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ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
23 March 2023

REVISED
12 May 2023

ACCEPTED FOR PUBLICATION
16 May 2023

PUBLISHED
26 May 2023

TOPICAL REVIEW

Achieving net-zero emissions in agriculture: a review

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Keywords: net-zero emissions, agriculture, food security, water-energy-food nexus, climate solutions

Supplementary material for this article is available online

Abstract

Agriculture accounts for 12% of global annual greenhouse gas (GHG) emissions (7.1 Gt CO_2 equivalent), primarily through non-CO_2 emissions, namely methane (54%), nitrous oxide (28%), and carbon dioxide (18%). Thus, agriculture contributes significantly to climate change and is significantly impacted by its consequences. Here, we present a review of technologies and innovations for reducing GHG emissions in agriculture. These include decarbonizing on-farm energy use, adopting nitrogen fertilizers management technologies, alternative rice cultivation methods, and feeding and breeding technologies for reducing enteric methane. Combined, all these measures can reduce agricultural GHG emissions by up to 45%. However, residual emissions of 3.8 Gt CO_2 equivalent per year will require offsets from carbon dioxide removal technologies to make agriculture net-zero. Bioenergy with carbon capture and storage and enhanced rock weathering are particularly promising techniques, as they can be implemented within agriculture and result in permanent carbon sequestration. While net-zero technologies are technically available, they come with a price premium over the status quo and have limited adoption. Further research and development are needed to make such technologies more affordable and scalable and understand their synergies and wider socio-environmental impacts. With support and incentives, agriculture can transition from a significant emitter to a carbon sink. This study may serve as a blueprint to identify areas where further research and investments are needed to support and accelerate a transition to net-zero emissions agriculture.

1. Introduction

Agriculture is a prime driver and the first victim of climate change [1–3]. Emissions related to agriculture account for 12% of global greenhouse gas (GHG) emissions, or about 7.1 billion tons of CO_2 equivalent (Gt $CO_{2\text{-eq}}$) (figure 1). Moreover, climate change affects agricultural productivity [4], and a growing, wealthier human population is expected to increase global demand for agricultural products by 50% by mid-century [5, 6], causing GHG emissions to exceed international climate targets [7, 8]. Therefore, agriculture must be integrated into any climate change stabilization strategy that aims at achieving net-zero GHG emissions [2]. Previous studies have highlighted the climate mitigation potential of food systems [9, 10]. Yet, despite its importance for the functioning of modern societies, a comprehensive review of the mitigation potential of strategies and technologies to achieve net-zero emissions in agriculture is not available yet.

Agriculture faces a unique challenge in that it causes climate change through non-CO_2 emissions. The majority of GHG emissions from agriculture come from methane, accounting for 54%, followed by nitrous oxide at 28%, and carbon dioxide at 18% (figure 1(C)). Both methane and nitrous oxide are potent GHGs, with a global warming potential about 28 and 265 times greater than carbon dioxide considering a 100 year timescale, respectively [1, 2]. Therefore, net-zero emissions in agriculture will require not only net-zero carbon dioxide (CO_2) emissions, but also net-zero methane (CH_4) and nitrous oxide (N_2O) emissions.

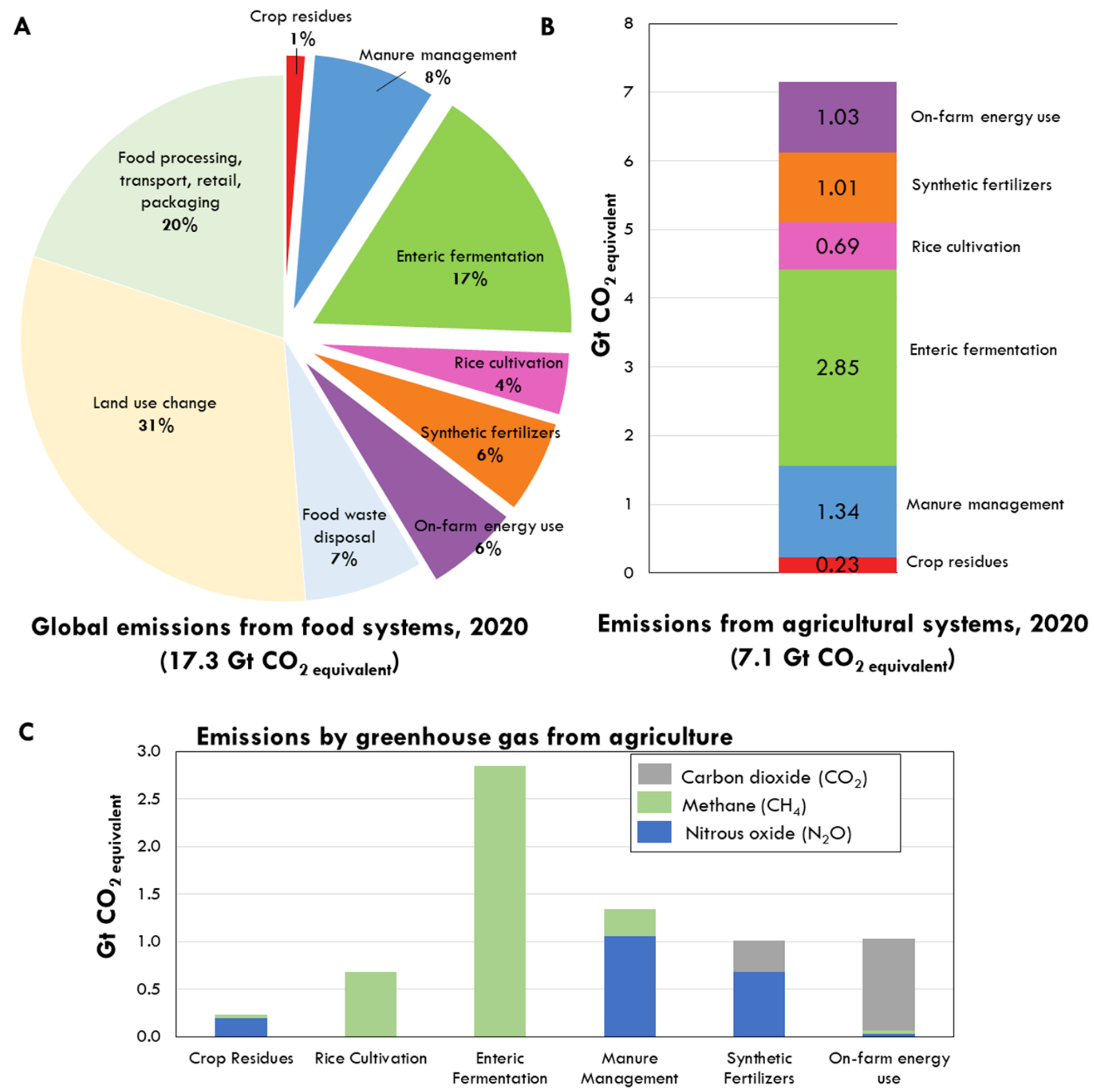

Figure 1. Greenhouse gas emissions from agriculture in 2020. (A) Shares of GHG emissions related to food systems by sector. (B) Estimates of GHG emissions related to agriculture by sector. (C) Breakdowns of estimates of GHG emissions from agriculture by sector and GHG (carbon dioxide, methane, nitrous oxide). Totals and breakdowns are based on the most up-to-date data from FAO [13].

Our society does not need agriculture itself, but rather the food, energy, and fibers that agriculture provides. When including a full farm-to-fork life-cycle analysis, GHG emissions related to food systems account for about 30% of global annual GHG emissions (17.3 Gt $CO_{2\text{-eq}}$ per year) [11, 12] (figure 1(A)). Agriculture was responsible for 42% of GHG emissions from food systems in 2020, with land use change accounting for 31%, food processing, transport, retail, packaging for 20%, and food waste disposal contributing to 7% (figure 1(A)). The focus of this study is on GHG emissions and net-zero emissions solutions from agriculture only (figures 1(B) and (C)).

