhibitors on ammonia-oxidizing microorganisms, denitrifying bacteria, and greenhouse gas emissions in greenhouse vegetable fields. Environ Res 237:116781. https://doi.org/10.1016/j.envres.2023.116781
20. You X, Wang S, Du L, Wu H, Wei Y (2022) Effects of organic fertilization on functional microbial communities associated with greenhouse gas emissions in paddy soils. Environ Res 213:113706. https://doi.org/10.1016/j.envres.2022.113706
21. A.G.J.S.S.K.W.D.D.A.J. Kacprzak M, Malińska K, Meers E (2023) Cycles of carbon, nitrogen and phosphorus in poultry manure management technologies - environmental aspects. Crit Rev Environ Sci Technol 53(8):914–938. https://doi.org/10.1080/10643389.2022.2096983
22. Shaaban M, Khalid MS, Hu R, Zhou M (2022) Effects of water regimes on soil N_2O, CH_4 and CO_2 emissions following addition of dicyandiamide and n fertilizer. Environ Res 212:113544. https://doi.org/10.1016/j.envres.2022.113544
23. Omirou M, Stephanou C, Anastopoulos I, Philippot L, Ioannides IM (2022) Differential response of N_2O emissions, N_2O-producing and N_2O-reducing bacteria to varying tetracycline doses in fertilized soil. Environ Res 214:114013. https://doi.org/10.1016/j.envres.2022.114013
24. Wabo SG, Klepel O (2021) Nitrogen release and pore formation through koh activation of nitrogen-doped carbon materials: an evaluation of the literature. Carbon Lett 31(4):581–592
25. Yang H, Guo Y, Fang N, Dong B (2023) Life cycle assessment of greenhouse gas emissions of typical sewage sludge incineration treatment route based on two case studies in china. Environ Res 231:115959. https://doi.org/10.1016/j.envres.2023.115959
26. Komatsuzaki M, Ohta H (2007) Soil management practices for sustainable agro-ecosystems. Springer, Tech. rep
27. Kamyab H, Chelliapan S, Hayder G, Yusuf M, Taheri MM, Rezania S, Hasan M, Yadav KK, Khorami M, Farajnezhad M, Nouri J (2023) Exploring the potential of metal and metal oxide nanomaterials for sustainable water and wastewater treatment: a review of their antimicrobial properties. Chemosphere 335:139103. https://doi.org/10.1016/j.chemosphere.2023.139103
28. Feng ZY, Meng LY (2021) Hierarchical porous carbons derived from corncob: study on adsorption mechanism for gas and wastewater. Carbon Lett 31:643–653
29. Hu Y, Su M, Jiao L (2023) Peak and fall of china's agricultural ghg emissions. J Clean Prod 389:136035. https://doi.org/10.1016/j.jclepro.2023.136035
30. Warsame AA, Mohamed J, Mohamed AA (2023) The relationship between environmental degradation, agricultural crops, and livestock production in Somalia. Environ Sci Pollut Res 30(3):7825–7835
31. Yang HY, Ahn YH (2023) Analysis of electrification and its greenhouse gas reduction potential in the industrial sector of Korea using mixed methods. J Clean Prod 419:138160. https://doi.org/10.1016/j.jclepro.2023.138160
32. Xie P, Gong N, Sun F, Li P, Pan X (2023) What factors contribute to the extent of decoupling economic growth and energy carbon emissions in china? Energy Policy 173:113416. https://doi.org/10.1016/j.enpol.2023.113416
33. Lamichhane JR, Alletto L, Cong WF, Dayoub E, Maury P, Plaza-Bonilla D, Reckling M, Saia S, Soltani E, Tison G, Debaeke P (2023) Relay cropping for sustainable intensification of agriculture across temperate regions: crop management challenges and future research priorities. Field Crop Res 291:108795. https://doi.org/10.1016/j.fcr.2022.108795

34. Yahaya SM, Mahmud AA, Abdullahi M, Haruna A (2023) Recent advances in the chemistry of nitrogen, phosphorus and potassium as fertilizers in soil: a review. Pedosphere 33(3):385–406. https://doi.org/10.1016/j.pedsph.2022.07.012
