2024 BREAKTHROUGH AGENDA REPORT AGRICULTURE

Accelerating sector transitions through stronger international collaboration

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Foreword

Agrifood systems are remarkable, providing food and nutrients for a growing population. Yet they are facing unprecedented and accelerating challenges. They are highly vulnerable to the adverse impacts of climate change and a significant contributor to global greenhouse gas emissions. Transformed, agrifood systems can safeguard food and nutrition security, build resilience to climate impacts, help meet our climate mitigation needs, protect and restore nature, and create prosperous and inclusive societies and economies.

COP28 was a landmark moment for agrifood systems and saw remarkable momentum from actors across the agrifood value chain. Over 150 heads of state signed the COP28 UAE Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action, pledging to put food and agriculture at the heart of national climate and other policies and increasing investment in resilient, equitable, and sustainable food systems. Hundreds of non-state actors, including farmers, cities, businesses, financial institutions, and civil society, endorsed the Food Systems Call to Action, aligning around a shared vision and priority set of actions to transform food systems to deliver positive outcomes for people, nature, and climate, and centering on the need to support farmers and other frontline food systems actors and vulnerable groups. Several other initiatives were also launched and funding was committed. We must deliver on these pledges and take urgent action now.

The *2024 Breakthrough Agenda Report – Agriculture* is the first standalone report to focus on agriculture within the Breakthrough Agenda series, with the 2022 and 2023 iterations featuring a chapter on the sector. The report draws on CGIAR's expertise to assess the state of development in international collaboration and propose clear recommendations for governments to scale up clean technologies and sustainable solutions in agrifood systems, to achieve the Agriculture Breakthrough's objective: to "make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030." It also draws on global expertise shared by governments, businesses, and civil society organizations active in the space.

This year's report focuses on opportunities to scale up clean technologies to reduce emissions from enteric methane and from the production and use of fertilizers – the two subsectors with the highest emissions in the agrifood sector. This report is an important contribution, providing granular, actionable recommendations in these specific areas. It is also important to emphasize that a holistic, multipronged, food systems approach must be taken, covering all agrifood areas and entry points in agrifood value chains to achieve equitable, resilient, and sustainable food systems. Many solutions across agricultural production, consumption, food loss and waste, and protecting and restoring nature are needed. A just transition including meaningful consultation with all actors and with the goal of equitably distributing the risks, burdens, and benefits of the transition, with a particular focus on vulnerable groups, is essential when developing and scaling up solutions. Technologies and solution sets will likely vary between countries depending on local contexts.

We hope that the recommendations in this report provide practical and implementable actions for stronger international collaboration to make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030. We will continue to engage with governments, businesses, and civil society organizations in their efforts to implement the recommendations of this report.

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Executive summary

Strengthening international collaboration to accelerate agricultural transitions

Agriculture is a significant source of global greenhouse gas (GHG) emissions, and food systems contribute to nearly one-third of global emissions. The 2024 Breakthrough Agenda Report – Agriculture highlights the need for stronger international collaboration to transform the sector into a more climate-resilient, low-emissions system that meets other societal and environmental goals. This report emphasizes the importance of international collaborative actions to accelerate the deployment of these technologies, recognizing that agriculture's contribution to emissions reduction is crucial to keeping the world within 1.5°C to 2°C by the end of the century as per the Paris Agreement goals.

Livestock and fertilizer are two of the most significant contributors to agricultural emissions: hence the focus of this year's report. However, the report acknowledges that the sector's transformation into a resilient and low-emissions system, while catering to broader societal and environmental goals, will require systemic changes involving multiple approaches and interventions, including improvements in land management and water use, dietary shifts, and reductions in food loss and waste, as was documented in last year's Agriculture chapter of the Breakthrough Agenda Report 2023 and the accompanying deep dive report into seven technological areas.

The Agriculture Breakthrough principles

The Breakthrough Agenda was launched at COP26 in 2021, and 17 countries have signed up for the Agriculture Breakthrough Agenda since then. In 2024, for the first time, the Agriculture Breakthrough Report is a standalone report led by CGIAR, while all other sector progress is covered in the IEA-led Breakthrough Report. The Agriculture Breakthrough Agenda aims to make sustainable, climate-resilient agriculture the most attractive and widely adopted option for farmers globally by 2030. Specifically, progress in the agricultural sector is measured against four guiding principles (called the agriculture breakthrough principles):

1. **Sustainable increases in agricultural productivity and incomes, especially in low- and middle-income countries (LMICs).**
2. **Reduction in GHG emissions from the agrifood sector.**
3. **Improved soil, water resources, and natural ecosystems.**
4. **Improved adaptation and resilience to climate change, particularly for smallholder producers.**

These principles guide the evaluation of international collaboration and technological progress in the sector. This year's report focuses on reducing emissions, and hence the focus on two subsectors (livestock and fertilizer), while stressing that emissions reductions must not compromise food and nutrition security, particularly for the most vulnerable populations in the LMICs.

Agricultural emissions have remained stagnant in the past few years

Global emissions from agrifood systems remained steady at around 16 gigatons of CO_2 equivalent between 2019 and 2021, indicating insufficient progress in reducing emissions. Livestock methane and fertilizer use are among the sector's most significant contributors to GHGs. Making immediate and substantial reductions in these areas is crucial if the agricultural sector is to meet the global climate targets outlined in the Paris Agreement in 2015.

Increasing momentum in international collaboration signals the need for urgent action

Since the launch of the Breakthrough Agenda at COP26 in 2021, international cooperation in agriculture has gained momentum, recognizing the sector's critical role in climate mitigation, adaptation, food security, and environmental sustainability. The Sharm el-Sheikh Implementation Plan, endorsed at COP27 in 2022, was pivotal in highlighting the interconnectedness of water, food security, and the environment in climate action. Multiple initiatives have since been launched, including the COP28 UAE Declaration on Sustainable Agriculture, the Call to Action for Transforming Food Systems for People, Nature and Climate (Food Systems Call to Action), and several other technical cooperation programs on agriculture, showing that countries and actors across the agrifood value chain increasingly recognize the importance of incorporating food systems into climate action. These initiatives aim to enhance knowledge sharing, build resilience, and increase financial support for sustainable agriculture. Meanwhile, climate finance for the agrifood sector continues to be low, receiving just 4.3% of total global climate finance, and is even on a downward trajectory. Additionally, innovation in research, development, and demonstration (RD&D) remains underfunded. Gaps in developing common metrics and indicators, particularly in measuring resilience, further hamper coordinated global efforts, highlighting the need for more robust international collaboration and accountability to accelerate meaningful progress.

Table 1: Summary of progress on international collaboration

	Agriculture and food systems
International sharing of knowledge on policy and implementation (Good progress)	↑
Development of common metrics and indicators (Moderate progress)	↑
Finance (Minimal progress)	↓
Research, development, and demonstration (RD&D) (Moderate progress)	=
Private sector, markets, and trade (Minimal progress)	=

Good progress · Moderate progress · Minimal progress

Arrows indicate relative progress compared to last year's assessment in the 2023 Breakthrough Agenda Report:

↑ *Improved assessment* ↓ *Downward assessment* = *Same assessment*

Technologies and approaches for reducing emissions from livestock and fertilizers

This report focuses on four technologies within two major subsectors of agriculture: reducing enteric methane emissions from livestock and reducing emissions from fertilizer. These technologies are methane inhibitors and low-methane forages for livestock and green ammonia and site-specific nutrient management (SSNM) for fertilizer use. Methane inhibitors, such as 3-NOP (Bovaer®), have shown the ability to reduce methane emissions by up to 30%. At the same time, low-methane forages offer a complementary approach by modifying livestock feed to naturally lower emissions. Meanwhile, green ammonia, produced using renewable energy, provides a pathway to decarbonizing fertilizer production, which currently relies heavily on fossil fuels. SSNM optimizes fertilizer application to match the specific nutrient needs of crops, reducing waste and minimizing nitrous oxide emissions. However, there are several barriers to adopting these technologies and approaches. These include high costs and limited access to these technologies, particularly in the LMICs; regulatory challenges, such as inconsistent regulatory frameworks across countries that create obstacles to scaling these technologies; lack of knowledge and technical support for adoption and scaling of new technologies; and lack of market demand and consumer awareness, such as limited demand for low-emission agricultural products.

Priority actions to strengthen international collaboration

The report outlines five priority actions for international collaboration, to overcome existing barriers and drive progress, as shown in the table below. The transition to sustainable, climate-resilient agriculture is both urgent and achievable. The technologies discussed in this report offer promising solutions but are only part of the broader transformation required.

Table 2: Five priority actions for international collaboration

	A1	A2
PRIORITY ACTION	**Increased international climate finance should be directed toward unlocking the potential of sustainable agricultural technologies and approaches with proven effectiveness**	**Promote international sharing of knowledge on policy and implementation to create demand for and facilitate faster uptake of proven technologies**
WHAT NEEDS TO BE DONE?	**A.** Include proven technologies discussed in this report in green finance frameworks to drive demand, spur innovations, and make them eligible for green finance. At the same time, multilateral development banks and donor countries should provide concessional loans and grants for adoption in LMICs. **B.** Governments should repurpose the more than US$600 billion spent annually on agricultural support, much of which incentivizes unsustainable practices, and redirect it toward research and development (R&D) for productivity-enhancing and emissions-reducing agricultural technologies. **C.** The Breakthrough Agenda should link more closely with the G7 and G20 agendas to showcase scalable technologies that address hunger and climate goals and require financial support for upscaling.	**A.** Governments are encouraged to launch a Nitrogen Use Efficiency (NUE) Pledge to reduce nitrous oxide emissions from fertilizers by setting targets and to leverage the Methane Pledge to create global demand for methane inhibitors and low-methane forages. **B.** Countries should collaborate within the Codex Alimentarius framework of FAO-WHO to establish maximum food safety residue limits for inhibitor compounds in livestock products, facilitating international trade. **C.** Countries should use platforms like the Global Agriculture Policy Dialogues to exchange knowledge and best practices on policies that support farmers' adoption of these technologies.

International collaboration will be critical to ensuring these technologies are deployed at scale and that agriculture contributes its fair share to meeting global climate targets. *The 2024 Breakthrough Agenda Report – Agriculture* provides a roadmap for urgent action.

A3

Develop common metrics and indicators to track the adoption of sustainable agricultural solutions

A. Governments and fertilizer companies should be encouraged to reduce emissions by expanding GHG accounting to include Scope 3 emissions from fertilizer application, alongside a certification mechanism for full carbon accounting and mandating green ammonia production for new plants; set up clear globally aligned regulatory frameworks and metrics, reporting, and verification (MRV) requirements for credible GHG emission reporting; and scale up adoption of livestock low-emissions technologies.

B. Countries should develop “Codex Planetarius,” which can set forth criteria for crops and animal-derived products (to be certified as compatible with international climate targets), which will in turn incentivize all actors in the value chain to adopt low-emissions and climate-compatible technologies.

A4

Increase support for food system research, development, and demonstration (RD&D) to support the uptake and scaling of promising technologies and approaches

A. Strengthen global knowledge exchange and collaboration on reducing agricultural emissions by enhancing research networks, supporting innovation in fertilizer management and methane reduction technologies, and fostering data-sharing and capacity building, especially in LMICs.

A5

International efforts should work toward enabling the private sector to scale up solutions through global markets

A. The World Trade Organization Agreement on Environmental Goods and Services should be revived to include low-carbon fertilizers and livestock feed additives in future negotiations, promoting harmonized standards and certifications to facilitate global trade in green and low-emission agricultural products.

1 Introduction

The breakthrough objective for the food and agriculture sector is to *"make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030."*

Agrifood systems account for approximately one-third of all greenhouse gas (GHG) emissions globally when food production, transport, processing, and retailing are considered (Crippa et al. 2021; IPCC 2022). Therefore, sustained reductions in this sector are needed to meet the Paris Agreement target of maintaining the global temperature increase below 1.5–2.0°C (IPCC 2023). In addition to mitigation, adaptation is critical to safeguarding the livelihoods of millions of the world's poorest and ensuring a just transition to a 1.5-degree world.