Halting cropland expansion, increasing crop resource efficiency, improving agricultural productivity over currently underperforming croplands, reducing food loss and waste, and transitioning diets away from meat and dairy consumption are some of the key recommendations required to reduce GHG emissions and meet international climate targets [14]. Unfortunately, demand-side measures alone are not likely to solve climate change, as they require drastic behavioral and societal changes [15]. While degrowth measures can contribute to solving climate change [16], in the past decade progress was limited and slow [15]. Today, ∼40% of food is lost or wasted, and food systems are still highly inefficient [17]. Meanwhile, current trends of animal-based diets are hindering the ability to reach climate change goals [18]. Since 2000, an accelerated cropland expansion has increased the global farming area by 9%, primarily due to agricultural expansion in Africa and South America [19]. Large yield gaps—the difference between actual on-farm yield and the yield potential with good management that minimizes yield losses—remain a persistent issue in developing countries [20–23]. Improvements in the fertilizer industry, irrigation, and other farming technologies increased land and energy efficiency in agriculture [24]. However, increased efficiency led to a higher demand, hence to a rebound effect that prevented resource savings [25]. Therefore, in addition to demand-side solutions, novel technologies, innovations, and practices are needed to achieve net-zero emissions in agriculture [26–29].

Here, we provide a blueprint for innovations, technologies, and practices needed to reach net-zero emissions in agriculture. We review the challenges and opportunities associated with agricultural systems that do not add GHGs to the atmosphere (net-zero agriculture). Net-zero agriculture is the concept of agricultural practices that achieve a balance between the amount of GHGs produced and the amount removed from the atmosphere, resulting in no net contribution to climate change. Based on recent data from the Food and Agriculture Organization of the United Nations FAOSTAT dataset [13, 30], we provide a breakdown of current GHG emissions in agriculture by sector and GHG (figure 1). Further, we discuss technological opportunities and challenges for eliminating and/or managing emissions related to agriculture and highlight critical areas of research and development.

2. GHG emissions from agriculture

To effectively pursue net-zero emissions in agriculture, it is essential to first comprehend the current contribution of agricultural practices and industries to GHG emissions and their primary origins (figure 1).

2.1. On-farm energy use

In 2020, fossil fuels-based on-farm energy use accounted for 1.03 Gt $CO_{2\text{-eq}}$, or 2% of global total GHG emissions (figure 1). These emissions are due to the use of fossil fuels for a variety of purposes, including machinery and equipment, irrigation water pumping, electricity used for lighting, heating, and cooling. About half of on-farm energy use emissions are from electricity (0.46 Gt $CO_{2\text{-eq}}$ per year) and half are from fuel combustion from farm operations (0.53 Gt $CO_{2\text{-eq}}$ per year), such as diesel oil, gasoline, coal, and natural gas [13, 31].

2.2. Synthetic fertilizers

Synthetic fertilizers are an important input in modern agriculture, but they also contribute to about 1.01 Gt $CO_{2\text{-eq}}$ per year, or 2% of global total GHG emissions (figure 1). One third of GHG emissions come from direct CO_2 emissions due to energy inputs for ammonia production [32–34], while two thirds are from nitrous oxide produced during soil microbial conversion of excess nitrogen-based fertilizers (figure 1(C)).

2.3. Rice cultivation

Accounting for one fifth of global calorie intake, rice is a critical food source for billions of people around the world [35]. However, rice cultivation also contributes to 0.69 Gt $CO_{2\text{-eq}}$ per year, or 1.2% of global total GHG emissions (figure 1). Most of the rice grown globally is produced in flooded fields, resulting in high levels of methane emissions and extensive water usage for irrigation. The flooding of rice paddies contributes to methane production as it creates anaerobic conditions in the soil, fostering the growth of methane-producing microbes. Additionally, the anaerobic environment during rice cultivation also produces biogenic CO_2 emissions, which are considered carbon-neutral and do not contribute to GHG emissions from a climatic perspective.

2.4. Enteric fermentation

Enteric fermentation is a process that occurs in the digestive system of ruminant animals, such as cattle, sheep, and goats. Ruminants have the advantage of being able to consume forage and graze on lands unsuitable for crops. However, 2%–12% of the gross energy consumed is converted to enteric methane during ruminal digestion [36], which contributes approximately 40% (2.85 Gt $CO_{2\text{-eq}}$ per year) of global agricultural GHG emissions or ∼5% of global total GHG emissions (figure 1). Additionally, enteric fermentation also produces biogenic CO_2 emissions, which are considered carbon-neutral and do not contribute to GHG emissions from a climatic perspective.

2.5. Manure management

Manure management is a critical aspect of modern agriculture, but it also contributes to 1.34 Gt $CO_{2\text{-eq}}$ per year, or about 2% of global total GHG emissions (figure 1). Manure management generates emissions of methane (0.28 Gt $CO_{2\text{-eq}}$ per year) and nitrous oxide (1.06 Gt $CO_{2\text{-eq}}$ per year) through the decomposition of organic matter in the manure (figure 1(C)). Methane is released from the anaerobic decomposition of organic material, whereas nitrous oxide is released during the storage and processing of manure. During decomposition, manure management generates biogenic CO_2 emissions, which are carbon-neutral from a climactic point of view and therefore do not account for GHG emissions.

2.6. Crop residues

Crop residues, such as straw, stover, and leaves, contribute to 0.23 Gt $CO_{2\text{-eq}}$ per year, or 0.4% of global total GHG emissions. Crop residues can generate emissions of methane (0.03 Gt $CO_{2\text{-eq}}$ per year) and nitrous oxide (0.20 Gt $CO_{2\text{-eq}}$ per year) through their decomposition in the fields or during crop burning (figure 1(C)). During burning and decomposition, crop residues also generate biogenic CO_2 emissions, which are carbon-neutral from a climactic point of view and therefore do not account for GHG emissions.

3. Mitigation strategies

We describe mitigation practices and technologies that could enable net-zero emissions in agriculture, and we quantify the feasibility of such net-zero strategies (figure 2). Figure 3 shows an estimate of the technical potential of emissions reduction resulting from innovations, technologies, and practices to reach net-zero emissions in agriculture worldwide. Nonetheless, the actual climate change mitigation potential of such measures might be reduced due to economic, environmental, societal, financial, and political factors. Indeed, agricultural frameworks possess intricate design and customization, which are impacted by regional social, economic, environmental, and political elements. However, no comprehensive information is available to estimate the actual potential, as well as the uncertainty associated with the technical potential.

Strategies for net-zero agriculture include (i) decarbonization of on-farm energy use, (ii) sustainable management of nitrogen fertilizers, (iii) alternative rice cultivation methods, (iv) feeding and breeding technologies for reduced enteric methane, and (v) carbon dioxide removal (CDR) technologies, such as bioenergy with carbon capture and storage (BECCS) and enhanced rock weathering. Such net-zero strategies are illustrated in figure 2; their technical mitigation potential is shown in figure 3 with respect to the emissions of the corresponding agricultural activity; their technological readiness, technical emissions reduction potential, and degree of deployment are reported in table 1. Due to the difficulty in providing objective values of technology readiness level (TRL), in this study we refer to technological readiness by using the qualitative description introduced by Herrero *et al* [26] (table 1) instead of using the TRL scale introduced by NASA [37]. In fact, several of the net-zero strategies of interest are not well studied, hence it is difficult to determine their TRL value (supplementary information).

3.1. Decarbonization of on-farm energy use

Agriculture is an energy-intensive sector that accounts for ∼3% of global energy consumption (13 EJ yr^{-1}) [25]. Agriculture uses fossil fuels for various purposes, such as producing fertilizers and pesticides and powering farming activities (e.g. plowing, harvesting, sowing, threshing, lighting, heating, cooling, and irrigation water pumping) [54]. Moreover, the future projected intensification of agriculture from small-holder to large-scale farming is expected to increase energy use, energy intensity, and reliance on fossil fuels [55].