35. Zhang D, Li D, Wang H, Li H, Li R, Batchelor WD, Ju H, Li Y (2023) Tillage practices offset wheat yield reductions under limited irrigation regime in the north china plain. Soil Tillage Res 230:105687. https://doi.org/10.1016/j.still.2023.105687
36. Yun JS, Kim JH, Kang SC, Im JS (2023) Mechanism of activated carbon-catalyzed CH_4 decomposition process for the production of hydrogen and high-value carbon. Carbon Lett 1–11
37. Tuohy P, O'Sullivan L, Bracken C, Fenton O (2023) Drainage status of grassland peat soils in Ireland: extent, efficacy and implications for ghg emissions and rewetting efforts. J Environ Manage 344:118391. https://doi.org/10.1016/j.jenvman.2023.118391
38. Kamyab H, Khademi T, Chelliapan S, SaberiKamarposhti M, Rezania S, Yusuf M, Farajnezhad M, Abbas M, Hun Jeon B, Ahn Y (2023) The latest innovative avenues for the utilization of artificial intelligence and big data analytics in water resource management. Results Eng 20:101566. https://doi.org/10.1016/j.rineng.2023.101566
39. Kamran M, Yan Z, Ahmad I, Jia Q, Ghani MU, Chen X, Chang S, Li T, Siddique KH, Fahad S, Hou F (2023) Assessment of greenhouse gases emissions, global warming potential and net ecosystem economic benefits from wheat field with reduced irrigation and nitrogen management in an arid region of china. Agric Ecosyst Environ 341:108197. https://doi.org/10.1016/j.agee.2022.108197
40. Hashim H, Zubir MA, Kamyab H, Zahran MFI (2022) Decarbonisation of the industrial sector through greenhouse gas mitigation, offset, and emission trading schemes. Chem Eng Trans 97:511–516. https://doi.org/10.3303/CET2297086
41. Abyar H, Nowrouzi M (2023) Trickling filter systems for sustainable water supply: an evaluation of eco-environmental burdens and greenhouse gas emissions. Environ Res 237:117011. https://doi.org/10.1016/j.envres.2023.117011
42. Li Y, Li ZL, Wu H, Zhou C, Liu X, Leng P, Yang P, Wu W, Tang R, Shang GF et al (2023) Biophysical impacts of earth greening can substantially mitigate regional land surface temperature warming. Nat Commun 14(1):121
43. Bellebcir A, Merouane F, Chekroud K, Bounabi H, Vasseghian Y, Kamyab H, Chelliapan S, Klemeš JJ, Berkani M (2023) Bioprospecting of biosurfactant-producing bacteria for hydrocarbon bioremediation: optimization and characterization. Korean J Chem Eng 1–16
44. Ly NH, Nguyen NB, Tran HN, Hoang TTH, Joo SW, Vasseghian Y, Kamyab H, Chelliapan S, Klemeš JJ (2023) Metal-organic framework nanopesticide carrier for accurate pesticide delivery and decrement of groundwater pollution. J Clean Prod 402:136809. https://doi.org/10.1016/j.jclepro.2023.136809
45. Yingying Zhang WW, Yao H (2023) Urea-based nitrogen fertilization in agriculture: a key source of n2o emissions and recent development in mitigating strategies. Arch Agron Soil Sci 69(5):663–678. https://doi.org/10.1080/03650340.2022.2025588
46. Periakaruppan R, Palanimuthu V, Abed SA, Danaraj J (2023) New perception about the use of nanofungicides in sustainable agriculture practices. Arch Microbiol 205(1):4
47. Francaviglia R, Almagro M, Vicente-Vicente JL (2023) Conservation agriculture and soil organic carbon: principles, processes, practices and policy options. Soil Syst. https://doi.org/10.3390/soilsystems7010017
48. Quandt A, Neufeldt H, Gorman K (2023) Climate change adaptation through agroforestry: opportunities and gaps. Curr Opin Environ Sustain 60:101244. https://doi.org/10.1016/j.cosust.2022.101244
49. Hao X, Abou Najm M, Steenwerth KL, Nocco MA, Basset C, Daccache A (2023) Are there universal soil responses to cover cropping? A systematic review. Sci Total Environ 861:160600. https://doi.org/10.1016/j.scitotenv.2022.160600