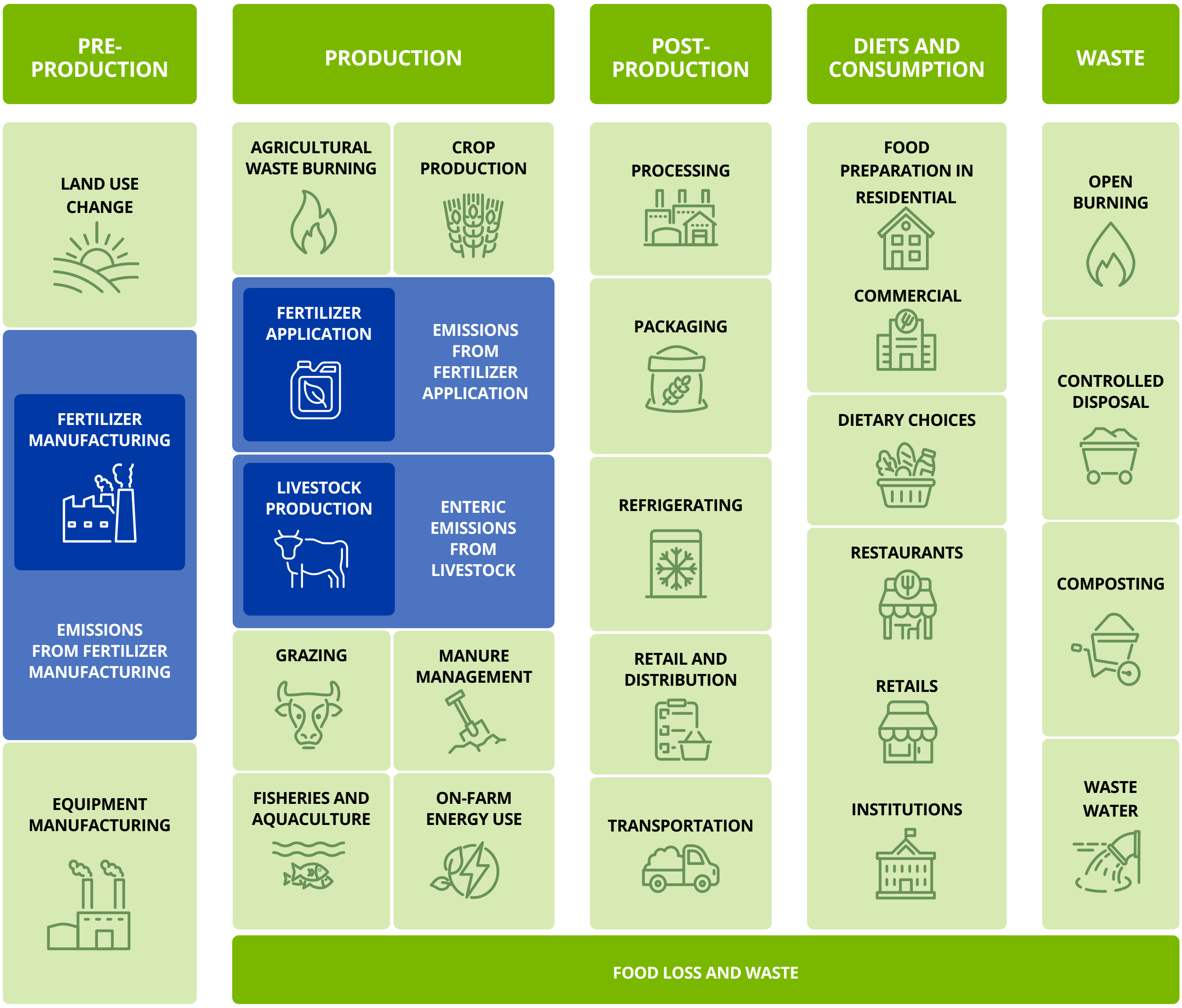
The 2023 Breakthrough Agenda Report revised the four guiding principles to measure progress against the breakthrough objective adopted by signatory countries at COP 26. Success is: (i) sustainable increases in agricultural productivity and incomes, particularly in low- and middle-income country (LMIC) contexts; (ii) reduced GHG emissions from the agrifood sector; (iii) improved soil, water resources, and natural ecosystems; and (iv) improved adaptation and resilience to climate change, particularly for vulnerable smallholder producers.

In this year's report, we have prioritized the emissions-reduction goal over the other three, provided that emissions reductions do not negatively affect the other three objectives, particularly for the vulnerable farmers in LMIC contexts. As such, this year's report will look at emissions reductions from technologies related to enteric methane emissions and emissions in both production and use of fertilizers – the two categories with the highest emissions in the sector (see section 5). To remain within the Paris agreed targets of 1.5 to 2°C by the end of the century, the Climate Bonds Initiative's Agriculture Criteria guidelines, using the best available science, concluded that an overall reduction of 20 percent in GHG would be needed between 2020 and 2030 and a 30 percent reduction between 2020 and 2040, where emissions are defined as the net emissions resulting from GHG emissions and carbon sequestration and measured as tons of carbon dioxide equivalent (tCO_2e). It is important to emphasize that emissions reductions from the agrifood sector must be a multipronged approach covering all subsectors and at different points in the value chain (see Figure 1). The reason for prioritizing two subsectors from the seven considered in the agriculture chapter of the 2023 Breakthrough Agenda Report and the companion piece of CGIAR's deep dive report is to arrive at more granular and implementable recommendations.

Three caveats are in order before we focus on these selected technologies for the remainder of the report.

First, without deep systemic and behavioral changes (both individual and corporate), technological approaches alone will not lead to desired emissions reductions. For example, efforts should be made to limit food loss and waste. Similarly, reducing the consumption of animal source proteins in high-income countries where such consumption can be above dietary guidelines is an essential pathway for emissions reductions in the livestock sector. Such dietary shifts, according to a study published in Nature, could reduce annual agricultural production emissions of high-income nations' diets by 61 percent while sequestering as much as 98.3 (55.6–143.7) Gt CO2 equivalent. Second, the onus of emission reduction must be guided by principles of historical responsibility, and those with greatest emissions should be doing more to align their mitigation targets, policies, and measures with a 1.5°C-compatible pathway. In other words, those who have emitted the least must not be held responsible for emissions reductions at the cost of their food and nutrition security needs. For example, in Africa, which only accounts for 4 percent of all historical emissions, increasing fertilizer use to boost food production must be an acceptable pathway, albeit with technology and finance allowing the continent to invest in low-emissions fertilizer production and use. Third, with just six years left to 2030, it is becoming clear that the world is not on track to end hunger and food insecurity (SDG Target 2.1) and end malnutrition in all its forms (SDG Target 2.2) despite decades of increasing food production and yields. Addressing these three trends will contribute significantly to meeting the overall Agriculture Breakthrough goals. Next year's report should explore these issues in more detail.

Figure 1. Sources of greenhouse gas (GHG) emissions from various components across the entire value chain of the agrifood system. (Adapted from Balasubramanian et al. 2021 and Rosenzweig et al. 2021). The sectors where we do a deep dive are marked in blue.



2 The state of the transition

Transforming the global agrifood system to limit global warming to 1.5°C above preindustrial levels; end soil, water, and ecosystem degradation; adapt to our changing climate; and sustainably and nutritiously feed and support a growing population requires several interconnected shifts. Before narrowing the focus of this report to consider just reducing enteric emissions from livestock and lowering emissions from fertilizers, we review progress in the agrifood system against the four breakthrough principles.

While crop yields and ruminant meat productivity per hectare increased slightly between 2021 and 2022, based on calculations from FAOSTAT, recent trends since 2018 for both indicators are off track from the pace of growth needed for 2030, as shown in the 2023 State of Climate Action report (World Resources Institute 2023). Total agricultural output has risen steadily over the last decade, reaching US$44.2 trillion in 2019, the last available year (Our World in Data 2024). Breaking down agricultural output by crop type, the production of wheat and maize – both requiring high fertilizer inputs – has also climbed. Wheat production reached 808.44 million tons in 2022, a 37.6 percent increase from 2000 (Our World in Data 2024). Meanwhile, maize production rose to 1.16 billion tons in 2022, an 86.8 percent increase since 2000 (Our World in Data 2024). However, there are insufficient data to assess progress made in productivity and the average income of small-scale producers (SDG indicators 2.3.1 and 2.3.2, respectively) (FAOSTAT 2024).

World total emissions from agrifood systems remained constant from 2019 to 2021 at about 16 Gt CO_2 equivalent but exhibited a 14 percent growth since 2001. The contribution to global mean surface temperature rise from agriculture and land use is also increasing, with approximately 0.6°C of the temperature climb attributable to this sector in 2022 (Friedlingstein et al., 2023).

The planet's land area is 13 billion hectares. The agricultural area accounts for 37 percent of this – a total of 4.8 billion hectares. Global agricultural area is divided into categories: cropland (33 percent of the total agricultural land area) and pastures (67 percent) (Our World in Data 2024).

Global cropland – land used to grow crops, excluding pasture used for livestock grazing – is increasing (Our World in Data 2024). Over the past two decades, global cropland expansion has accelerated, with a near doubling of the annual expansion rate, most notably in Africa (Potapov et al. 2021). Agricultural expansion continues to drive deforestation globally and particularly in the tropics (Pendrill et al. 2022) – half of this new cropland area replaced natural vegetation and tree cover (Potapov et al. 2021). This worldwide expansion will have to cease if the global target to end deforestation (with resulting biodiversity protection, as codified in the Convention on Biological Diversity) by 2030 is to be met. If warming is not limited to 1.5°C, climate change will likely become the dominant cause of biodiversity loss in the coming decades (WWF 2022). Between 1970 and 2018, the planet experienced an average decline of 69 percent in the relative abundance of monitored wildlife populations (WWF 2022).

Meanwhile, the extent of global pasture has been on a slow decline since around 2000, taking up an estimated 3.2 billion hectares in 2023. This represents 66.6 percent of total agricultural land, a 3.7 percent decrease from pasture's turn-of-the-century height (Taylor and Rising 2021; FAO 2024; HYDE 2023; Our World in Data 2024). This pasture contraction is not outweighed by cropland expansion for animal feed. While cropland for cattle feed has increased by around 25 million hectares, the total agricultural land devoted to producing meat and milk from ruminants has shrunk by approximately 50 million hectares since 2000 (Mottet et al. 2017; Alexander et al. 2015). We are past "peak pasture," despite global meat consumption rising, for several reasons. Firstly, there has been a shift in how meat is produced and what types of meat we eat. We now consume more pork and chicken, which are not fed on pasture. Secondly, a lot of beef production has moved from open pasture grazing toward more intensive farming methods, which has spared land. It is important to note that while grain-fed livestock is more land-efficient than pasture-fed livestock, biodiversity is often higher on grazing lands than on intensive croplands. Notably, a peak in global pastureland does not mean it has peaked everywhere; in tropical

regions – which are richest in biodiversity and carbon – it continues to rise, often at the expense of carbon-rich habitats (Our World in Data 2024; Godde et al. 2018; Blaustein-Rejto 2019). The expansion of grazing land for beef production is still the leading driver of global (and tropical) deforestation (Ritchie 2021).

The level of water stress worldwide – calculated as the proportion of freshwater withdrawn from all available freshwater resources – has risen by 1.2 percent since 2015, to 18.2 percent in 2022 (FAO 2024). Global water stress specifically from agriculture stands at 13 percent in 2021 (the most recent year with available data at the time of publication). However, this masks substantial regional variations, and is expected to rise as climate change renders certain extreme weather events more frequent. Agricultural irrigation accounts for 70 percent of water use worldwide (OECD 2024), and agricultural water use efficiency (value of output per cubic meter of water) is one of the “worst performers” of the SDG indicators, having deteriorated since the baseline year (FAO 2024).

The lack of universally applicable indicators for measuring adaptation and resilience to climate change for smallholder producers is a concern. Indicator SDG 5.a.1 - (a) related to the percentage of people with ownership or secure rights over agricultural land (out of total agricultural population) by sex is a good proxy indicator of adaptation and resilience, as land and asset ownership is often positively correlated with better adaptive capacities. However, reporting on global progress in this indicator is impossible due to data unavailability (FAO 2024). Similarly, the SDG 2.3.2 indicator on the average income of small-scale food producers by sex and indigenous status, while a promising indicator of adaptation and resilience, does not have comparable global data to measure year-on-year progress (FAO 2024). Direct agricultural loss attributed to disasters is an indicator under the Sendai Framework, and all countries report data to the United Nations Office for Disaster Risk Reduction (UNDRR). This indicator works well to measure the negative impact of hazards on adaptation and resilience, but the downside is that it also captures non-climatic hazards. Over the last 30 years, an estimated US$3.8 trillion worth of crops and livestock production has been lost due to disaster events, corresponding to an average loss of US$123 billion annually, or 5 percent of annual global agricultural GDP (FAO 2023).

In sum, the most recent year of data collection reveals a uniform lack of progress across the metrics selected in last year’s report.

3 Assessment of international cooperation

Since the Breakthrough Agenda was launched in November 2021 at COP26, there has been growing recognition of the need to spotlight the agrifood system in international efforts to mitigate, adapt to, and prevent loss and damage from human-caused climate change. In this section, we provide a non-exhaustive assessment of international cooperation that meets any of the four principles of the Agriculture Breakthrough Agenda since then. Efforts are categorized by different forms of international cooperation, corresponding to the recommendations made in the 2023 Breakthrough Agenda Report (Figure 2).

3.1 International sharing of knowledge on policy and implementation

The Sharm el-Sheikh Implementation Plan – the decision text of COP27, in 2022 – was the first global climate pact agreed at a Conference of the Parties (COP) to formally recognize water, food security, and forests as key issues relating to climate action. "Nature-based solutions" were included in the text for the first time, with forests, oceans, and agriculture each having a dedicated section. The Sharm el-Sheikh Joint work on implementation of climate action on agriculture and food security, a four-year work program was launched to promote a holistic approach to addressing issues related to agriculture and food security through knowledge and information sharing.

Agriculture was the focus of one of the thematic task forces established the following year, in 2023. COP28 saw the launch of the COP28 UAE Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action. Signatories include 160 national governments (including the EU), representing over 5.7 billion people, 70 percent of the food consumed, nearly 500 million farmers, and 76 percent of total emissions from the global food system. These signatories have committed to several actions, including scaling up adaptation and resilience to reduce the vulnerability of all food producers to the impacts of climate change and promoting food security and nutrition by increasing efforts to support vulnerable people. A Technical Cooperation Collaborative (TCC) was launched at SB-60 in Bonn in 2024 to support the implementation of the COP28 UAE Declaration mentioned above. The Call to Action for Transforming Food Systems for People, Nature and Climate and the three-year Agrifood Sharm el-Sheikh Support Programme were also announced at COP28. This latter initiative aims to facilitate dialogue and knowledge sharing among global and regional policymakers and to help countries unlock finance and support for farmers, food producers, small agribusinesses, and local communities.

The COP29 Presidency has announced the launch of 14 initiatives, of which 3 are of relevance for the agrifood sector. These are: HARMONIYA 4 Climate Resilience: Empowering Farmers, Villages, and Rural Communities; Baku Dialogue on Water and Climate: Enhancing Action on Climate Change and Water Nexus; and Clean Hydrogen Initiative. These all involve knowledge sharing and coalition building.