Non-fossil fuel-based agriculture is important for meeting climate targets and increasing food system resilience. Agricultural practices that rely heavily on fossil fuels are not sustainable in the long term due to their dependence on fossil fuels [54]. Subsidized fossil fuel-based agriculture in energy-importing countries is vulnerable to energy crises and fluctuations in fuel prices [54], and lack of energy security affects rural areas in low and middle-income countries, limiting access to affordable and reliable energy for agriculture [55].

On-farm energy use includes the use of fossil fuels for operating machinery, and the use of fossil fuels and electricity for pumping of irrigation water. The electrification of on-farm energy use, i.e. replacing the use of fossil fuels and current electricity with renewable electricity, can reduce the carbon footprint by up to 95% [56]. However, when considering the life cycle assessment of electric and conventional machinery, the GHG emissions reduction decreases to up to 70% [39], or 0.72 Gt $CO_{2\text{-eq}}$ per year (table 1; figure 2). In 2020, 28% of on-farm energy consumption was electrified, up from 16% in 2000 [13]. Today, ∼40% of global electricity generation is from low-carbon electricity (wind, solar, hydro, nuclear) [40]. However, from a global perspective, significant improvements are still needed towards low-carbon electricity, as the global average carbon footprint of electricity is currently around 450 g $CO_{2\text{-eq}}$ kWh^{-1} [57] and the carbon footprint of wind and solar power ranges from 5 to 100 g $CO_{2\text{-eq}}$ kWh^{-1} due to their lifecycle carbon footprint [56]. Therefore, full decarbonization of on-farm energy use will still require offsetting residual emissions through CDR techniques (see section 3.5).

Electricity can be directly produced on farmlands. The integration of large-scale wind turbines on agricultural land has become common practice, with little effect on crop production and even offering a leasing income for the landowner [58]. Similar considerations hold true for solar photovoltaics panels when adopted in the form of agrivoltaics installations, which can increase resource use efficiency, agricultural productivity, low-carbon electricity generation, and reduced water use [59].

In addition to electrification, bio-based drop-in fuels, such as ethanol, biodiesel, and biogas (see section 3.5), are potential options to reduce on-farm fossil fuel use [60]. Drop-in fuels are renewable fuels that can be used as a direct replacement for fossil fuels in existing combustion engines without requiring any engine modification. Drop-in fuels can be produced from a variety of sources such as waste products, non-food crops, and algae [61]. These fuels can be used in tractors, harvesters, irrigation pumps, and other farm equipment that traditionally use diesel or gasoline.

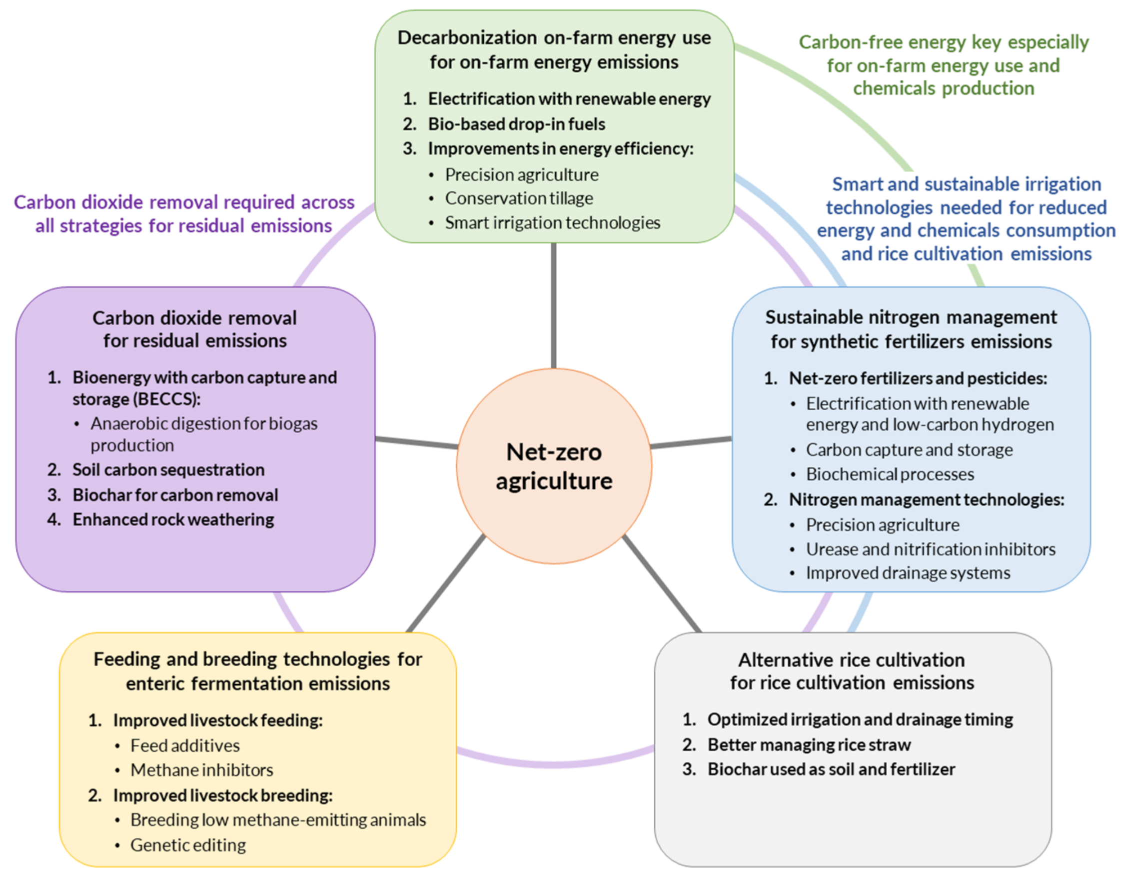

Figure 2. Summary of strategies to achieve net-zero emissions in agriculture, organized in mitigation categories as discussed in this study. Connecting measures key to achieving net-zero agriculture are also reported: carbon-free energy (green connection), smart and sustainable irrigation (blue), and carbon removal (purple).

3.1.1. Energy efficiency and conservation agriculture
Electrification can also improve the energy efficiency of on-farm energy use [27]. Fossil fuel-powered conventional tractors can be replaced by smaller and lighter electric machines, opening new avenues for the implementation of precision robotics and automation technologies [27, 62]. Digitalization of agriculture with sensors, robots, and artificial intelligence can increase resource efficiency and reduce the need for energy and inputs (e.g. fertilizers and pesticides) [63]. The major barrier to these alternatives is the additional initial investment and higher costs compared to current technologies powered by fossil fuels. Importantly, improved efficiency can sometimes lead to a rebound effect that increases overall energy consumption due to lower costs that increase demand [25].

Practices like conservation tillage, organic agriculture, and crop rotation can also reduce energy use by reducing the need for energy and inputs (e.g. fertilizers and pesticides) [54, 64–66]. For example, annual soil tillage is one of the most energy-intensive activities on farms [54]; previous studies have shown that moving to no-till systems can halve on-farm energy inputs [62]. However, the impact of no-till on GHG emissions would vary by region, and no-till practices would lead to greater fertilizer and pesticide expenditures [67]. On the other hand, decreasing tilling, for example through perennial grain crops, would conserve soil and water resources, yielding additional energy savings [54].