50. Gao B, Li Y, Zheng N, Liu C, Ren H, Yao H (2022) Interactive effects of microplastics, biochar, and earthworms on CO_2 and N_2O emissions and microbial functional genes in vegetable-growing soil. Environ Res 213:113728. https://doi.org/10.1016/j.envres.2022.113728
51. Alshehri DM (2023) Blockchain-assisted internet of things framework in smart livestock farming. Internet Things 22:100739. https://doi.org/10.1016/j.iot.2023.100739
52. Karabay A, Bolatov A, Varol HA, Chan MY (2023) A central Asian food dataset for personalized dietary interventions. Nutrients. https://doi.org/10.3390/nu15071728
53. Fangueiro D, Merino P, Pantelopoulos A, Pereira JLS, Amon B, Chadwick DR (2023) The Implications of animal manure management on ammonia and greenhouse gas emissions. Springer International Publishing, pp 99–136. https://doi.org/10.1007/978-3-031-19730-7_5
54. Saranya T, Deisy C, Sridevi S, Anbananthen KSM (2023) A comparative study of deep learning and internet of things for precision agriculture. Eng Appl Artif Intell 122:106034. https://doi.org/10.1016/j.engappai.2023.106034
55. Darjee S, Shrivastava M, Langyan S, Singh G, Pandey R, Sharma A, Khandelwal A, Singh R (2023) Integrated nutrient management reduced the nutrient losses and increased crop yield in irrigated wheat. Arch Agron Soil Sci 69(8):1298–1309. https://doi.org/10.1080/03650340.2022.2084535
56. Liu A, Imran M, Nassani AA, Binsaeed RH, Zaman K (2023) Reducing carbon emissions with geoscience solutions: a look at the contributions of nuclear energy, technology, and green finance. Geosci Front. https://doi.org/10.1016/j.gsf.2023.101698
57. Raya I, Kzar HH, Mahmoud ZH, Al Ayub Ahmed A, Ibatova AZ, Kianfar E (2021) A review of gas sensors based on carbon nanomaterial. Carbon Lett 1–26
58. Tan SS, Kuebbing SE (2023) A synthesis of the effect of regenerative agriculture on soil carbon sequestration in southeast Asian croplands. Agricu Ecosyst Environ 349:108450. https://doi.org/10.1016/j.agee.2023.108450
59. Mustafa A, Saeed Q, Karimi Nezhad MT, Nan S, Hongjun G, Ping Z, Naveed M, Minggang X, Nú nez-Delgado A (2023) Physically separated soil organic matter pools as indicators of carbon and nitrogen change under long-term fertilization in a Chinese mollisol. Environ Res 216:114626. https://doi.org/10.1016/j.envres.2022.114626
60. Kozar R, Djalante R, Leimona B, Subramanian SM, Saito O (2023) The politics of adaptiveness in agroecosystems and its role in transformations to sustainable food systems. Earth System Governance 15:100164. https://doi.org/10.1016/j.esg.2023.100164
61. Zhang B, Lan K, Harris TB, Ashton MS, Yao Y (2023) Climate-smart forestry through innovative wood products and commercial afforestation and reforestation on marginal land. Proc Natl Acad Sci 120(23):e2221840120. https://doi.org/10.1073/pnas.2221840120
62. Ansari SA, Shakeel A, Sawarkar R, Maddalwar S, Khan D, Singh L (2023) Additive facilitated co-composting of lignocellulosic biomass waste, approach towards minimizing greenhouse gas emissions: An up to date review. Environ Res 224:115529. https://doi.org/10.1016/j.envres.2023.115529
63. Low G, Dalhaus T, Meuwissen MP (2023) Mixed farming and agroforestry systems: a systematic review on value chain implications. Agric Syst 206:103606. https://doi.org/10.1016/j.agsy.2023.103606
64. Mallesh D, Swapna S, Rajitha P, Soujanya Y, Sumana C, Lingaiah N (2023) Synthesis, characterization and evaluation of porous

carbon adsorbents derived from waste biomass for CO_2 capture. Carbon Lett 1–16