3.2 Development of common metrics and indicators

The Sharm el-Sheikh Adaptation Agenda, endorsed at COP27 in 2022, presented over 30 global adaptation outcome targets urgently needed by 2030 to increase the resilience of 4 billion people. The latest climate meeting at Bonn in June 2024 (SB-60) saw progress in the UAE Framework for Global Climate Resilience, which initiated a two-year UAE–Belém work program aimed at developing indicators to measure advancements toward the targets established by the Global Goal on Adaptation (GGA) framework. Given the lack of indicators for measuring adaptation and resilience in the agriculture sector, progress in the GGA is much awaited.

Another initiative aimed at developing metrics and indicators is Regen10's Outcomes-Based Framework, which was launched at COP28. Having developed a zero draft framework to measure and support the transition to regenerative food systems, the organizations involved – Food and Land Use Coalition (FOLU), World Farmers' Organisation (WFO), World Business Council for Sustainable Development (WBCSD), International Union for Conservation of Nature (IUCN), and Sustainable Food Trust (SFT) – are testing this throughout 2024, with the aim of publishing an updated framework by early 2025.

3.3 Finance

As well as introducing the Agriculture Breakthrough Agenda, COP26 oversaw the launch of the Agriculture Innovation Mission for Climate (AIM4C). This aims to address climate change and global hunger by uniting participants to significantly increase investment in, and other support for, climate-smart agriculture and food systems innovation over five years (2021–2025). Most recently, at COP28, the initiative announced an increased investment of more than US$17 billion, up from US$8 billion at COP27. At COP28, the FAO and Egyptian Presidency announced the Food and Agriculture for Sustainable Transformation (FAST) Initiative, which aims to improve access to climate finance at farm and country levels to transform agriculture and food systems by 2030 while supporting food and economic security and the environment. A Climate Investment Fund for Future will be launched at COP29, seeking to increase the private sector's involvement in financing climate action and transition in the developing world.

International financial institutions and multilateral development banks have also launched many major flagship investment projects in the agrifood sector. The World Bank currently has 416 active or pipeline projects categorized under "agriculture."[1] The Asian Development Bank has 2,264 projects labelled "Agriculture, natural resources and rural development," and, as of April 2024, is on schedule to deliver its commitment to invest US$14 billion by 2025 to improve food security and support measures to ease the food crisis in Asia and the Pacific. Meanwhile, the Inter-American Development Bank lists 215 current and 24 pipeline projects relating to agriculture and food security.

Select initiatives aimed at mitigating GHG emissions from agriculture include the World Bank's Global Methane Reduction Platform for Development (CH4D), which supports investments in methane abatement in agriculture and waste, and the International Fund for Agricultural Development (IFAD)'s Reducing Agricultural Methane Programme (RAMP). This latter program supports countries with the integration of methane reductions into their Nationally Determined Contributions (NDCs) and in the design of new agricultural development projects with robust methane mitigation components. Both initiatives were launched at COP28.

The Group of Seven (G7) and Group of 20 (G20) agendas also include important initiatives to direct investment for broader development and environment objectives in the agrifood system. In 2024, G7 leaders launched the Apulia Food Systems Initiative to intensify efforts to overcome structural barriers to food security and nutrition and to build resilient sustainable and productive agriculture and food systems, and to ensure that all people can progressively realize the right to adequate food. The G7 Research Group, which provided a qualitative assessment of how well the G7 goals were achieved at the Apulia Summit in June 2024, gave a score of B- (on a scale that ranks from A+ to F) for food and agriculture. The commitment to accelerate innovation and investment for food safety and sustainable food production only scored a D+ (G7 Research Group 2024).

These figures and lists of initiatives belie a more cautionary tale. Agrifood systems include high-emitting and climate-vulnerable sectors, yet climate finance flowing to them is strikingly low (Climate Policy Initiative 2023). In 2019–20, agrifood systems received just 4.3 percent of total global climate finance tracked at the project level, with an annual average of US$28.5 billion (Climate Policy Initiative 2023).

1. N.B. Some of these are multicountry, while some are at the national or local level.

The amount of climate finance flowing to agrifood systems is also on a downward trajectory as a proportion of global climate finance flows (Galbiati et al. 2023). Climate finance toward adaptation more broadly is also on a downward trend, something the United Nations Food and Agriculture Organization (FAO) claims is "a cause for alarm" and a "missed opportunity" (Galbiati et al. 2023).

Over the period 2020–22, support to the agricultural sector in the 54 countries covered by the 2023 OECD Agricultural Policy Monitoring and Evaluation Report totaled US$851 billion per year. Only 12.5 percent, or US$106 billion of this, went to investments in agricultural innovation, infrastructure, and other public goods. Despite international calls for environmentally harmful support to be eliminated or reformed, efforts to reform support in agriculture over the past decade have largely stalled.

3.4 Research, development, and demonstration (RD&D)

Spending on RD&D has huge returns on investment, with a study by the USDA Economic Research Service finding that spending on public agricultural R&D from 1900 to 2011 generated, on average, $20 in benefits to the US economy for every $1 of spending, while another study found that adoption of CGIAR's innovations in developing countries raised economic welfare by US$47 million every year between 1961 and 2000. Despite well-documented benefits, public spending on agricultural R&D and innovation has been slowing in OECD countries. Public expenditure on innovation has declined relative to the sector's size, from 0.9 percent of the value of agricultural production in 2000–02 to less than 0.6 percent in 2020–22 (OECD, 2022).

3.5 Trade

In 2022, the European Commission stated that "A global mineral fertilizer crisis, of severity unseen since the 1970s, is currently unfolding," due to supply chain disruptions caused by the COVID-19 pandemic, the energy crisis, and war in Ukraine (European Commission 2022). Since then, fertilizer prices have fallen from those initial highs and new trade routes and patterns have emerged (Hebebrand and Glauber 2024).

In June 2023, Spanish multinational electric utility company Iberdrola and the world's largest seaborne trader of anhydrous ammonia, Trammo, signed the largest green ammonia framework agreement in

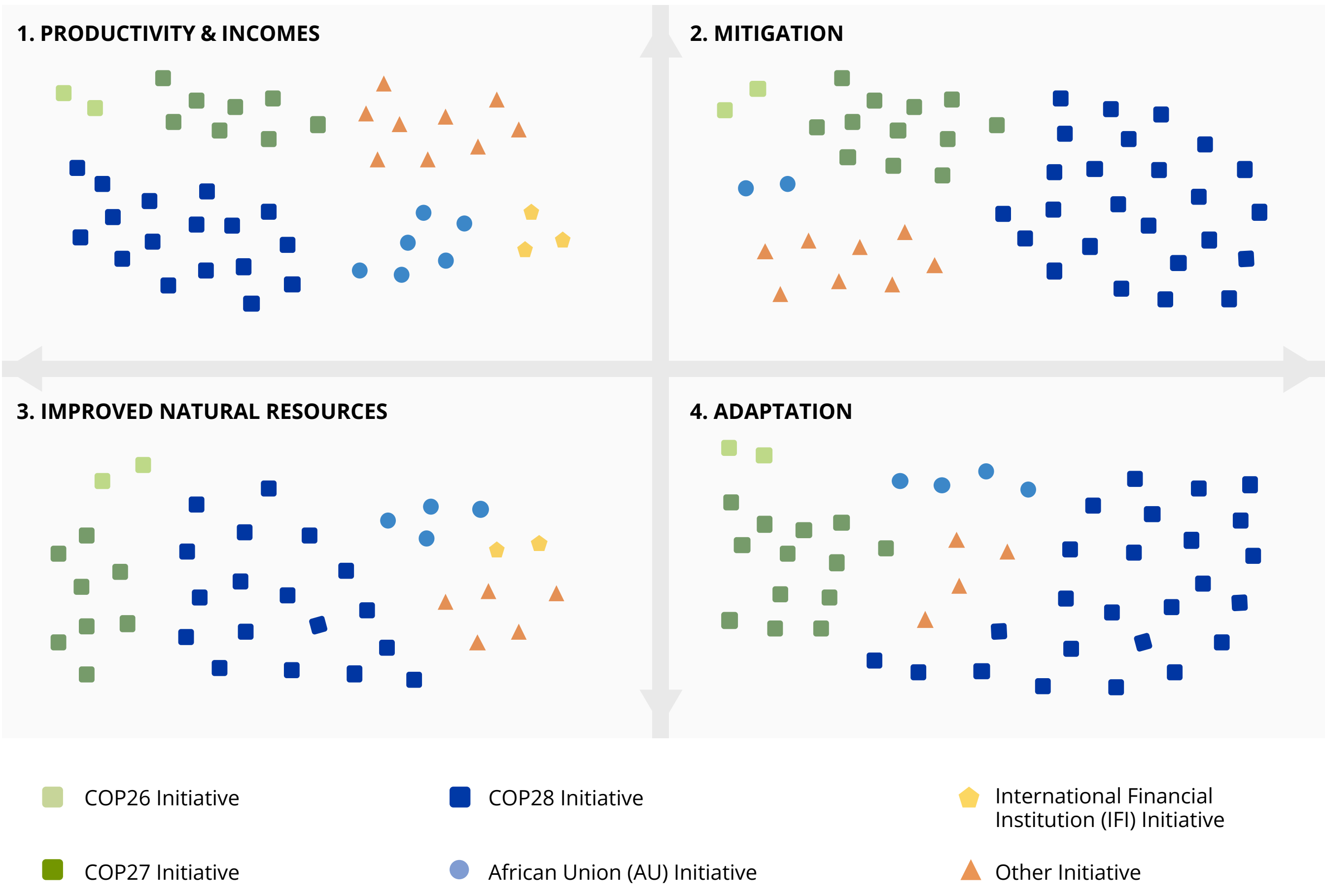
Europe for the purchase and sale of up to 100,000 tons of green ammonia per year from 2026. In March 2024, the Norwegian crop nutrition company Yara and GHC SAOC, a wholly owned subsidiary of renewable energy company Acme Cleantech, signed a binding agreement for supply of ammonia with reduced CO_2 emissions from Acme to Yara on a long-term basis.

As a derivative commodity of green hydrogen, the trade dynamics of green ammonia can be linked to those of the nascent green hydrogen industry. As the production of hydrogen produced via renewable energy increases, so too will the trade possibilities for green ammonia. Modeling from a 2022 analysis revealed that, in a world that has fully decarbonized by 2050, about a quarter of the total global hydrogen demand in a 1.5°C scenario could be satisfied through international trade (IRENA 2022). Of the traded hydrogen, 55 percent would flow through pipelines, while 45 percent would be shipped, predominantly as ammonia.

While there are early signs of growth in the global trade of green ammonia, and while the expected demand in clean shipping fuels is predicted to propel this further, green ammonia has not yet reached cost parity with other forms of ammonia (discussed in section 6.3).

Figure 2 maps all these initiatives across the four breakthrough principles and shows that the majority of the initiatives map across multiple criteria. Annex 1 lists relevant initiatives across the agrifood system, based on which Figure 2 was drawn.

Figure 2. Mapping of various agriculture and agrifood systems initiatives launched since 2021 against the four breakthrough principles. Note: Not exhaustive, particularly when it comes to AU, IFI and other initiatives. Detailed information in Annex 1 (Source: Authors).



4 Progress against priority actions

Based on the recommendations from the agriculture chapter of the 2023 Breakthrough Agenda Report, a set of priority international actions were formulated. There was at least one action identified for each recommendation. Generally, progress has been made against all areas covered in the 2023 report, though the fulfillment of the priority actions is inadequate to satisfy the broader recommendations and the overarching breakthrough principles, which are much more ambitious. There is more to be done, but the period October 2023 – October 2024 saw several developments (see Annex 2 for the full progress tracker). There is a need to set an even higher ambition this year to ensure strong progress in 2025, halfway to the Breakthrough Agenda deadline.

As noted in section 3.3, climate finance to the agrifood sector needs attention. While there has been progress on all the priority actions that fall under recommendation A1, "Deliver greater quantity and quality of climate finance to support the deployment of sustainable agricultural technologies and approaches with proven effectiveness," there need to be more international finance mechanisms that directly benefit farmer organizations, as well as increased blended finance mechanisms. Countries should repurpose budgetary transfers to individual farmers, which distort trade and production and are environmentally harmful, toward funding R&D to enhance the productivity of the agriculture sector and its ability to grow more food using fewer resources.

The priority international actions identified that relate to the recommendation to "Test, develop evidence, and share learning on policy and implementation" have all been completed. The specific policy dialogues and working group meetings are listed in Annex 2.

Some progress has been made against the recommendation to develop common metrics and indicators to track the adoption of agricultural solutions. A priority next year could include finalizing the FAO Agriculture Ecosystem-based Solutions Expert Working Group guidelines, promoting awareness and uptake of these guidelines, and developing guidelines for projects pertaining to aspects other than water management.

For the priority international actions relating to research and development, good progress has been made. In particular, the Global Research Alliance on Agricultural Greenhouse Gases (GRA) has contributed to activities of the Enteric Fermentation R&D Accelerator Innovation Sprint, which has made progress in several priority research areas, including funding the development of low-cost methane measurement, microbiome characterization, low-methane genetics, and vaccines.

Good progress has also been made toward recommendation A5, "Begin strategic dialogues on how to ensure international trade facilitates the transition to sustainable and resilient agricultural systems." Countries engaged with the Trade and Environmental Sustainability Structured Discussions (TESSD) to discuss potential positive and negative environmental effects of subsidies as well as related trade impacts, focusing on agricultural subsidies and subsidies related to the transition to a low-carbon economy. Going forward, the 76 countries that are members of the TESSD will address further types of subsidies and focus on identifying best practices and recommendations on how to enhance transparency. More could be done to discuss how the World Trade Organization (WTO) can promote and facilitate trade in agricultural technologies that are needed to meet international climate and environmental objectives.

> "For the priority international actions relating to research and development, good progress has been made.