3.1.2. Irrigation water pumping
Irrigation accounts for 90% of global freshwater usage, occupies 22% of cultivated land and enables the production of 40% of global food [68]. In the future irrigation is expected to be expanded over croplands as an adaptation strategy to climate change [69, 70]. In fact, irrigation can alleviate heat and water stress on crops and reduce climate variability and extremes [68, 71]. Irrigation has significant environmental impacts, including carbon emissions from fossil fuel-powered water pumping [72, 73]. Currently, groundwater pumping accounts for approximately 80% of global energy consumption and CO_2 emissions from irrigation, making the reduction of groundwater-based irrigation critical [74]. Overall, irrigation pumping contributes to 0.22 Gt CO_2 emissions and uses 1.8 EJ per year, or ~15% of global GHG emissions and energy use in farming [75]. Globally, about half of irrigation is performed with electric pumping and half with diesel pumping [75, 76]. Electric pumping and

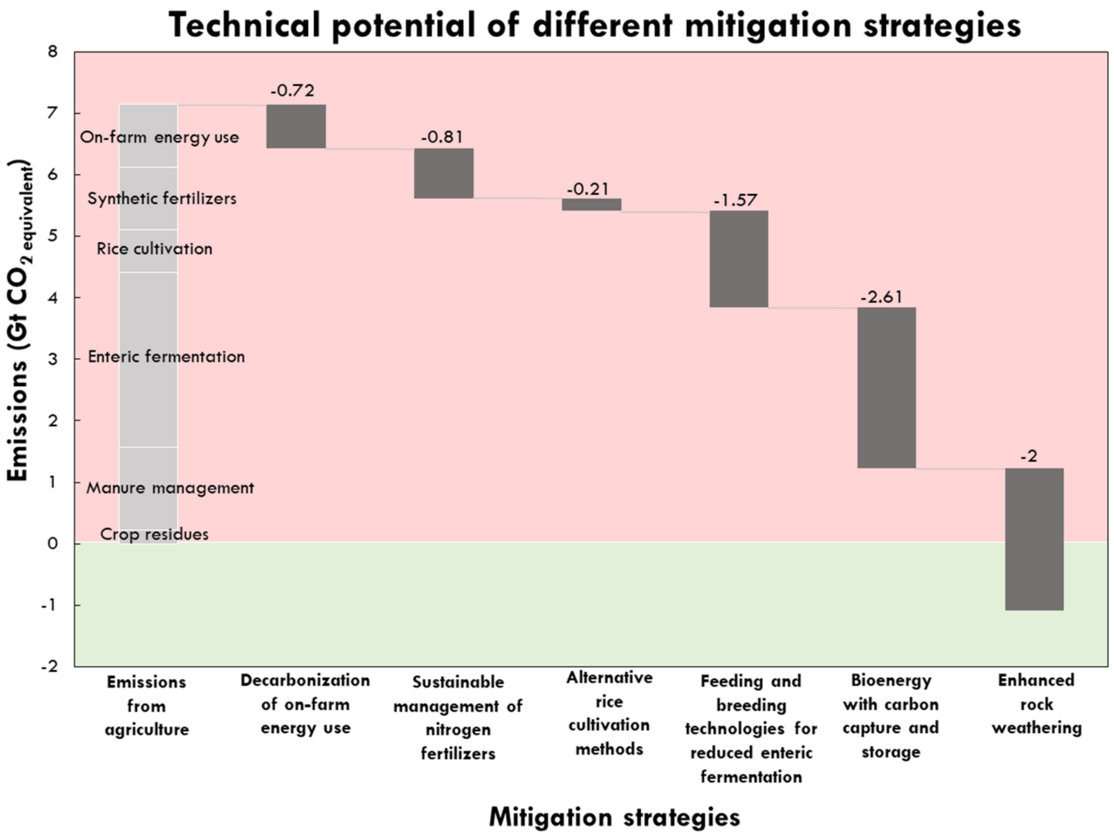

Figure 3. Technical emissions reduction potential resulting from different strategies to reach net-zero emissions in agriculture. The figure shows the reference mitigation potential of each strategy, whereas ranges of emissions reduction are shown in table 1 when available from the literature.

low-carbon electricity-powered irrigation technologies, such as solar-powered drip irrigation, can reduce energy consumption and carbon emissions by up to 95% (table 1). In fact, the energy and carbon emission intensity of diesel pumping (800 g CO_2 per kWh) is significantly higher than that of electric pumping with solar photovoltaics (45 g CO_2 per kWh) [56].

Smart irrigation technologies, such as soil moisture sensors and controllers, can improve irrigation efficiency, reduce unproductive water use, and decrease energy consumption [77]. Agricultural practices such as no-till farming, mulching, and agrivoltaics can help retain more water in the soil by reducing soil evaporation and therefore reduce irrigation water demand [78]. Deficit irrigation, which involves growing crops under mild water-stress conditions, can further reduce water and energy consumption and CO_2 emissions [71]. Because they require much less water to produce energy compared to fossil energy sources, solar and wind energy can enhance drought resilience and reduce water scarcity [79].

Irrigation water management is crucial for improving water use efficiency and reducing emissions from irrigation water pumping in regions facing water scarcity [80]. Although there is potential for adopting water management techniques, there are challenges in its practicality due to a lack of reliable control over irrigation water. More research is needed to estimate benefits and encourage farmers to adopt water management practices on a larger scale. Irrigation also contributes to soil nitrous oxide and methane emissions. For example, field-scale comparisons show that nitrous oxide emissions can increase by 50%–140% in irrigated cropping systems relative to non-irrigated land [81], but drip irrigation would stimulate 32%–46% less nitrous oxide compared to furrow or sprinkler irrigation [82]. Little is known about these GHG emissions.

3.1.3. Fertilizers and pesticides

Fertilizers and pesticides have played a crucial role in boosting food production across the globe. The production, distribution, and transportation of mineral fertilizers and pesticides result in an energy consumption of about 5.4 EJ per year (table 2), or 42% of energy use from agriculture. Fertilizers are the largest contributor to energy inputs in agriculture, while pesticides are the most energy-intensive agricultural input on a per-kilogram basis of pesticides and fertilizers (table 2).

3.1.3.1. Fertilizers

The use of synthetic fertilizers has increased crop yields by providing essential nutrients such as nitrogen, phosphorus, and potassium [20]. Fertilizer

Table 1. Technological readiness, technical emissions reduction potential, and degree of deployment of practices to reach net-zero emissions in agriculture. Technological readiness is divided into three levels: research, pilot, and commercial. *Research level* means that the technology concept has been formulated and validated at a lab scale. *Pilot level* means that there is a demonstrator in an operational environment. *Commercial level* means that the technology is proven and deployed at the commercial scale. Technical emissions reduction potentials are depicted with a range of estimates when available from previous literature (supplementary informations).

Mitigation strategies		Technological readiness	Technical emissions reduction potential (% reduction, Gt $CO_{2\text{-eq}}$ per year)	Degree of deployment (%)
Decarbonization of on-farm energy use		Commercial [38]	70%, 0.72 Gt $CO_{2\text{-eq}}$, (range: 70%–95%) [39]	28% of on-farm energy is electrified [13] 40% of electricity generation is low carbon [40]
Sustainable management of nitrogen fertilizers	Net-zero synthetic fertilizers production	Commercial [41]	95%, 0.37 Gt $CO_{2\text{-eq}}$, (range: 90%–100%) [33, 34]	0.01% of ammonia produced via low-carbon electricity [42]
	Nitrogen management technologies	Pilot [43]	Up to 70%, 0.44 Gt $CO_{2\text{-eq}}$ [34, 43]	0%
Alternative rice cultivation methods		Pilot [44, 45]	Up to 30%, 0.21 Gt $CO_{2\text{-eq}}$ [44, 45]	0%
Feeding and breeding technologies for reduced enteric methane	Improved feeding Improved breeding	Pilot [46–49]	Up to 55%, 1.57 Gt $CO_{2\text{-eq}}$ [46–49]	0%
Carbon dioxide removal	Bioenergy with carbon capture and storage (BECCS)	Commercial [50]	1.05 Gt $CO_{2\text{-eq}}$ from global BECCS potential; 1.56 Gt $CO_{2\text{-eq}}$ from avoided methane and nitrous oxide emissions from agricultural waste and residues, (range: 0.9–1.2 Gt $CO_{2\text{-eq}}$) [51]	0.2% of global BECCS potential [52]
	Enhanced rock weathering	Pilot [53]	2 Gt $CO_{2\text{-eq}}$, (range: 0.5–2 Gt $CO_{2\text{-eq}}$) [53]	0%

production relies on fossil fuels as a feedstock and source of energy. The energy required to produce a kilogram of nitrogen fertilizers is ∼70 MJ, while 1 kg of phosphate and potash fertilizers requires ∼8 MJ and ∼6 MJ respectively [83] (table 2). The CO_2 emissions associated with fertilizer production depend on the type and feedstock used [85]. Note that the energy needed to produce one kg of nitrogen from air (for example via air separation unit) is relatively small (about 1 MJ) [86]. However, producing nitrogen fertilizers (e.g. urea) requires producing hydrogen and nitrogen first, converting hydrogen and nitrogen into ammonia, and converting ammonia into synthetic nitrogen fertilizers [87].