65. Rasouli K, Rasouli J, Mohtaram MS, Sabbaghi S, Kamyab H, Moradi H, Chelliapan S (2023) Biomass-derived activated carbon nanocomposites for cleaner production: a review on aspects of photocatalytic pollutant degradation. J Clean Prod 419:138181. https://doi.org/10.1016/j.jclepro.2023.138181
66. Babu KN, Mandyam S, Jetty S, Dar AA, Ayushi K, Narayanan A, Somaiah S, Narayanaswamy P (2023) Carbon stocks of tree plantations in a western Ghats landscape, India: influencing factors and management implications. Environ Monit Assess 195(3):404
67. de Sá CD, Søndergaard N, Barioni LG, Camargo RC (2023) The Brazilian way of farming: potential and challenges to agricultural decarbonization. Springer International Publishing, Cham, pp 145–163. https://doi.org/10.1007/978-3-031-29853-0_8
68. Phiri C, Njira K, Chitedze G (2023) An insight of chickpea production potential, utilization and their challenges among smallholder farmers in Malawi—a review. J Agric Food Res 14:100713. https://doi.org/10.1016/j.jafr.2023.100713
69. Li K, Li Q (2023) Towards more efficient low-carbon agricultural technology extension in china: identifying lead smallholder farmers and their behavioral determinants. Environ Sci Pollut Res 30(10):27833–27845
70. Zhao N, Wang K, Yuan Y (2023) Toward the carbon neutrality: forest carbon sinks and its spatial spillover effect in china. Ecol Econ 209:107837. https://doi.org/10.1016/j.ecolecon.2023.107837
71. Ding T, Steubing B, Achten WM (2023) Coupling optimization with territorial lca to support agricultural land-use planning. J Environ Manage 328:116946. https://doi.org/10.1016/j.jenvman.2022.116946
72. Shen X, Gatto P, Pagliacci F (2023) Unravelling the role of institutions in market-based instruments: a systematic review on forest carbon mechanisms. Forests. https://doi.org/10.3390/f14010136
73. Yanes AR, Martinez P, Ahmad R (2020) Towards automated aquaponics: a review on monitoring, IoT, and smart systems. J Clean Prod 263:121571. https://doi.org/10.1016/j.jclepro.2020.121571
74. Hu R, Shahzad F, Abbas A, Liu X (2022) Decoupling the influence of eco-sustainability motivations in the adoption of the green industrial IoT and the impact of advanced manufacturing technologies. J Clean Prod 339:130708. https://doi.org/10.1016/j.jclepro.2022.130708
75. Ding S, Ward H, Cucurachi S, Tukker A (2023) Revealing the hidden potentials of internet of things (IoT)—an integrated approach using agent-based modelling and system dynamics to assess sustainable supply chain performance. J Clean Prod 421:138558. https://doi.org/10.1016/j.jclepro.2023.138558
76. Pirson T, Bol D (2021) Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach. J Clean Prod 322:128966. https://doi.org/10.1016/j.jclepro.2021.128966
77. Kongboon R, Gheewala SH, Sampattagul S (2022) Greenhouse gas emissions inventory data acquisition and analytics for low carbon cities. J Clean Prod 343:130711. https://doi.org/10.1016/j.jclepro.2022.130711
78. Kocak E, Alnour M (2022) Energy r &d expenditure, bioethanol consumption, and greenhouse gas emissions in the united states: non-linear analysis and political implications. J Clean Prod 374:133887. https://doi.org/10.1016/j.jclepro.2022.133887
79. Kumar M, Choubey VK, Raut RD, Jagtap S (2023) Enablers to achieve zero hunger through IoT and blockchain technology and transform the green food supply chain systems. J Clean Prod 405:136894. https://doi.org/10.1016/j.jclepro.2023.136894
80. Kopac T (2023) Current overview of the valorization of biowastes for adsorbed natural gas applications. Carbon Lett 1–29

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