5 Role of focus technologies

For the 2024 Agriculture Breakthrough Report, we selected deep dives into two subsectors of the agrifood system, namely reducing emissions from fertilizer (during both the production and the application stage) and reducing enteric methane emissions from livestock.

Agriculture, forestry, and land use (AFOLU) directly account for approximately 21 percent of GHG emissions (IPCC 2022). When we account for the food system as a whole, including post-production and processing phases, emissions from this sector are about one-third of global emissions (Costa Jr et al. 2022; Crippa et al. 2021). Of the total 21 percent emissions from AFOLU, the two top contributors are (i) emissions from livestock and manure (primarily of methane, CH_4) and (ii) emissions of nitrous oxide (N_2O) from fertilizer application.

Methane emissions account for 35 percent of agrifood system GHG emissions (expressed in CO_2e) consistently across developed and developing countries (Crippa et al. 2021), with livestock production being the most significant contributor. Indeed, livestock emissions from manure and enteric fermentation represent 32 percent of all global anthropogenic emissions of methane (Global Methane Assessment 2021).

Methane is an extremely powerful GHG, and the need for action is urgent. Unlike carbon dioxide (CO_2), which stays in the atmosphere for hundreds of years, methane starts breaking down quickly, with most of it gone after a decade. This means cutting methane emissions now can rapidly reduce the rate of warming in the near term.

The synthetic nitrogen (N) fertilizer supply chain is responsible for approximately 10.6 percent of agricultural emissions, or 2.6 percent of global GHG emissions (Menegat 2022). Of this, synthetic N fertilizer production accounts for 38.8 percent of total synthetic N fertilizer-associated emissions, while field emissions account for 58.6 percent and transportation accounts for the remaining 2.6 percent (Menegat 2022). Reducing emissions from fertilizer production and application can therefore contribute to climate change mitigation efforts while maintaining crop yields.

Given the importance of these two subsectors, this year's report focuses on concrete recommendations for reducing emissions from the livestock and fertilizer sectors. Emissions from enteric fermentation have been rising (Figure 3), as have emissions from fertilizer production and fertilizer application (Figure 4), showing that, like the rest of the sector, emissions-reduction goals are not being met.

Figure 3. GHG emissions in Gt CO_2e from enteric emissions (Source: FAO 2024).

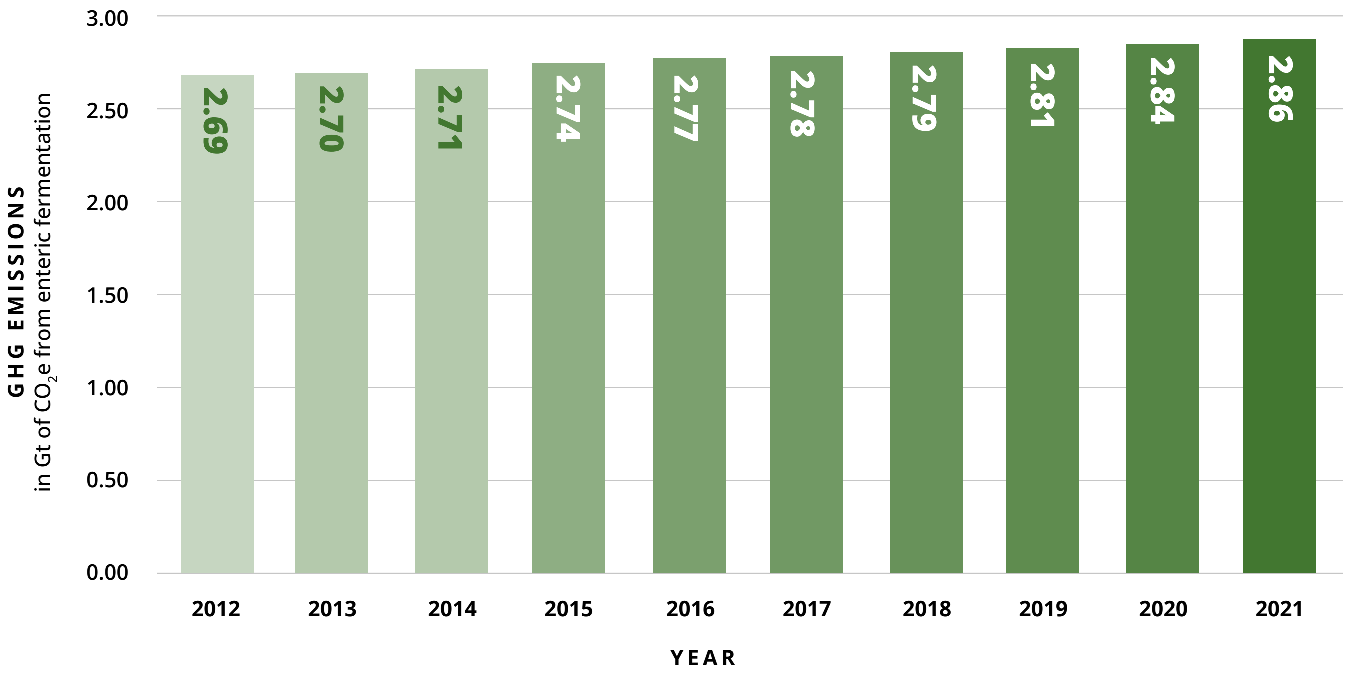
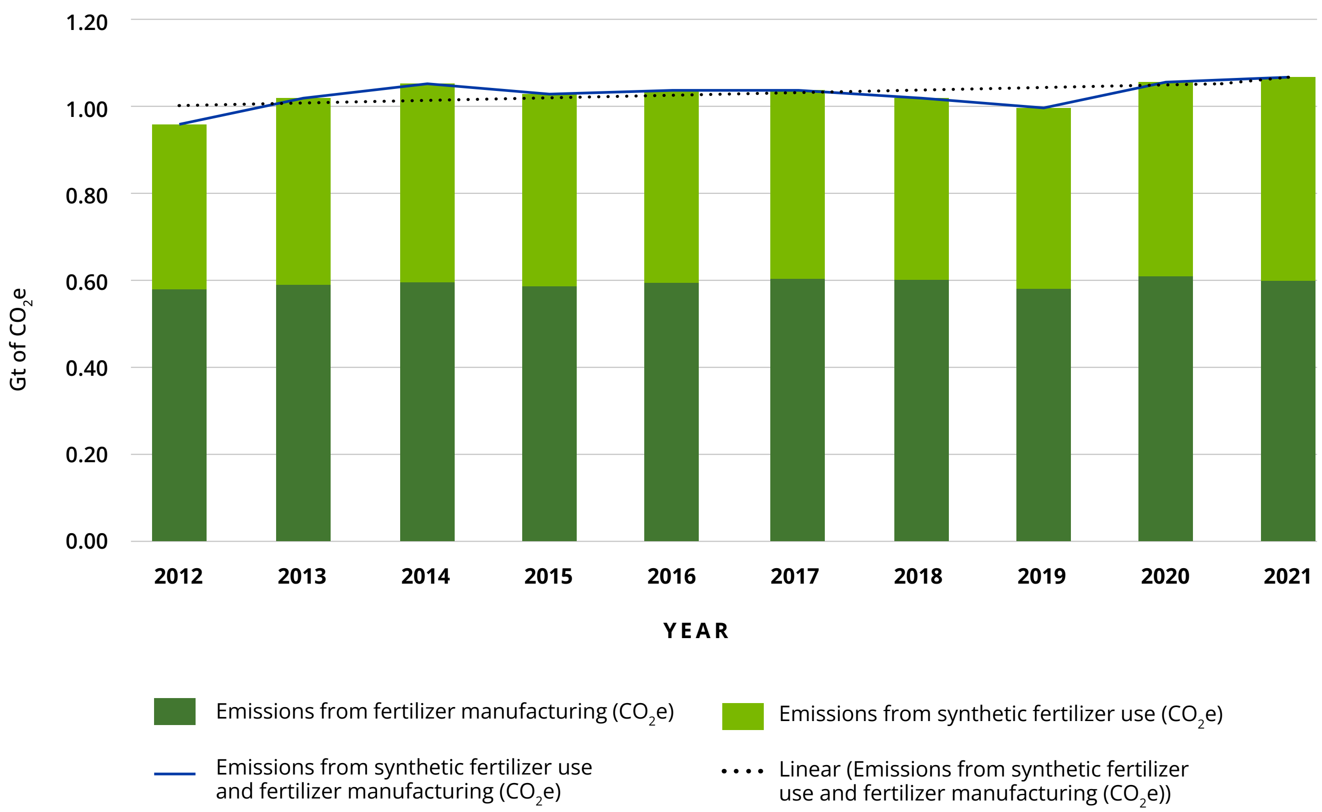


Figure 4. GHG emissions in Gt CO_2e from fertilizer manufacturing and application (Source: FAO 2024).



In this report, we focus on specific technologies within these two subsectors of our agrifood system: enteric methane emissions from livestock and emissions from fertilizer production and application. More specifically, we look at technologies that improve animal feed efficiency and reduce emissions through low-methane forages and methane inhibitors. Regarding fertilizers, we focus on green ammonia, as it has the potential to eliminate all CO_2 emissions from ammonia production, but also refer to other ways of reducing emissions from ammonia production. A further appeal of green ammonia is that it could offer a more decentralized ammonia production, with reduced transportation costs, and make fertilizers less prone to trade or supply shocks. Considering that the bulk of GHGs derive from the application of fertilizers in the field, we also point to the scaling up of site-specific nutrient management (SSNM) as a way to reduce these (see section 6 for deep dives on each of these technologies).

The decision to focus on these technologies was based on their current technological maturity, financial viability, and broad geographic applicability, and it was vetted via several stakeholder consultations.

5.1 An update on international actions in the livestock subsector

The Global Methane Pledge was launched at COP26 by the European Union and the United States and aims to catalyze the rapid reduction of methane emissions from a variety of sectors, including from food and agriculture. The Pledge target is for participants to collectively reduce global methane emissions by 30 percent from 2020 levels by 2030. As of March 2024, participants numbered 158 countries, representing just over 50 percent of global anthropogenic methane emissions.

Over the last year, several initiatives have enhanced research and development in the livestock sector. For example, the ongoing work of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases (GRA) and the FAO's Livestock Environment Assessment and Performance Partnership (LEAP). In 2023, the Global Methane Hub launched the Enteric Fermentation R&D Accelerator Initiative at COP28 with US$200 million in funding, supported by philanthropic organizations, making it the largest globally coordinated research effort into livestock methane reduction. Research being supported by the Global Methane Hub includes the development of a feed ration optimization tool (with University of California Davis), co-design of a Global Grazing Management Platform with WWF, and High Potential Shrub Forage Banks to reduce emissions with CIRAD. Public policy and finance projects include IFAD's Reducing Agricultural Methane Programme (RAMP), support to the World Bank for establishing the Global Methane Reduction Platform for Development (CH4D), and the Parliamentary Action Platform in Latin America.

Bezos Earth Fund also provided a US$5 million grant to Wageningen University in collaboration with the Global Methane Hub, as part of the abovementioned Enteric Fermentation R&D Accelerator, initiating a global effort to select breeding cows with low methane emissions specifically. Following COP28, there have been several conferences and awareness-raising events that have aimed to strengthen international partnerships, including the Launch of the Expert Panel on Livestock Methane, which works together voluntarily to bring the latest peer-reviewed science to the media and policy debate about livestock and climate change.

Dairy Methane Action Alliance was launched at COP28 and is a global initiative to accelerate food industry action to reduce dairy methane emissions. Signatory companies commit to annually account for and publicly disclose methane emissions within their dairy supply chains. International events featuring knowledge sharing on reducing livestock emissions include Global Methane Forum Switzerland 2024, CAAC Conference Nairobi 2024, and a series of dialogues held by the Environmental Defense Fund. The Global Methane Pledge was launched at COP26 in 2021 to catalyze action to reduce methane emissions.

The dairy sector is driving collective change through implementation programs and quantifying the impact via the Dairy Sustainability Framework. These are collaborative programs that encourage solutions for a diverse industry including GHG accounting, animal nutrition, dairy processing, and research on global warming potential, carbon credits, and cattle health.

In 2023, at COP28, the FAO launched Pathways Towards Lower Emissions: A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems, and an accompanying analysis: Methane Emissions in Livestock and Rice Systems (FAO 2023). In July 2024, the CAAC-facilitated Technology and Economic Assessment Panel (TEAP), co-led by Ireland and Senegal, released a key report that spotlights two promising and immediately implementable solutions for methane mitigation relevant to reducing livestock emissions in low- and middle-income countries: digital agricultural services, and results-based payments.

Within the last year, some governments have shifted to a more regulatory approach, albeit with financial disincentives/incentives. The first scheme to tax methane emissions from livestock was launched by Denmark in June 2024; however, the majority of the scheme will not be implemented until 2030. The New Zealand government has meanwhile committed to a fair and sustainable pricing system for on-farm emissions by 2030. Garnering support from a diverse coalition, including agricultural and environmental groups alike, the US Enteric Methane Innovation Tools for Lower Emissions and Sustainable Stock (EMIT LESS) Act seeks to reduce enteric methane by integrating emissions-reduction practices into US Department of Agriculture conservation programs and providing financial incentives to farmers that voluntarily adopt them. However, there is limited inter-government policy coordination on the global deployment of methane-reducing technologies. The dairy industry is quantifying its environmental, social, and economic impact via the Dairy Sustainability Framework, with one aim being to reduce its carbon footprint.