The production of synthetic nitrogen fertilizers, which is necessary to feed half of the world's population [33], is the most energy-intensive and accounts for ∼85% of fertilizer GHG emissions (389 Mt $CO_{2\text{-eq}}$ per year) (table 2). The emissions of nitrogen fertilizers are one order of magnitude higher than those resulting from the manufacturing of phosphate (45 Mt $CO_{2\text{-eq}}$ per year) and potash (34 Mt $CO_{2\text{-eq}}$ per year) fertilizers (table 2). The demand for synthetic fertilizers is expected to increase with population growth and increased food and fiber demands [88, 89]. Decarbonizing the fertilizer industry will be critical to meet emissions goals without reducing agricultural production and ensuring food security [33].

Emissions from phosphorus and potash fertilizers come from mining, transportation, and processing through energy-intensive chemical and physical transformations [83]. Emissions from phosphorus fertilizer production are also due to the heat generated during phosphate rock pretreatment [83]. Using low-carbon energy sources, carbon capture and storage, and electrification can help achieve net-zero emissions in potash and potassium fertilizer production. Low-carbon heat can be generated via electricity-driven heat pumps or waste heat when

Table 2. Energy content and GHG emissions from fertilizers and pesticides. The table lists the energy intensity, global energy consumption, and global GHG emissions of fertilizers and pesticides. However, the full life-cycle energy consumption, which includes the extraction of chemical raw materials, transportation to the manufacturing facility, and delivery of the final product to the field, varies widely based on various factors, such as the location of raw materials, ease of extraction, manufacturing processes, and transportation distances. Data source [13, 54, 83, 84].

Production and transport		Energy needed for production (MJ kg^{-1} input)	Global energy consumption (EJ per year)	Global GHG emission (Mt $CO_{2\text{-eq}}$ per year)
Fertilizers	Nitrogen	70	4.09	389
	Phosphate	8	0.52	45
	Potash	6	0.26	34
Pesticides	Insecticide	200	0.09	7
	Herbicide	240	0.34	23
	Fungicide	92	0.06	4

low-temperature heat is required, and via carbon-free fuels (e.g. hydrogen boilers) when high-temperature heat is required, e.g. for process heat [90, 91]. Despite the availability of such technologies to decarbonize potash and phosphorus fertilizers, a quantification of their emission reduction potential is not available, yet.

The production of ammonia for nitrogen-based fertilizers accounts for 2% (4.09 EJ per year) of global energy consumption (table 2). About 90% of such emissions are due to the high energy and carbon intensity of ammonia production via the Haber–Bosch process, which takes hydrogen and nitrogen as inputs; hydrogen production currently requires large quantities of natural gas or, as in China, coal [87]. Improvements in efficiency and carbon intensity have reduced the emission intensity of nitrogen fertilizer production by 12% in the last 15 years [87]. However, further efficiency gains in conventional production processes are expected to have a relatively modest impact in terms of energy and emissions savings [92, 93], and more transformative measures will be required, such as (i) continued use of fossil fuels coupled with carbon capture and storage, (ii) water electrolysis fed by carbon-free electricity, and (iii) biochemical processes [33]. The development of such production methods can reduce ammonia production emissions by 95% (table 1) [33]. A 100% emissions reduction—i.e. net-zero emissions—can be achieved by offsetting residual emissions with CDR technologies [33, 93, 94]. In fact, carbon capture and storage technologies typically abate about 90% of emissions, whereas the carbon intensity of renewable energy technologies, especially solar photovoltaics, is greater than zero [56].

Alternative technologies to the Haber–Bosch process are currently being researched. These include electrochemical synthesis and plasma-activated processes, where light is used to drive the chemical reduction of nitrogen to ammonia instead of high temperature and pressure [95–100]. These discoveries offer a fundamentally new way to generate ammonia from nitrogen, contrasting the energy-intensive Haber–Bosch process. Solar-driven ammonia synthesis could provide a path to zero-carbon distributed fertilizer distribution and reduce reliance on imports and supply chain shocks [99, 101]. Optimization and scaling-up of these processes will be needed to determine whether they will be able to provide a viable solution.

Another potential solution to decarbonize ammonia production, hence nitrogen fertilizer production, is the use of biological nitrogen fixation. This involves the conversion of atmospheric nitrogen into ammonia by soil nitrogen-fixing bacteria, which can then be utilized by crops [102]. Therefore, biological nitrogen fixation can reduce the amount of nitrogen fertilizer required in agricultural applications. Currently, only legumes like beans and peas can host soil bacteria to turn nitrogen into ammonia. Genetic engineering efforts are trying to implement biological nitrogen fixation to cereal crops [103, 104]. However, biological nitrogen fixation is still being researched and developed and is not commercially viable.

Using manure as a fertilizer may increase GHG emissions [34]. In fact, manure currently produces twice as many GHG emissions per unit of nitrogen as synthetic nitrogen fertilizers [34]. This is mainly due to the methane emissions generated during the storage and transportation of manure. In fact, the adoption of synthetic nitrogen fertilizers caused a geographic disconnect between cultivation and livestock farming [105]. This led to highly productive crops being cultivated in the most fertile regions, while livestock farming was pushed to less fertile regions, where feed had to be imported as production scaled up [105]. This geographic separation creates barriers to the transport and reuse of manure in crop production [67]. Reconnecting livestock and cropping systems via manure can reduce GHG emissions [105].

3.1.3.2. Pesticides

While fertilizers are used to supply nutrients, pesticides are used to protect crops from weeds, pests, and diseases. Pesticides include insecticides, herbicides, fungicides, disinfectants, and repellents. The production of synthetic pesticides is energy intensive and can emit even more GHG per kg than the production of synthetic fertilizers (table 2). However, little attention has been given to the GHG emissions resulting from pesticide production and use. Although more updated research is needed, researchers have calculated the energy use associated with the production of specific pesticides, which can then be used to estimate GHG emissions [106]. Considering that pesticide production requires 0.5 EJ per year [13] and has an average emission factor of 69 Mt $CO_{2\text{-eq}}$ per EJ [106], we estimate that pesticides emit 34 Mt $CO_{2\text{-eq}}$ per year (table 2). Meanwhile, declining efficacy and climate change impacts are expected to lead to increased needs in pesticide use [107], creating a vicious cycle between chemical dependency and intensifying global warming [108].

Pesticides are derived from fossil fuels and contribute to climate change through their entire lifecycle, from production to disposal [109]. Like nitrogen fertilizers, pesticides also release GHG emissions after application, with some pesticides shown to increase nitrous oxide production in soils [110]. Some pesticides, such as sulfuryl fluoride, are themselves powerful GHGs, having nearly 5000 times the potency of carbon dioxide [111].

As for fertilizers and chemicals [93], implementing electrification with low-carbon energy, carbon capture and storage, and biochemical processes can mitigate emissions from pesticide production. Alternative agricultural systems like agroecology can minimize pesticide use [112]. Robots are being developed to reduce pesticide use and improve farming efficiency by accurately delivering pesticides [67, 113]. While the use of genetically engineered crops is often touted as a tool for pesticide reduction [114], scientific research shows the opposite to be true [115]. In fact, the adoption of genetically engineered crops has led to herbicide-resistant weeds, causing farmers to apply more herbicides [115].

3.1.4. Remaining gaps

Accurate estimates of GHG emissions are essential for developing net-zero emissions strategies. While recent work quantified GHG emissions and mitigation technologies from synthetic nitrogen fertilizers [33, 34], little is known about GHG emissions and strategies to achieve net-zero emissions from potash and phosphorus fertilizers, pesticides, and farming activities (e.g. plowing, harvesting, sowing, threshing, lighting, heating, cooling, and irrigation water pumping). Net-zero fertilizer production via electrolytic hydrogen (for ammonia) and biochemical processes eliminates the use of fossil fuels as an energy source. However, even with rising carbon taxes, these methods have limited scale and high investments and operating costs compared to conventional production. The high capital costs associated with investing in innovative synthetic pesticides and fertilizers have slowed their commercialization. In fact, today only 3% of global hydrogen is produced via water electrolysis [87], and 0.01% (0.02 Mt) of global ammonia is low carbon [42] (table 1). Although a manufacturing capacity of 15 Mt per year of low-carbon ammonia is projected by 2030 [42]. Decarbonization of on-farm energy use is possible but may have environmental trade-offs in terms of energy, land, water, and biomass use [33, 34], further exacerbating land and water scarcity [116–118]. For example, net-zero ammonia production via water electrolysis requires twenty-five times more energy, land, and water than business-as-usual production [33]. Therefore, the available net-zero routes (carbon capture and storage, electrification, biomass) need to be combined based on the local resources available. Production may move from countries with abundant fossil resources to countries with abundant renewable energy infrastructure, land, and water resources, depending on energy prices and environmental targets [33, 93]. Therefore, integrated design of future energy and food systems is needed.

3.2. Nitrogen management technologies

Two thirds of GHG emissions from fertilizers come from the conversion of excess nitrogen-based fertilizers into nitrous oxide by soil microbes (figure 1(C)). This is because only 40% of nitrogen-based fertilizers used in agriculture are harvested as crops [119, 120], while the rest is lost to the environment leading to GHG emissions and other environmental impacts such as water eutrophication [121]. Nitrous oxide emissions can be reduced by up to 70% through better management practices and technologies, such as precision agriculture and use of inhibitors (table 1) [43, 122]. Combined mitigation interventions can reduce synthetic nitrogen fertilizers emissions by ~85%, or 0.81 Gt $CO_{2\text{-eq}}$ per year [34] (table 1, figure 2). Specifically, mitigation technologies can reduce GHG emissions from synthetic fertilizers production by ~95% [33], while precision agriculture and inhibitors can reduce nitrous oxide emissions by 70% [43, 122] (table 1).

Precision agriculture technologies, such as drip irrigation and fertigation [123], and increased use of controlled-release fertilizers can increase nitrogen use efficiency by applying the 4R Nutrient Stewardship concept, which involves applying the right source of nutrients, at the right rate, at the right time, and in the right place [124]. Robotics, artificial intelligence, sensors, and autonomous systems are being developed to reduce fertilizer use and improve farming efficiency by accurately delivering fertilizers [62, 63, 67]. Drainage systems can reduce nitrous oxide emissions and fertilizer inputs, but they can also increase downstream nitrous oxide emissions due to increased nitrate leaching [125]. However, denitrification bioreactors and wetlands can help remove nitrates from fields and main drains, potentially mitigating the negative impact of increased leaching [125].

Urease and nitrification inhibitors are chemicals that can be deployed along with fertilizers to prevent bacteria from performing nitrification and denitrification reactions [34]. Urease and nitrification inhibitors can minimize ammonia volatilization—an indirect source of nitrous oxide [43, 126]. Urease and nitrification inhibitors can also extend the release of nitrogen, keeping the mineral nitrogen fertilizer in the soil for longer, increasing the chance that crops take it up, and achieving higher nitrogen use efficiency [43]. The application of nitrification inhibitors could suppress the activity of nitrifiers in the soil, thus reducing nitrous oxide emissions by ~40%, compared to conventional fertilizers [127].

3.2.1. Remaining gaps
Improving the efficiency of fertilizer supply chains is crucial in reducing GHG emissions. Today, only approximately 20% of the ammonia produced is used in food production, while the remaining 80% is wasted or lost due to the inefficiencies of our food systems [33]. Enabling circular economy models that return materials and energy flows as agricultural inputs can reduce emissions [67]. In fact, today only 2% of usable post-consumption nutrients are recycled back to agricultural systems, the rest being released into the environment as pollutants or concentrated in municipal waste [128]. While urease and nitrification inhibitors are already used, their application has been limited so far largely due to cost, and their effectiveness remains uncertain [43]. Further research and product development is needed to make these technologies more affordable, to better understand the synergies between them, and to improve understanding of wider environmental impacts.

3.3. Alternative rice cultivation methods
Flooded conditions in paddy rice production create anaerobic environments that lead to the production of methane as organic matter decomposes [129]. At the same time, global warming is expected to change the functional community of microorganisms in the soil and accelerate the decomposition of soil organic matter further increasing the rate of methane emissions from rice cultivation [130].

Reducing the periods and increasing the frequency of flooding has been shown to be a promising technique for curbing methane emissions [129]. This is because flooding blocks oxygen from entering the soil, creating a conducive environment for methane-producing bacteria [129]. By reducing flooding, bacterial methane production is reduced, leading to a decrease in methane emissions [44, 45] although it can lead to increases in nitrous oxide emissions [131]. Better managing rice straw (i.e. the non-grain part of the plant), can reduce emissions by averting its decomposition in anaerobic conditions or open burning of the straw [129]. Straw returned to the field in the form of biochar (see section 3.5) in combination with optimized drainage timing and aerobic rice cultivation are measures that can reduce methane emissions by 30%, or 0.21 Gt $CO_{2\text{-eq}}$ per year (table 1; figure 2) [44, 45].

3.3.1. Remaining gaps
Many of the world's rice-producing regions face water scarcity and unsustainable irrigation practices [70, 132]. Optimized irrigation provides a win-win solution that increases water use efficiency, alleviates water scarcity, and leads to lower emissions from irrigation water pumping, but more research is needed to estimate these benefits and encourage farmers to adopt these practices on a larger scale. Although there is potential for adopting water management techniques in rice farming, there are challenges in its practicality due to a lack of reliable control over irrigation water [129]. There is also limited information on the precise conditions for effective and economically viable water management methods in rice farming.

3.4. Feeding and breeding technologies for reduced enteric methane
Global per capita consumption of livestock products has more than doubled in the past 40 years [133] and livestock methane emissions are projected to grow by another 30% by 2050 under current policies [48]. In the past few decades, improvements in production efficiency and animal performance have led to a continuous decline in methane emission intensity, which is measured as emissions per unit of meat and milk [134]. However, this trend may not be enough to counteract the rising emissions from the increasing demand for animal protein [36, 48]. Therefore, it is necessary to decrease both the emission intensity and the absolute emissions of the ruminant industry in a continued growth scenario [36]. The two primary strategies to reduce methane emissions resulting from enteric fermentation, thus the emission intensity of the ruminant industry, are improving livestock feeding and breeding.

3.4.1. Feeding technologies
Improving feed quality and livestock management practices that create rapid weight gain or higher production of milk per animal has been the main options for reducing methane emissions from ruminant animal production [133]. Various additions to livestock diets through feed additives have been shown to reduce methane emissions [46]. For example, newly developed methane inhibitors are a promising option for reducing emissions from dairy cows, as they can decrease methane emissions up to 40% while simultaneously increasing body weight and without having any impact on milk yields or composition (table 1) [46–48]. However, the efficacy of inhibitors and feed additives is typically significantly lessened over time because of adjustments made by the rumen microbial

ecosystem [47]. Moreover, some inhibitors and feed additives may have unforeseen environmental implications, and public acceptance issues could greatly impede their widespread implementation [47].