5.2 An update on international actions in the fertilizer subsector

Turning to international actions pertaining to fertilizers, there are no binding international agreements in place, but at the United Nations Environmental Assembly (UNEA) in 2019, a resolution on sustainable nitrogen management was adopted, followed by a second resolution in March 2022 (UNEA-5.2) encouraging Member States to accelerate actions to significantly reduce nitrogen waste globally by 2030 through the improvement of sustainable nitrogen management and to share information on national action plans, as available, according to national circumstances. That same year, 15 UNEP Member States launched the Colombo Declaration on Sustainable Nitrogen Management, which called upon countries to develop national roadmaps for sustainable nitrogen management with an ambition to halve (economywide) nitrogen waste by 2030. Funded by the Global Environment Facility, UNEP undertook a project being implemented by the International Nitrogen Initiative to pursue an International Nitrogen Management System.

The FAO published in 2019 The International Code of Conduct for the Sustainable Use and Management of Fertilizers (including mineral, synthetic and organic sources). The Code addresses the judicious use and management of fertilizers to prevent inappropriate use, underuse, and overuse. It serves to help ensure global food production and food security while maintaining soil fertility, ecosystem services, and protecting the environment, and to optimize the effective and efficient use of fertilizers to meet agricultural demands while minimizing nutrient losses to the environment, which contribute to soil and water pollution, ammonia volatilization, GHG emission, and other nutrient loss mechanisms. The Code of Conduct was developed to support the 2017 Voluntary Guidelines on Sustainable Soil Management, which included nutrient imbalances and soil pollution, involving fertilizer applications that can be excessive, insufficient, or polluting.

A number of other initiatives to mention include the launch by the US at COP27 of the Global Fertilizer Challenge, which supports innovative research, demonstrations, and training to help countries with high fertilizer usage and loss adopt nutrient management and alternative fertilizers. The Efficient Fertilizer Consortium was established by the Foundation for Food & Agricultural Research as a multistakeholder collaboration to invest in solutions to reduce the environmental impacts from fertilizer use. Legislative actions at the regional and national level include the longstanding EU Nitrates Directive, which is targeted at reducing leaching of nitrogen compounds from mineral fertilizer and manure into groundwater. The EU Farm to Fork Strategy aims for a reduction in nutrient losses from mineral and organic fertilizers of at least 50 percent by 2030. The EU's Common Agricultural Policy for 2023 to 2027 also includes eco schemes, rewarding farmers who reduce use of inorganic fertilizers and engage in other practices that help to contribute to sustainable nutrient management. In the Netherlands, a plan to cut nitrogen emissions by half (mainly from manure from livestock operations) to become compliant with EU law led to widespread farmer protests and a political crisis. Undeterred by developments in the Netherlands, Denmark is proposing a scheme that requires landowners to pay a levy based on emissions from livestock and fertilizer.

The Croplands Research Group of the Global Research Alliance on Greenhouse Gases established the Integrated Nutrient Management Network, which involves 20 researchers from 10 countries undertaking research on effective practices to lower GHGs from fertilizer application. Multistakeholder partnerships such as the Coalition of Action 4 Soil Health (CA4SH) and the FAO Global Soil Partnership (GSP) International Network on Soil Fertility and Fertilizers (INSOILFER) promote sustainable soil management and sustainable fertilization practices.

On the fertilizer production side, the International Energy Agency put out an Ammonia Technology Roadmap in 2021. Referring to the industry's then current trajectory as "unsustainable," it set forth two pathways for future ammonia production – leading to 70 percent and 95 percent CO_2 emissions reduction by 2050.

> "The EU Farm to Fork Strategy aims for a reduction in nutrient losses from mineral and organic fertilizers of at least 50 percent by 2030.

Of note on the production side is also the European Union Emissions Trading System, which has announced its plan to phase out free emissions allowances, which had been granted to European fertilizer producers in order to not penalize them vis-à-vis imported fertilizers, starting in 2026 and running until 2034, while simultaneously introducing a Carbon Border Adjustment Mechanism.

Decarbonization of fertilizer production and use is also a top priority of the International Fertilizer Association (IFA), a body representing the global fertilizer value chain. It monitors developments in low-carbon ammonia production capacity, raises awareness in the industry of technological developments and financial opportunities in this space, monitors (together with FAO) cropland nitrogen use efficiency (NUE) globally, supports the development of databases for supporting decision-making support tools for efficient fertilizer use, and supports development of innovative solutions by engaging with AgTech and Climate Tech startups.

6 Deep dive into four technological areas

6.1 Reducing enteric methane emissions via methane inhibitors

The use of methane inhibitor feed additives has the potential to lower methane emissions from livestock and is thus one tool to slow the progression of climate change in the short term. Long-term emissions reductions will necessitate less food loss and waste and a protein transition: both shifting toward more sustainably produced livestock products, and also dietary shifts to lower meat consumption – where this is very high – and greater consumption of both plant and alternative proteins, which have less environmental impacts.

Global methane emissions need to be greatly reduced to limit warming to less than 1.5°C or 2°C, but unlike carbon dioxide do not need to fall to zero by 2050 (IPCC 2022). Climate Action Tracker has set the 1.5°C-aligned target for agricultural production emissions as a 39 percent absolute reduction by 2050 relative to 2017 (Climate Action Tracker 2023). They note that, as global population and food demand are projected to continue growing through at least the year 2050, the emissions intensity of agricultural production per calorie of food produced will need to fall even faster than this 39 percent absolute target.[2] Rapidly reducing the emissions intensity of livestock is therefore critical by 2030.

One way to reduce methane emissions from the digestive process of ruminant animals, such as cattle, sheep, and goats, is through the development of feed additives that lower emissions by interfering in the processes that generate methane.

The methane reduction potential of 3-NOP

Life-cycle assessments over eight years or so have confirmed the sustained inhibitory effect of 3-NOP on methane production (Alemu et al. 2021). Applied in small doses (60 to 200 mg/kg of dry matter intake [DMI], on average, 3-NOP decreases methane production in beef and dairy by 30 percent (Dijkstra et al. 2018; Kim et al. 2020), although decreases of 80 percent or greater have been obtained in some studies with high-concentrate diets (Yu et al. 2021). The effect of 3-NOP on methane production is related to its level of inclusion in the diet (Yu et al. 2021) and diet composition (Kebreab et al. 2023; Dijkstra et al. 2018; Yu et al. 2021; Hristov et al. 2023). Some studies have observed a slight decline in effectiveness over time (Hristov et al. 2023). No residues occur in animal products (Hegarty et al. 2021) and no effects have been observed on manure emissions (Beauchemin et al. 2021).

A one-year trial has confirmed the long-term effectiveness of Bovaer® (Gastelen et al. 2024), while further long-term studies are ongoing to address the concern of a potential reduction in the efficacy of methane inhibitors as rumen microbes adapt to supplementation over the long term (Expert Panel on Livestock Methane, 2024). Studies show that diet can have an impact on this efficacy (Gastelen et al. 2024). A partial life-cycle assessment of 3-NOP use on a dairy herd in California found a 13.7 percent reduction in GHG footprint of the herd (Feng and Kebreab 2020). Further studies in Australia and Canada state the carbon footprint of emissions associated with 3-NOP production can be up to 23 percent less than without these methane inhibitors (Hegarty et al. 2021). The use of 3-NOP, as with other methane inhibitors, can be easily combined with other mitigation strategies, providing opportunities to raise livestock productivity simultaneously.

2. It is also important to note that, despite increased agricultural productivity over the last several decades, hunger and malnutrition in all forms have continued to rise. Cropland expansion has primarily not been for direct food consumption but for biofuel and livestock feed. In addition, a third of all food produced is lost or wasted. Addressing these three trends will do more to meet growing food demand than solely focusing on agricultural productivity.

Feed additives that lower rumen methane production fit two classifications:

- Rumen modifiers that modify the rumen microbial ecosystem with some resulting in >30 percent methane-reducing efficacy.
- Compounds that inhibit methane-producing enzymes reduce methane production by 30–95 percent, depending on type, dose, and duration of use (Cornell CALS 2024).

In the last five years, there has been significant progress in the development of methane inhibitors (GRA 2021), including 3-nitrooxypropanol (3-NOP, trade name Bovaer®) made by DSM (dsm-firmenich), Agolin Ruminant® (a blend of plant extracts), Enterix™ (garlic and citrus extracts), SilvAir™ (a nitrate-based additive), and red seaweed extracts produced by CH_4 Global, Symbrosia, FutureFeed, Dulabio, and Volta Greentech.

The most significant development and market capture is DSM's 3-NOP or Bovaer®. First approved for commercial use by Brazilian and Chilean authorities in 2021, it received EU market approval for dairy cows in 2022, and as of June 2024 is approved and available in 65 countries, including the recent additions of the USA and Canada. Dsm-firmenich is rapidly scaling up production capacity for Bovaer®, with a major new production facility underway in Scotland. Global commitments to reducing emissions have contributed to the relatively fast-track development of such solutions and the swift uptake of such products.

6.1.1 Barriers to uptake of methane inhibitors

6.1.1.1 Insufficient investment and global cross-sector collaboration in product development

Product development has mainly relied on the private sector to cover costs, and it will likely take more than five years before products are broadly adopted if left to market forces. Insufficient production capacity is also a risk, even if new factories are under development. Though farmers are willing to test the use of methane inhibitors, few are reporting on GHG emissions reductions. Science-based protocols such as MiLCA (developed by the dairy sector to include the use of methane inhibitors and other mitigation technologies into life-cycle assessments) can encourage such reporting.

Additionally, there is limited technical know-how on using methane inhibitors and their impact, and there is a disconnect between commercial sector development of products and the farmers who should be using them. Briefs produced by organizations such as the Global Research Alliance (GRA), e.g., on feed additives, help to raise awareness. Still, national producer bodies in high-income countries are increasingly asking for more information on methane inhibitors, including how they work, animal and food safety, and optimal feeding regimes (e.g., UK NFU 2023). In low- to middle-income countries (LMICs), there is increasing interest but a lack of access due to high costs (Gomaa and Gado 2021; Maze et al. 2024).

6.1.1.2 Higher production costs when using methane inhibitors reduce incentives for adoption

The cost of methane inhibitors can be restrictive and limits their use to more high-value intensive beef production. Bovaer® has an additional cost of US$0.30 per head per day, and as there is little to no significant impact on the growth of animal or milk production, it increases the cost per unit of animal product, estimated around 5 percent extra feed cost for a dairy cow per day (Newbold et al. 2022).

Enteric methane reduction technologies are largely developed through collaborations between the private sector, including dairy producer companies and users, e.g., Danone, supported by GMH and Nestle. There are some emerging schemes, e.g., the US Department of Agriculture awarding US$89 million in funding to support farms using technologies like Bovaer® as incentives. However, there is ambiguity in carbon accounting rules that allow baselines to be moved to capture carbon payment advantages, reducing trust in carbon accounting processes. Feed additives are not yet included in the agriculture criteria of Climate Bonds Initiative's and most national taxonomies, which would make them eligible for green finance. A feed additive calculator tool (FACT) considers carbon prices, costs, and animal performance impacts to advise farmers on the use of feed additives. Feed additive inclusion in carbon offsetting protocols should continue to be explored, as should feed additive – and more specifically methane inhibitor – deployment subsidies.

6.1.1.3 Insufficient information on meat and dairy consumers' willingness to pay

There is limited information about consumers' willingness to pay extra for products that directly reduce livestock methane emissions, including those that have used methane inhibitors. Those who are willing to pay extra for sustainable beef or other livestock may not be so willing to pay for meat produced using methane inhibitors. Resistance to change, concern about food safety aspects, or skepticism about the effectiveness of mitigation strategies such as feed additives can impede the uptake of technologies (Katare et al. 2023). Increasing consumer willingness to pay for such products requires investment both in terms of research and in raising awareness, as well as labeling. Meanwhile, some retailers are working to reduce the emissions intensity of their product range, including by working with suppliers to shift to using feed additives, but consumer-level awareness remains limited.

6.1.1.4 Current inappropriateness for extensive pasture-based systems

Methane inhibitors, including the current launch form of 3-NOP (Bovaer®), are most suited to livestock systems reliant on total mixed ration/feedlot and partial mixed ration plus partial grazing (6–8 hours per day) where exact feed control is possible. This has led to skepticism on the global potential of methane inhibitors by such as the FAO (FAO 2023a) because of the limited transferability to LMICs where extensive grazing systems are the norm. It is estimated that >50 percent of livestock intake is supplied by grazing (Wolf et al. 2021) and 9 percent of the world's beef comes from grazing systems (de Haan et al. 1997).

Research is underway to develop slow-release methane inhibitors, including by DSM, working with companies such as Marks and Spencer UK. Recently, the Government of Ireland announced €1.4 million funding to progress government and academia collaboration on methane abatement in grazing systems. This includes trials on slow-release methane inhibitors called RumenGlas in beef and dairy cattle.

6.1.1.5 Limited collaboration on regulatory frameworks, sharing of data and metrics, reporting, and verification (MRV)

National regulatory frameworks governing the use of environmental (including methane) inhibitors is varied and ranges from none or very little regulation, to strict regulatory requirements. Regulation often depends on how these substances are used and integrated into feeding regimes (FAO 2023). At present there is no food safety maximum residue limit established by the Codex Alimentarius Commission to facilitate trade in products produced using the substances. New Zealand is promoting awareness raising within the Codex on environmental inhibitors and has convened two side events at relevant Codex committees to discuss the issues.

There has been an increase in standards and certifications by the private sector, such as from Cargill, causing confusion among producers and other value chain actors, and risking the credibility of a sector already under pressure. Some governments are also developing certifications; for example, Argentinian research institutes are working with the private sector and the International Environmental Product Declaration System to develop a national certification scheme (Winters 2024).

Delays in approvals can also be inhibiting. In the US, new drug approval processes can take 5 to 10 years and cost an average of US$30 million (EDF 2022). The EU provides an expedited regulatory approval process for products with a significant positive environmental benefit. Still, unless products are approved within the next two years and marketed immediately, they are unlikely to contribute to 2030 targets, emphasizing the need for an expedited process. Global regulatory frameworks that could speed up the approval processes and provide greater consistency across countries, together with more transparency and opportunities for monitoring, such as user payments, are needed. Within these regulatory frameworks, necessary standards and certifications can be developed.

Additionally, various data gaps hinder understanding of methane inhibitors' progress and impact (Climate Policy Initiative 2023)[3]. Tracking investments in methane abatement has been taken up by the Climate Policy Initiative (Landscape of Methane Abatement Finance) but is not split by technology use, and projects are in the early stages. Tools such as GLEAM cannot quantify the impact of mitigation options. An improved GLEAM-X will offer various on-demand simulations under different scenarios while increasing access to more users. Data needs to be constantly updated, and farmers want farm-specific data to guide and monitor their production decisions. Information on feed, including embedded emissions numbers and feeding regimes, is limited.

3. For example, an inability to quantify and link methane reductions to tracked finance (particularly complex with livestock due to fragmented value chains), limitations in assessing intent during screening process, a lack of standardized reporting, difficulty distinguishing methane finance from usual expenditure, variations in reporting practices across sources and entities, and a lack of alignment in investment needs assessment.

Global databases such as the Global Feed LCA database are consolidating some of this information. However, not all companies are willing to share necessary information. Developments such as a methodology for quantifying the reduction of methane emissions, including the application of feed supplements by Global Standard for the Global Goals, are in progress.

There is also a need to track technology uptake, with greater opportunity for tracking potential emissions reductions. Consistency of methodology for mitigation technologies is important for inclusion in countries' national inventories. Most LMICs have significant data gaps across the board.

6.2 Reducing enteric methane emissions via low-methane forages

Improved forages, including legumes and grasses enriched with anti-methanogenic compounds (AMC) such as tannins, saponins, or flavonoids, offer a potentially cost-effective solution for reducing methane production from livestock systems, both pastoral and cut-and-carry (Bratta 2015), while meeting the increasing demand for livestock-based products (FAO 2018). These compounds can reduce methane emissions by inhibiting methanogenic microbes in the rumen and altering the microbial community to favor alternative fermentation pathways that produce less methane without negatively affecting animal productivity (Molina-Botero et al. 2024; Arndt et al. 2022).

Therefore, access to high-yielding, tropically adapted forages with methane mitigation potential can improve animal nutrition in grassland systems, leading to increased productivity and significantly lower total GHG emissions and emission intensities (emissions per unit of product) as well as increased incomes for farmers and pastoralists in developing nations (Arango et al. 2022; Costa Jr et al. 2022; Leyte et al. 2021; Seketeme et al. 2022; Paul et al. 2020).

Improved forages are already a part, though limited, of livestock systems in the global South (Fuglie et al. 2021). Adoption is particularly high in Latin America, with Brazil leading the way (Fuglie et al. 2021), and significant productivity benefits have been observed in areas that have adopted improved forages. Due to their adaptability to diverse agroecological conditions, the adoption and scaling of low-methane forage options could be facilitated. In an optimistic scenario, large-scale adoption of low-methane forages would reduce dairy animal methane emissions by 35 percent (Arndt et al. 2022).

In addition to reducing enteric methane emissions, these innovations could have several other environmental benefits, including improved carbon sequestration in soil and enhanced soil health with the potential for developing land-based GHG removal projects (Costa Jr et al. 2022; Paul et al. 2020).

Ongoing research and development (R&D) efforts through international cooperation on forage-based livestock production aim to identify and develop high-yielding, nutritious, and drought-tolerant forages to improve animal productivity and decrease enteric methane emissions through enriched AMC. These R&D efforts are focusing on three key areas:

- Identifying and promoting low-methane forage legumes with high levels of AMC directly into ruminant production systems in the global South.
- Breeding a methane emission-reducing trait into widely used forage grass cultivars and major cereals with feed value from silage and crop residues, either through conventional or precision breeding (gene-editing) approaches.
- Enabling deployment of low-methane forages into forage-based livestock (ruminant) systems in the global South.

International and national forage genebanks conserve seeds representing very high biodiversity. Most of the forage germplasm accessions conserved in these genebanks are legumes, and the low-methane legumes identified from these genebanks are ready for immediate use. The discovery of AMCs in low-methane legumes can pave the way for increasing AMC content in widely sown forage grasses through breeding or gene editing. International cooperation through the Global Methane Hub, including funding from the Bill & Melinda Gates Foundation and the Bezos Earth Fund, has enabled new investments in this area.

These grasses and fodder crops could, therefore, offer the potential for additional farmer income and increased milk availability while protecting the environment and posing no environmental risks (Fuglie et al. 2021). For example, smallholder dairy farmers in Africa will benefit from new forage varieties of nutritious forage grasses that increase productivity, improve soil health, and sequester carbon in deep soil layers.

Many countries are including food and feed management as a priority issue in their Nationally Determined Contributions (NDCs). There is a need to raise awareness of the potential of this low-methane forage technology.

6.2.1 Barriers to uptake of low-methane forages

Major barriers to the widespread adoption of improved forage systems, which would also need to be addressed with low-methane forages, include upfront costs when adopting new technology. These costs include: (i) working capital for planting improved forages and purchasing animals; (ii) capital investments in infrastructure, such as corrals, barns, and fencing; and (iii) opportunity costs of land and labor, which could limit adoption by some resource-poor farmers (Micol and Costa Jr 2023; White et al. 2013).

Farmers may also require training to effectively manage these new systems. Resistance from older farmers, who may be less open to changing traditional practices, further complicates the situation but could be addressed through farmer participatory research. Effective implementation requires supportive public policies and agreements between governments, which are often lacking (Micol and Costa Jr 2023; White et al. 2013).

Climate finance (e.g., grants, credit lines, impact funds, and carbon markets) can support de-risking investments and incentivize farmers (World Bank, 2021). Demonstrating and testing livestock productivity gains is essential to convince stakeholders of the benefits of adopting low-methane forages. Finally, solutions need to be tailored to specific regions – e.g., for adaptation to local soil and weather conditions – as a one-size-fits-all approach will not be effective.

6.3 Reducing emissions from fertilizer production via green ammonia

Global ammonia production in 2023 was estimated at around 183.6 million tons (IFA 2024). Ammonia manufacturing is estimated to contribute around 2 percent of global GHG emissions, emitting more than 2.4 tons of $C0_2$ per metric ton of ammonia produced, four times as much as per ton of cement production.

Ammonia is a key building block of many nitrogenous fertilizers. Around 85 percent of all ammonia is used to produce synthetic fertilizers (IRENA Innovation Outlook Renewable Ammonia 2022) but ammonia also has many uses in the petrochemical industry, i.e., plastic, paper, pharmaceuticals, and refrigerants, and the scope for mitigation thus goes beyond the agrifood sector.

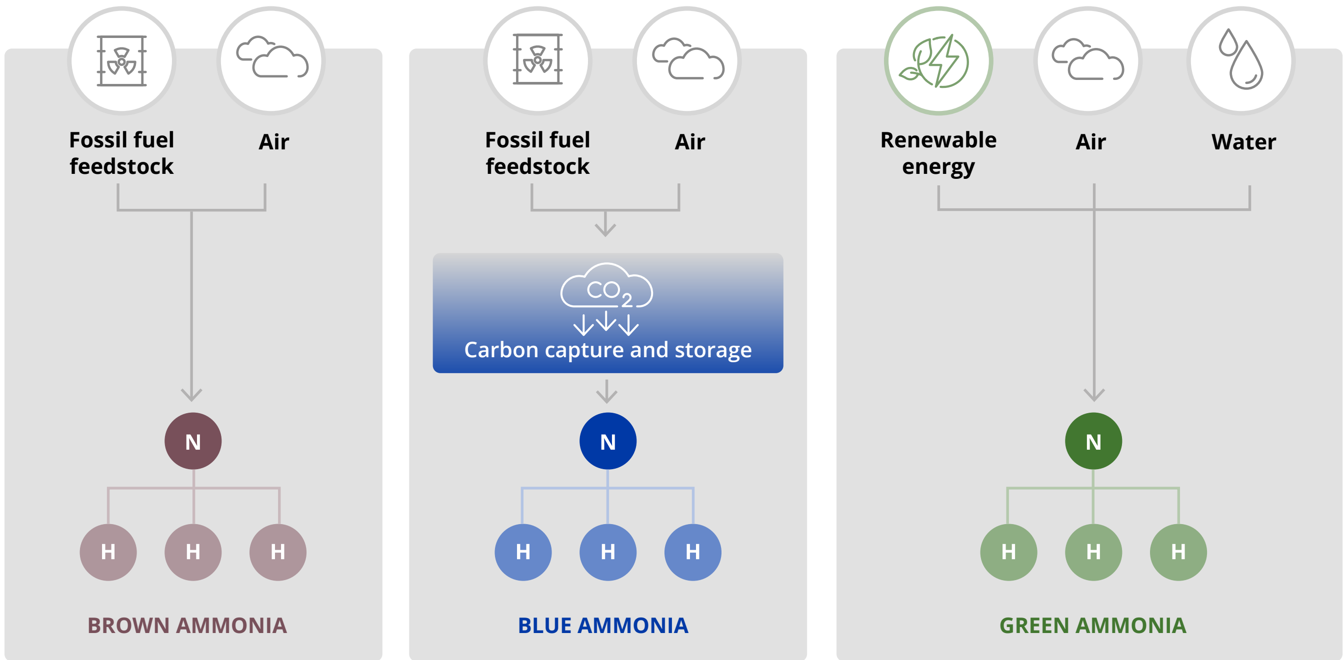
The Haber–Bosch process, invented in the early 1900s, remains the primary source of ammonia from hydrogen and nitrogen. The process is highly energy intensive: it relies on hydrocarbons as a *feedstock* for producing hydrogen through steam methane reforming (or coal gasification), as well as for subsequently ***powering the energy-intensive ammonia synthesis*** process, which fixes nitrogen from the air with the hydrogen obtained from steam methane reforming (called brown ammonia).

Some improvements in the energy efficiency of ammonia production have occurred over time and can continue to occur, with newer plants and improved catalysts coming online. Phasing out ammonia production from coal (still widely used in some countries, with China being the main user) and relying only on natural gas would also reduce emissions. However, the process remains highly energy intensive. Carbon capture, utilization, and storage (CCUS) in fossil fuel-based ammonia production can lead to much more significant emissions reductions, with the Rocky Mountain Institute indicating that emissions can be reduced by more than 90 percent. So-called "blue ammonia" production combines large-scale ammonia production with CCUS and has been demonstrated to work worldwide. It is used or planned to be used by some of the major international fertilizer producers.

Zero carbon ammonia, called "green ammonia," uses renewable energy to power electrolysis to produce hydrogen from water (replacing the steam methane reforming process based on hydrocarbon feedstocks) and the subsequent ammonia synthesis. Figure 5 depicts the difference in production processes of three different types of ammonia. Numerous green ammonia pilot plants have been set up, and the first large-scale green ammonia facilities may come online in the next five years. Startup companies have developed smaller, modular green nitrogen fertilizer plants, which are vastly less expensive than large plants and could facilitate decentralized nitrogen fertilizer production.

There are multiple green ammonia pilot plants and some larger-scale commercial plants now up and running. Between 2024 and 2028, the International Fertilizer Association (IFA) are tracking 55.9 Mt of ammonia capacity, of which 8.9 Mt is expected to be commissioned using electrolysis as feedstock (that is, green ammonia). According to their forecasts, the volume of projects under development but not yet expected to commission

Figure 5. Production process of brown, blue, and green ammonia (Source: https://www.nature.com/articles/s44160-023-00362-y).



in the next five years is much larger, including 146 Mt of green ammonia capacity that could be commissioned after 2028 (IFA Short-Term Fertilizer Outlook 2023–2024).