Red seaweed, such as Asparagopsis algae, appears to have a significant emission reduction potential and has been found to reduce methane emissions in ruminants by 20%–98% under experimental conditions [36, 48, 135, 136]. But the long-term persistence of this effect is unclear. Scientific results justify ambitious rapid efforts to explore the use of this algae, its production in closed-loop systems, and alternative ways of generating and using its most active, methane-inhibiting ingredient [48]. However, the active ingredients in Asparagopsis, namely bromoform and bromochloromethane, are animal and human carcinogens, presenting regulatory and market challenges [48]. Tests have found no adverse health effects on cattle, but more testing is needed to guarantee the lack of long-term effects [48].

3.4.2. Breeding technologies

Efforts are being made to breed ruminant animals that are more efficient in utilizing their feed and thus emit less methane. Some scientists are approaching it from a conventional breeding approach, breeding low methane-emitting animals [49], while others are exploring the use of gene editing techniques such as clustered regularly interspaced short palindromic repeats (CRISPR) to improve the efficiency of bacteria in the animal's stomach [137]. Research has shown that genetics play a role in the methane emissions of cattle, and breeding for reduced emissions is a possibility [48]. One estimate suggests that a 15% reduction in methane emissions could be achieved through breeding within a decade (table 1) [49]. It is important to select for genetics that can generate additional reductions when combined with feed additives and inhibitors.

3.4.3. Remaining gaps

Reducing the consumption of animal-sourced food is the most cost-effective approach to reducing environmental and climate impacts from livestock farming [138, 139, 140]. However, few cost-effective approaches are available for producers to decrease methane emissions via feeding and breeding, and most innovations are still at the experimental level [36]. Combined feeding and breeding technologies can individually reduce enteric fermentation emissions by 55% [141], or 1.57 Gt $CO_{2\text{-eq}}$ per year (table 1; figure 2). However, more research is needed to determine if combining strategies will consistently have additive effects [36]. It is also uncertain if reducing methane production leads to consistent improvements in animal performance, which is crucial for adoption by producers [46]. The cost of mitigation strategies, the application of mitigation strategies to grazing ruminants, inconsistent effects on animal performance, and lack of information on animal health, reproduction, and product quality are all barriers to decreasing global enteric methane emissions [36, 46]. More research and investment are needed to increase the affordability and adoption of mitigation practices, develop breakthrough technologies, moderate consumption of livestock products where appropriate, and avoid negative impacts on livelihoods, economic activities, and the environment.

3.5. CDR technologies

CDR technologies remove carbon dioxide from the atmosphere. There are several CDR technologies currently being researched and developed, including direct air carbon capture and storage, biomass carbon removal and storage (e.g. BECCS), soil carbon sequestration, and biochar), ocean fertilization, and enhanced rock weathering [142, 143]. BECCS and enhanced rock weathering are of particular interest as they can be developed over agricultural lands to achieve net-zero emissions agriculture through permanent carbon sequestration [144]. While biochar and soil carbon sequestration can remove carbon dioxide from the atmosphere over agricultural lands, the permanence of carbon sequestration is still to be verified [144, 145]. Biochar is a carbon-rich material produced through pyrolysis—heating biomass in a low-oxygen environment—that is applied to soil for carbon sequestration [146]. Soil carbon sequestration consists of the uptake of atmospheric carbon by plants and subsequent storage in soils [147]. Importantly, CDR technologies should not be seen as a replacement for reducing GHG emissions, which is still the most effective way to mitigate climate change.

3.5.1. BECCS

Although the use of purpose-grown biomass for biofuels production (or first-generation biofuels) has shown to have several negative socio-environmental implications [148, 149], the use of agricultural waste and residues is a promising solution to mitigate emissions in agriculture. Agricultural waste and residues, including crop residues and livestock manure, are challenging to manage and emit a significant amount of GHGs (1.56 Gt $CO_{2\text{-eq}}$ per year) (figure 1). Improving the management of agricultural waste and residues through circular economy models can play a key role in reducing GHG emissions while producing bioenergy that can be used to replace fossil fuels [150].

The treatment of crop residues and livestock manure with anaerobic digestion in a biogas plant can avoid methane and nitrous oxide emissions [150]. Anaerobic digestion is a bioenergy technology that can play a vital role in achieving net-zero agriculture by breaking down organic matter into biogas and digestate [151, 152]. Biogas is composed of approximately 60% methane and 40% carbon dioxide and can be used locally for heating or for combined heat and power production [60]. Alternatively, energy producers can upgrade biogas to biomethane, which has similar properties to natural gas, allowing it to be directly substituted for natural gas using the existing infrastructure and technologies [60]. The digestate generated can be used as a fertilizer and applied on land in a circular economy approach, reducing fertilizer inputs and promoting nutrient recycling [150]. Anaerobic digestion for biogas and digestate can improve farm finances through energy sales and reduce fertilizer costs [150].

Anaerobic digestion is a well-established technology used worldwide to produce biogas. While biogas production using organic wastes can potentially reduce GHG emissions, it can also increase emissions due to methane leakage from biogas digesters, piping, and appliances. It is important to consider leaks in biomethane supply chains in future planning, as current measurements show leakage rates of ∼6% [153]. To guarantee that biogas plants will have positive environmental effects, it is essential to ensure minimum methane fugitive emissions.

The CO_2 separated during biogas upgrading can be captured and permanently sequestered to generate CDR and offset residual emissions from agriculture [154]. This technique, known as BECCS, converts biomass into bioenergy and permanently stores carbon emissions generated during bioenergy production [154]. However, the potential for achieving CDR via anaerobic digestion of agricultural waste and residues is limited to 1.05 Gt CO_2 and 28 EJ of biomethane per year worldwide (table 1; figure 2) [51]. In addition to the CDR potential of 1.05 Gt CO_2 from crop residues and livestock manure (table 1), the treatment of crop residues and livestock manure with anaerobic digestion in a biogas plant can avoid methane and nitrous oxide emissions of 1.56 Gt $CO_{2\text{-eq}}$ per year, bringing the total mitigation potential of BECCS to 2.61 Gt $CO_{2\text{-eq}}$ per year (figure 2). Importantly, site-specific life cycle assessments are needed to determine the negative emissions that can be generated from biogenic CDR potentials [155]. Additional CDR can be obtained by capturing and storing the CO_2 resulting from the combustion of biomethane or from the conversion of biomethane into hydrogen via steam methane reforming [156]. It is estimated that CDR via BECCS costs US$100-200 per ton of CO_2 sequestered [2].

To perform CDR, CO_2 needs to be permanently stored [143]. CO_2 can be stored permanently underground in geological formations, a practice that requires complex supply chains to capture, transport, inject, store, and monitor CO_2 [157]. Suitable geological formations for storage can be found in various parts of the world [158]. However, CO_2 storage still faces issues related to the availability, accessibility, and acceptance of storage sites [159]. An alternative to geological storage is to use and store CO_2 in construction materials such as concrete, but current estimates of storage capacity in building materials show that this is not sufficient to store significant amounts of CO_2, hence, to achieve net-zero agriculture [160–162].

3.5.2. Remaining gaps

Despite its potential, the market for BECCS is still in its early stages. The current deployment rate of BECCS is low, necessitating the upscaling of both existing and new BECCS technologies at an unprecedented pace [142]. Today, only 2 Mt CO_2 per year are currently captured via BECCS, mainly in bioethanol applications [52]. Based on projects currently in the early and advanced stages of deployment, carbon removal via BECCS could reach ∼40 Mt CO_2 per year by 2030 [52]. There are still many remaining gaps in our understanding of BECCS that need to be addressed. The sustainability of biomass production is a major concern with BECCS [156]. Large-scale biomass production could lead to deforestation, soil degradation, and competition with food crops for land and water resources [116]. More research is needed to determine the sustainable limits of biomass production and the environmental impacts of large-scale production. There are concerns about the efficiency and cost of capturing and storing carbon dioxide from biomass [155]. There are also technical challenges associated with the production and transport of biomass, as well as the storage of captured carbon dioxide [163, 164]. The amount of carbon dioxide that can be captured and stored underground may depend on factors such as the type of biomass used, the location of biomass production, and the storage capacity of the geological formations used for storage [154]. The cost of biomass production, carbon capture and storage, and the infrastructure required for large-scale implementation may be prohibitively expensive [50].

3.5.3. Enhanced rock weathering

Enhanced rock weathering is a CDR technology that amends soils with crushed calcium- and magnesium-rich silicate rocks to accelerate natural CO_2 sequestration processes, while also providing co-benefits for crop production, increasing soil health and fertility [53]. Enhanced rock weathering involves the release of base cations that generate alkalinity, converting atmospheric CO_2 into dissolved inorganic carbon that is removed via soil drainage waters [142]. Basalt, a fast-weathering rock that releases plant-essential inorganic nutrients, has a significant potential for implementing enhanced rock weathering in agriculture [53]. This approach, deployable over croplands, would enable 0.5–2 Gt of CO_2 to be removed from the atmosphere each year, with estimated costs of US$80-180 per ton of CO_2 sequestered (table 1; figure 2) [53].

3.5.4. Remaining gaps

There are still many remaining gaps in our understanding of enhanced rock weathering that need to be addressed. More research is needed to determine the effectiveness, environmental impacts, and economic feasibility of this technique on a large scale [142]. Most of the research on enhanced rock weathering has been conducted in small-scale experiments. Scaling up this technique to large areas is a significant challenge [142]. The logistics of mining, transporting, and spreading large quantities of rocks would be a significant undertaking, and the cost of this process is currently uncertain [144]. While enhanced rock weathering has the potential to remove carbon dioxide from the atmosphere, the amount of carbon that can be sequestered through this process is still uncertain [53]. The effectiveness of enhanced rock weathering may also depend on factors such as the type of rock used, the climate, and the location where the rocks are spread [53]. Weathering rates may decrease over time as the rocks become saturated with carbon dioxide and other nutrients, which could limit the amount of carbon that can be sequestered [144]. The cost of mining, transporting, and spreading rocks may be prohibitively expensive, and the economic benefits of this technique may not be realized for many years.

4. Novel technologies beyond agriculture

New and emerging technologies could pave the way to net-zero carbon emissions agriculture in the next decades. If scaled, they could help agriculture reach net-zero emissions. Here we describe some innovative technologies beyond agriculture that are currently being researched and developed.

4.1. Methane and nitrous oxide removal technologies

Methane and nitrous oxide account for 82% of GHG emissions from agriculture (figure 1(C)). While reducing GHG emissions is the most effective way to achieve net-zero emissions agriculture, little attention has been given to the idea of removing methane and nitrous oxide from the atmosphere. Futuristic as this may sound, there are technologies that aim to oxidize methane to carbon dioxide and water, yielding additional atmospheric carbon dioxide but eliminating approximately one sixth of total radiative forcing [165]. Methane can be oxidized to carbon dioxide and water using catalysts or bacteria that can break down methane [166]. The conversion of methane to carbon dioxide in the atmosphere is energetically favorable and could yield cost-effective climate benefits [165]. Approaches developed for atmospheric methane removal could also be applied to nitrous oxide [166]. The decomposition reaction of nitrous oxide into nitrogen and water is exothermic, like methane oxidation, but catalysis of the reaction is difficult [166, 167]. However, the effectiveness and feasibility of these technologies may vary depending on the specific application and the scale of implementation. Further research and development are needed to determine their commercial feasibility and understand their broader impacts.

4.2. Chemical and biological processes to produce food without agriculture

Recent studies have explored the idea of producing food without agriculture, by synthesizing edible molecules through chemical and biological processes [168]. Unlike the growing market for plant-, cell-, or fungi-based proteins and meat substitutes [169], which are largely made up of processed agricultural commodities, the carbon contained in synthetically produced food may be derived from fossil fuels, waste carbon, or directly from the atmosphere, using feedstocks that are not the product of agricultural photosynthesis. This concept is not entirely new, as during World War II, German converted coal into margarine [170].

Various carbon sources can be used to synthesize fats, proteins, and carbohydrates through chemical and biological pathways. Currently, fossil fuels and organic wastes are being converted to syngas or ethylene via gasification or steam cracking, respectively. In turn, syngas or ethylene may be converted either to paraffins, fatty acids, and then fats [171], to amino acids and then proteins [172], or to methanol and then carbohydrates [173]. Biological pathways, such as using atmospheric carbon to produce carbohydrates via catalysis [173] or proteins produced in cell culture via hydrogen-oxidizing bacteria, also exist [172, 174, 175].

These pathways have been demonstrated at small scales, but questions remain regarding the feasibility and benefits of producing synthetic food compared to traditional agriculture. Little attention has been given to the potential reduction of GHG emissions from synthetic food production, and public acceptance may be a challenge. However, these technologies could help reduce the environmental footprint of agriculture.

5. Conclusions

Agriculture contributes significantly to climate change and is extremely impacted by its consequences. Besides emitting 12% of global GHG emissions, agriculture is faced with a special challenge in that 82% of its GHG emissions come from methane and nitrous oxide, with the remaining 18% from carbon dioxide emissions. Satisfying global demand for food without causing further climate change and environmental degradation is a central challenge of the 21st century.

In this review, we examine various technologies, innovations, and practices that have the potential to achieve net-zero, and potentially net-negative, GHG emissions in agriculture. These include (i) technologies for decarbonization of on-farm energy use, (ii) nitrogen management technologies, (iii) alternative rice cultivation methods, and (iv) feeding and breeding technologies that reduce enteric methane. Taken together, these measures can cut GHG emissions from agriculture by 45%. However, residual emissions of 3.8 Gt $CO_{2\text{-eq}}$ per year need to be offset via CDR. BECCS and enhanced rock weathering are particularly promising techniques, as they can be implemented with agriculture and result in permanent carbon sequestration. Provided with sufficient support and incentives, these CDR techniques could transform agriculture from an emitter of GHGs to a carbon sink. Overall, achieving net-zero emissions in agriculture will be feasible only through some form of CDR and carbon capture and storage with permanent CO_2 sequestration.

Our study estimates the technical mitigation potential of different strategies to achieve net-zero emissions in agriculture (figure 3). However, future research is needed to quantify the actual mitigation potential of each strategy considering local site-specific technical, social, economic, and political constraints, as well as the uncertainty associated with the potential of all identified strategies.

While achieving net-zero emissions in agriculture is feasible with technologies and practices with a high technological readiness (solutions at the commercial or pilot phase), their adoption is constrained by underinvestment, a lack of effective policies, and high costs, especially in developing countries. To surmount these challenges, it is critical to eliminate adoption barriers and implement strategies that promote the widespread adoption of sustainable practices. Further research is required to make these technologies affordable and scalable and understand their socio-environmental impacts.

The urgency of the climate crisis requires a paradigm shift in agriculture towards net-zero or even net-negative emissions. This transition requires significant investment and government support, including financial incentives, research and development funding, education and training programs, and regulations to reduce emissions and promote carbon sequestration in agriculture. This study serves as a blueprint for future research and development of net-zero agriculture policies and technologies. Global coordination among researchers, investors, consumers, farmers, and policy regulators is vital for driving this paradigm shift in agriculture.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

The research of P G is partially funded by the Swiss National Science Foundation (SNSF) Exchange Grant No. 214037, for his research stay at the Department of Global Ecology at Carnegie Institution for Science.

Authors contribution

L R and P G conceived the study; L R designed, performed, and wrote the study with inputs from P G.

Conflict of interest

The authors declare no conflict of interest.

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