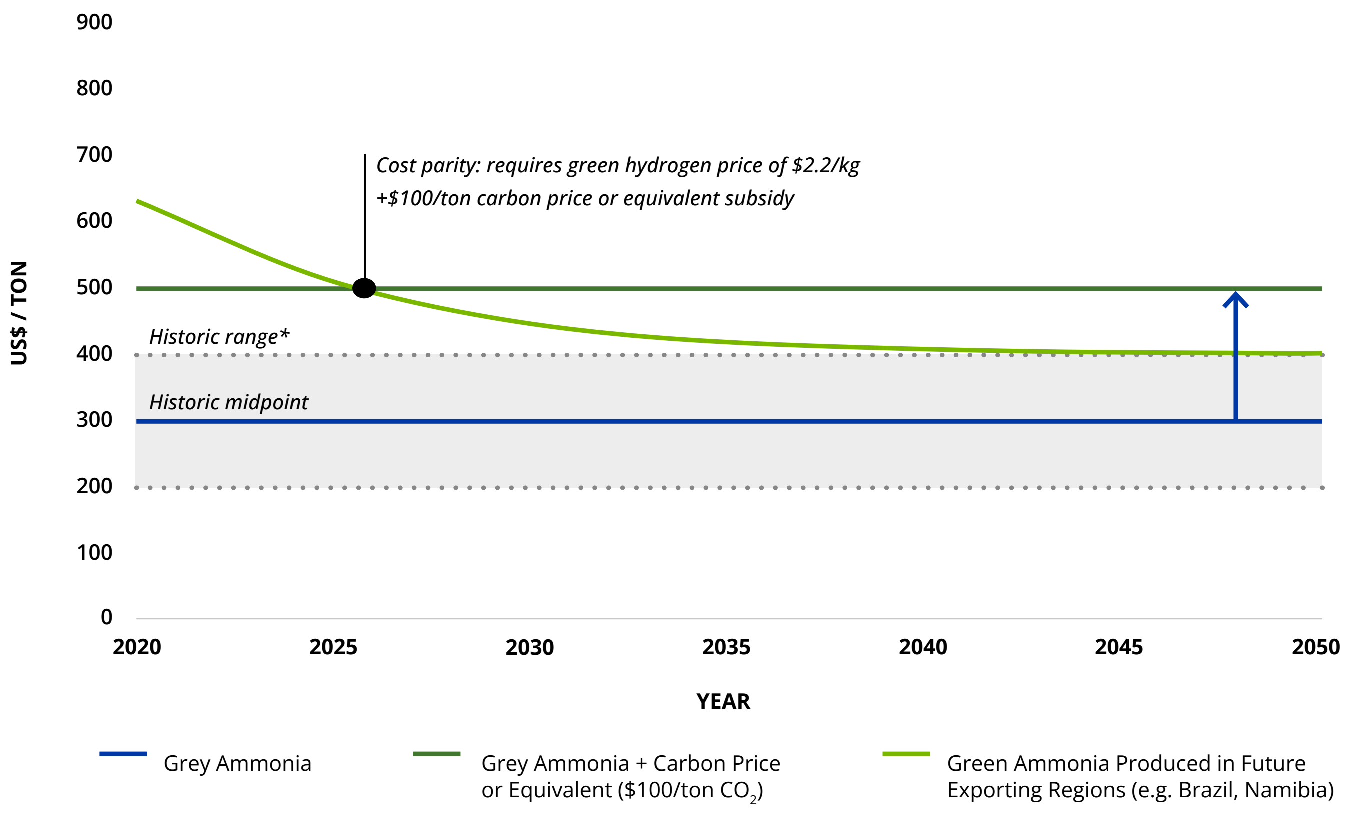
Green ammonia's commercial viability today is linked to the price of renewable energy, the capital cost of electrolysis, and government incentives. In some regions, the pricing point can be competitive, but the continued technological improvements in this space, coupled with the falling costs of electrolyzers and solar and wind power, will drive toward more general price competitiveness (Way 2022). Similarly, if the price of hydrocarbons continues to increase relative to renewable energy, the point of relative parity can be reached significantly faster (see Figure 6). Decentralized green ammonia production using affordable modular equipment can already be financially viable in geographies with low-cost renewable resource availability, due to savings from foregone transportation costs. A recent study found that the cost-competitiveness from green ammonia production is further enhanced by minimizing supply chain disruptions and estimates that it could become cost-competitive for up to 96 percent of global ammonia demand by 2030.

Further, green ammonia can be produced anywhere in the world with access to renewable energy. Today, most of the world's ammonia is produced in countries with access to affordable natural gas or coal, resulting in highly centralized production centers. Fertilizer prices are tied to the cost of natural gas, and gas and fertilizer supply shocks reverberate worldwide, as last witnessed in the aftermath of the 2022 invasion of Ukraine. More ammonia plants using renewable energy would make the sector less prone to shocks.

Smaller-scale green ammonia could be particularly relevant in developing countries and areas where transport and storage are costly or complex, particularly landlocked countries. Moreover, smaller plants can more easily be financed than large-scale ammonia plants.

Relatedly, green ammonia will also help to decarbonize the shipping industry, which could potentially result in an increase of up to five times in the world ammonia market. It could lead to a tighter global ammonia market, potentially affecting the nitrogen fertilizer supply of smallholder farmers. Development of small-scale decentralized nitrogen production is an option to minimize this risk.

Figure 6. Projected cost per ton of grey versus green ammonia for fertilizer production (Source: Mission Possible Partnership (2022), Making 1.5-Aligned Ammonia Possible).



6.3.1 Barriers to scaling of green ammonia

Considering that green ammonia today only makes up a tiny percentage of overall ammonia produced, it requires a hard look at possible barriers to adoption.

The cost of producing green ammonia is still higher than for blue ammonia (especially in the US, where blue ammonia is heavily subsidized by the Inflation Reduction Act), although over time, with an ongoing decrease in the price of renewable energy and electrolyzers, this barrier could be overcome. Given that between 10 and 15 percent of global ammonia production is traded, countries may be hesitant to impose regulations mandating emissions reductions so as not to disadvantage their producers (noting that the EU only recently announced a plan to gradually phase out free emission allowances provided to EU fertilizer producers, but at the same time introducing carbon border tax adjustments).

The fact that blue ammonia (traditional ammonia production with CCUS) has gained significant traction is unsurprising since CCUS is a feasible option for large-scale, existing fertilizer producers with access to carbon dioxide sequestration infrastructure and, importantly, often also government financial support. Considering that fertilizer plants can operate for more than 40 years, operators of existing plants may not feel incentivized to switch to green ammonia production, preferring instead to pursue blue ammonia because it does not require any changes to their existing plants and operations, except for securing access to carbon dioxide sequestration infrastructure. The established large-scale ammonia producers may therefore find blue ammonia a preferred approach to lowering their carbon footprint: a large push on blue ammonia could make investments in green ammonia harder to come by, and relatively smaller green ammonia producers may find it difficult to compete with large industrial players using CCUS. On the other hand, larger industry players may find it advantageous to invest in or construct new green ammonia plants so as to further lower their remaining carbon footprint from producing blue ammonia. In addition, if green ammonia becomes the preferred fuel of the shipping industry (a quite likely scenario beyond 2030), the new capacity needed will all be green ammonia. Some countries are also investing in green ammonia to substitute imports: for example, Morocco, to substitute their large ammonia imports to produce ammonium phosphates as well as fertilizers containing nitrogen, phosphorus, and sulfur (NPS) and nitrogen, phosphorus, and potassium (NPK).

There are also important safety and security considerations in the ammonia production process, storage, and transport, as well as at the level of on-farm application of fertilizers. Anhydrous ammonia, the end product of green ammonia plants, requires careful handling and specialized equipment for transportation and application at the farm level for safety reasons. Today, it is widely used mainly in the United States and parts of Canada and Brazil. Ammonia codes of practice and government regulations can overcome such risks, as can proper equipment, but this implies additional costs for value chain players, including farmers, and smallholder producers in particular. In fact, for safety reasons, direct use of anhydrous ammonia by smallholders is not an option. Safety concerns can also be mitigated by converting anhydrous ammonia into aqueous ammonia (ammonia water solution), which is not an overly complex process, but transporting aqueous ammonia is not cost-effective. Converting ammonia into stable products such as urea, ammonium nitrate, ammonium sulfate, or ammonium phosphate is another well-known strategy to facilitate the transport and use of nitrogenous fertilizers.

Urea remains the most widely used fertilizer worldwide. While urea is a derivative of ammonia, an external source of carbon dioxide is required to produce urea from ammonia (in traditional ammonia production, carbon dioxide is a byproduct of the steam reforming process, which can then be used in producing urea). Urea cannot be produced with green ammonia as there is no carbon dioxide byproduct, meaning the preferred nitrogen fertilizer used by farmers globally might no longer be available if there is a shift to green ammonia.

It is worth mentioning here that combining production of green nitrate using plasma technology to develop green ammonium nitrate holds the potential to be a zero carbon or close to zero carbon nitrogenous fertilizer.

Balanced fertilization is important for agricultural productivity, soil health, and sustainability, and further processing would be required to produce multi-nutrient fertilizers (nitrogen, phosphorous, potassium, and other micronutrients). These considerations imply that setting up green ammonia plants alone is not sufficient, and additional processes and costs would be required to provide fertilizer products that farmers prefer and that provide for more balanced plant nutrition.

6.4 Reducing emissions from fertilizer application via site-specific nutrient management (SSNM)

Fertilizer application on the field is responsible for two-thirds of the emissions from fertilizers, while fertilizer production contributes to one-third of the emissions. Site-specific nutrient management (SSNM) is an approach to achieve increased NUE through the precise application of balanced fertilizer inputs, leading to higher crop productivity and other environmental benefits (Dobermann and White 1998; Dobermann et al. 2002), and thereby to reduce emissions from field application. SSNM is an important axis of integrated soil fertility management (ISFM). ISFM aims at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity, and is built on two pillars: (i) a set of generic soil fertility management practices that necessarily include the use of fertilizer, organic inputs, improved germplasm, good agronomic practices, and other amendments such as lime and (ii) combining these practices with the knowledge on how to adapt them to local conditions (Vanlauwe et al. 2010).

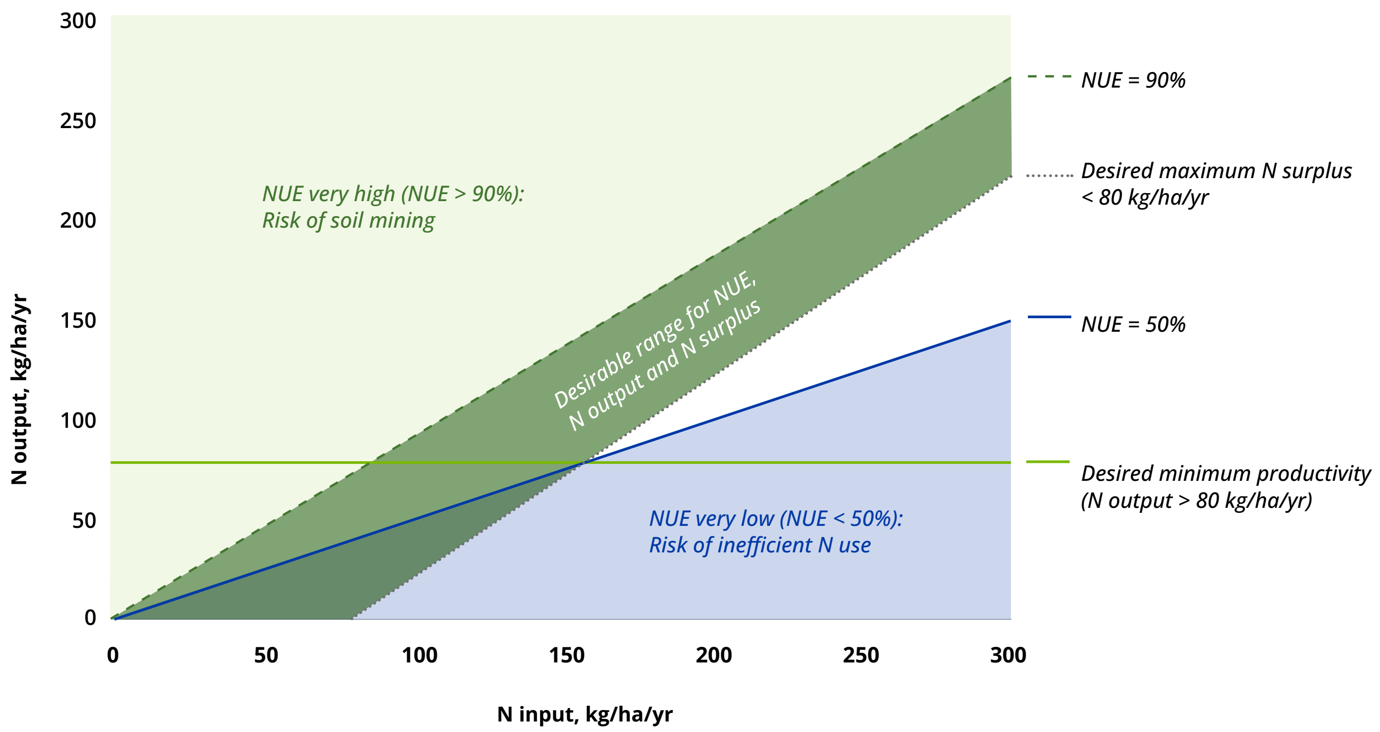
A recent review (Dreyfus et al. 2023) based on published literature has provided compelling evidence on the technical maturity, financial viability, and broad applicability of SSNM across geographies. Further, in a meta-analysis covering 11 countries in Africa and Asia, Chivenge et al. (2021) demonstrated that SSNM increased yields by 12 percent for maize, rice, and wheat and led to a reduction in nitrogen application by 10 percent and an increase in profitability of 15 percent at farm level.

Supported by advances in big data science, crop modeling, and geospatial analytics, and with the increasing availability of remote sensing products, SSNM is guided by an array of decision support tools that allows guidance on the right source at the correct rate, right time, and in the right place, i.e., the 4Rs (Johnston and Bruulsema 2014) to achieve site-specific nutrient management, which includes maximizing the use efficiency of nitrogen. The right fertilizer time means applying the fertilizer at the right stage of crop growth for improved uptake. It may also entail split application during the season to avoid losses. The right fertilizer place entails applying the fertilizer in the right location considering, for example, topography and the crop's growth habit and also foliar versus soil application. In some cases, incorporation of fertilizer in the soil is recommended to avoid losses. Efficiently used fertilizer will ensure that available nitrogen in the soil is minimal, thus reducing the potential for nitrous oxide emissions (Tian et al. 2020).

GHG emissions reductions are also observed with the implementation of SSNM. For instance, SSNM recommendations reduced nitrogen fertilizer application by 40 percent and reduced nitrous oxide emissions by 66.8 percent in cotton production in India (Gupta et al. 2022). Similarly, Pampolino et al. (2007) reported that reductions in fertilizer use with SSNM averaged 10 percent in the Philippines and 14 percent in Vietnam. Additional evidence from on-farm trials in India showed higher yields and lower total estimated GHG emissions per ha under SSNM compared with farmer practice (Sapkota et al. 2014; Zhang et al. 2018). Nitrogen application rate was reduced by 24 percent and nitrous oxide emissions by 19 percent under maize production in China over a nine-year experiment (Huang et al. 2021).

In the Indo-Gangetic Plains, current evidence suggests using Nutrient Expert® (see below) reduces the nitrogen application rate by 18 percent with SSNM (Sapkota et al. 2021). However, when SSNM tools recommend increased fertilizer input due to low baseline conditions (as in much of Africa), an increase in GHG emissions will ensue (Leitner et al. 2020), and is acceptable given the very low historical emissions from the continent, where improving food security is a higher priority (Falconnier et al. 2023). That said, the land-sparing effect of closing yield gaps can counteract the effect of the increased emissions from agricultural inputs; Africa is the region that witnessed the largest cropland expansion between 2003 and 2019 and is also projected to have the largest agricultural expansion to 2050 (Potapov et al. 2022).

Figure 7. EU Nitrogen Expert Panel (2015) Nitrogen Use Efficiency (NUE) – and indicator for the utilization of nitrogen in agriculture and food systems (Source: Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands).



Various decision support tools exist to support SSNM. Some examples include:

- Nutrient Expert®, which is an interactive, computer-based decision support tool that estimates the attainable yield for a farmer's field based on the growing conditions, determines the nutrient balance in the cropping system based on yield and fertilizer/manure applied in the previous crop, and combines such information with expected nitrogen, phosphorus, and potassium response in target fields to generate location-specific nutrient recommendations.
- Crop Manager is a computer- and mobile phone-based application that provides small-scale rice, rice-wheat, and maize farmers with site- and season-specific recommendations for fertilizer applications focused on Asia.
- RiceAdvice is an Android-based decision support tool that provides farmers with pre-season field-specific management guidelines for African rice production systems. The tool has guidelines on target yield, nutrient management, crop calendar, and good agricultural practices.
- AKILIMO provides evidence-based agronomy solutions at scale, addressing major agronomic decisions, applying state-of-the-art data analytics, implementing advanced statistics, mechanistic and empirical methods, and optimizing for profitability for cassava.
- AgWise is a framework that applies process-based crop models, machine learning algorithms, cutting-edge statistical models, and remote sensing technologies to address challenges enhancing food security, climate resilience, and sustainable resource use to improve soil health. AgWise is being integrated into different partner solutions through application programming interfaces (APIs).
- The Environmental Defense Fund (EDF) N Balance model: The model helps to calculate the N balance (N added minus N removed) and shows the amount of N left over and at risk of being lost to the environment. The model can be applied broadly across all crops in temperate climates, regardless of soil type or N source, including synthetic and organic N fertilizer

6.4.1 Barriers to adoption of SSNM

SSNM decision support tools are heavily dependent on data availability. The lack of standardized and open data hinders the application of big data science to decision support tools with sufficient accuracy/resolution, especially in low- and middle-income countries. The accuracy of these tools needs to be further improved to minimize the risk of under- or non-performance, as the performance of these tools is strongly related to data quality and availability.

There is limited bundling of decision support tools with other agro-inputs (e.g., seeds, mechanization), limiting the achievement of agronomic gains in terms of yields and other key performance indicators, which in turn makes it harder for farmers to adopt these tools.

The adoption of SSNM is closely tied to the availability of advanced agricultural technologies including digital decision support tools. The cost of these, coupled with limited digital literacy, can be prohibitive for many smallholder farmers.

The lack of sustainable business models, including revenue generation options, limits the sustainable deployment of decision support tools at a scale. There are limited financing models to fund the hosting data and tools. Notably, in LMICs, the cost and accessibility of fertilizer are major issues, and strong input markets are a prerequisite for SSNM, along with the availability of local nutrient sources such as manure and compost.

There are inadequate policies and incentives to encourage and facilitate the development of digital tools to support SSNM. Government support and subsidies can play a crucial role in promoting these practices.

The initial investment in SSNM decision tools such as GPS-guided machinery, plus fluctuating crop and fertilizer market prices, reduces the cost-effectiveness and incentives for adoption.

7 Recommendations for international collaborative action

A1. Increased international climate finance should be directed toward unlocking the potential of sustainable agricultural technologies and approaches with proven effectiveness

Given this year's focus on reducing enteric methane emissions from livestock (though feed additives and low-methane forages) and reducing emissions from fertilizer production, via green ammonia and field application (SSNM), we recommend the following actions:

- Undertake efforts to ensure that green ammonia, feed additives (methane inhibitors), enhanced efficiency fertilizers, and low-methane forages can benefit from green finance, particularly in high-income countries, by being included in Climate Bonds Initiative (CBI) Agriculture Criteria (under efforts to reduce GHG emissions, where the science has been proven), which in turn will make these investments a part of country taxonomies and regions, e.g., the EU taxonomy of permissible activities for green finance. Inclusion in CBI criteria and national/regional taxonomies would lead to both demand creation spurring innovations and making these investments eligible for green finance. Similarly, when an industry is involved (e.g., for green ammonia and methane inhibitors), setting emissions-reduction targets under the Science-based Target Initiatives (SbTI) will also spur investments in innovations geared toward emissions reductions in this sector.
- Encourage multilateral development banks and donor countries to provide concessional loans and grants for the two technologies that are particularly appropriate for LMICs, namely low-methane forages and fertilizer application with SSNM, where there are large opportunities for productivity improvement as well as reducing emissions, but upfront costs are a barrier to action. Such financing will also incentivize the development and scaling of carbon markets and impact financing with the private sector, create special credit lines within banking systems, and establish blended finance mechanisms that combine public and private investments.
- Seek and obtain international consensus on "repurposing" the more than US$600 billion spent annually by governments on agricultural support. Considering that much of the support provided to agriculture is market distorting and incentivizes unsustainable production, public support should be redirected. One of the most promising shifts in such investments would be an increase in funding for R&D dedicated to productivity-enhancing and emissions-reducing technologies. Investment in agricultural R&D is one of the most effective ways to reduce poverty and holds significant potential for addressing climate change.
- The Breakthrough Agenda should make stronger linkages to G7 and G20 agendas where parallel decisions are taking place to direct investment for broader development and environment objectives in agrifood systems. For example, the findings from this report should be presented to the G20 Task Force for a Global Alliance Against Hunger and Poverty to demonstrate that there are scalable technologies that can meet both hunger and climate goals simultaneously and those need financial support for upscaling.

"…setting emissions-reduction targets under the Science-based Target Initiatives (SbTI) will also spur investments in innovations geared toward emissions reductions in this sector.

A2. Promote international sharing of knowledge on policy and implementation to create demand for and facilitate faster uptake of proven technologies

This year's recommendation focuses on demand creation for innovations in low-emission technologies through the following concrete actions:

- Encourage governments to sign a NUE Pledge along the lines of the Methane Pledge. Such an NUE pledge will help reduce nitrous oxide emissions, as nitrogenous fertilizer is the top source of nitrous oxide emissions. NUE measures how much of the nitrogen applied is taken up by crops. Optimal NUE is between 75 and 90 percent (anything above 90 percent indicates that nutrients are mined from the soil because of insufficient nitrogen application) and will vary depending on soil conditions, weather and crop type (IFA 2022). On average, global NUE is estimated to be 55 percent, with wide geographic variations (FAO 2024). A pledge to reach a global NUE of 70 percent by 2030 is ambitious but feasible with appropriate policies and financial support (Zhang et al. 2015). IFA has set a similar target, but aimed at 2040 (IFA 2022). Once such a pledge is set, each country would need to look at how best to achieve this – in countries with NUE above 90 percent, more rather than less nitrogen would be required to reach optimal NUE. Such pledges, supported by appropriate policies, will generate demand for innovations to reduce nitrous oxide emissions and achieve optimum NUE, which will also help mobilize climate finance. This recommendation targets both production and use of fertilizers.
- Countries should work together within Codex Alimentarius of the FAO-WHO to establish a food safety maximum residue limit of inhibitor compounds in livestock products. Such standards will help facilitate the trade of products containing inhibitors.
- Countries should take advantage of the existing Methane Pledge and incentivize demand creation globally for methane inhibitors and low-methane forages through specific technology use pledges and targets. These will be supported by financial incentives including carbon offsetting and national tax incentives to encourage producer uptake of technologies and consumer purchase of low-methane dairy and meat. As supply increases and the enabling environment improves, regulation forcing use of these emission-reducing technologies can be considered.
- Countries should take advantage of existing platforms such as the World Bank and the UK Foreign, Commonwealth and Development Office (FCDO) facilitated Global Agriculture Policy Dialogues to engage in intensive exchanges of knowledge on questions such as which policies are most effective for encouraging and supporting farmers' adoption of SSNM and low-methane forages, to facilitate knowledge exchange and learning. Similarly, these Policy Dialogues should also engage with countries and the private sector to exchange best practices and barriers to a quicker transition to green ammonia and higher adoption of feed additives.

A3. Develop common metrics and indicators to track the adoption of sustainable agricultural solutions

These recommendations suggest concrete ways to develop standards, targets, metrics, and indicators that will spur innovations in reducing enteric methane emissions from livestock and reducing emissions from fertilizer production and field application.

Fertilizers remain crucial for food production and global food security. The move toward greener fertilizers through low-carbon production and innovative fertilizer solutions aimed at enhancing NUE would be encouraged by requirements for industry pledges coordinated across multiple countries and regions. Specifically, these actions can take the shape of the following:

- Fertilizer companies must be encouraged to expand their GHG accounting to include the GHG emitted as a result of fertilizer application in the field (so-called Scope 3 emissions). Greater scrutiny of Scope 3 emissions can incentivize greater efforts to reduce nitrous oxide emissions from fertilizer application and enhance NUE. For example, Nutrien, a Canadian producer of potash and nitrogen fertilizer, is already doing this through its Carbon Program and Sustainable Nitrogen Outcomes program, and could serve as a model for other fertilizer companies seeking to understand and measure their Scope 3 emissions while helping growers reduce theirs.
- Governments could set deployment targets for existing and planned ammonia facilities. Examples of such targets could be 30 percent of existing ammonia production facilities installing carbon capture and storage (CCS) infrastructure for capturing carbon dioxide by 2030, and mandating that all new ammonia plants set up henceforward produce green ammonia. This can be achieved through technology-forcing policies (following the example of the Zero Emission Vehicle Program of California). This approach would incentivize industry players to move toward green ammonia production, though the private sector could also lead by example and set their own targets for CCS on their green ammonia facilities.
- Governments should also set a target of deploying 80 GW of new renewables-powered electrolyzers, of which Green Hydrogen Catapult members have already committed 45 GW. To further stimulate increased low-carbon ammonia production, the industry should undertake a complete reporting structure or certification mechanism that will report the full production carbon dioxide equivalent footprint and the captured carbon of an associated ton.

Specific recommendations for the livestock sector (methane inhibitors) for common metrics and indicators include the following:

- Set up clear globally aligned regulatory frameworks and MRV requirements to ensure a fair playing field and credible GHG emission reporting to speed up scaling of methane inhibitors (feed supplements), which in the short term can deliver immediate and significant methane reductions in zero-grazing and grazing with feed supplementation livestock production systems. Further, we recommend collaboration among research institutions and international organizations (e.g., OECD, ISO) and the private sector and carbon market standards (e.g., Verra, Gold Standard, Plan Vivo) to develop and standardize cost-effective methodologies for evaluating standards for feed additives and low-methane forages across diverse socioeconomic and environmental contexts.

Overall, and of relevance to all low-emission agricultural technologies considered in this report and elsewhere, we recommend that:

- Countries should come together and develop "Codex Planetarius" along the lines of Codex Alimentarius, which develops internationally agreed food safety standards. This idea was first developed by The Markets Institute at WWF, who launched a two-year proof of concept to assess the overall viability of this concept at COP28 (Clay 2023). Codex Planetarius can set forth criteria for crops and animal-derived products (that is, end products for consumption) to be certified as compatible with international climate targets, which will then incentivize all actors in the value chain, such as fertilizer and livestock producers, to adopt low-emission and climate-compatible technologies. Adherence to Codex Alimentarius confers a presumption of compliance with the World Trade Organization (WTO) Agreement on Sanitary and Phytosanitary Measures. Similarly, adherence to Codex Planetarius could confer similar presumption of compliance with the WTO.

A4. Increase support for food system research, development, and demonstration (RD&D) to support the uptake and scaling of promising technologies and approaches

Given this year's focus on fertilizer and livestock emissions reductions, specific recommendations on RD&D are as follows:

- Strengthen global knowledge exchange by expanding and strengthening The Nutrient Management Network of the Global Research Alliance on Agricultural Greenhouse Gases. This recommendation is particularly suitable for reducing emissions from the field application of fertilizer. This would involve assembling scientific expertise in novel science areas; supporting the development of evidence-based decision support tools (e.g., artificial intelligence) and their translation into forms that diverse stakeholders can interact with; organizing science communication around best practices for nitrogen fertilizer recommendations and facilitating multistakeholder interactions (to exchange data, information, and lessons learned and use such coordination functions to provide technical support to fertilizer-related investment programs). Such decision support tools should account for local soil and weather conditions when determining the right application rates.
- The fertilizer industry must be mandated by governments to report on R&D spending and commit to higher spending levels on green innovations, as it is increasingly evident that increased spending on R&D underpins innovation. Currently, there are no estimates of R&D spending by the fertilizer industry.
- Taking advantage of the active livestock research group of the Global Research Alliance on Agricultural Greenhouse Gases (GRA), invest in the continued research on methane-inhibiting technologies and low-methane forages by documenting early success stories and increasing farmer options and market competition. Capacity building is required to undertake necessary research, particularly in LMICs. The GRA can also act as a global platform to centralize and facilitate greater sharing of data between public, commercial, scientific, and regulatory bodies for the development of standardized, science-based approaches to measuring product impacts, global standards, metrics, and accounting for methane reduction including through the use of methane inhibitors, low-methane forages, and other such technologies. Initiatives such as the Global Methane Hub's Enteric Methane R&D Accelerator provide opportunities for global research collaboration.

A5. International efforts should work toward enabling the private sector to scale up solutions through global markets

We recommend:

- Reviving the moribund WTO Agreement on Environmental Goods and Services. Plurilateral negotiations for an Environmental Goods Agreement were started in 2014 to promote trade in essential environmental products, i.e., solar panels and wind turbines. In future negotiations, the list of green goods and services should include low-carbon fertilizers like green ammonia and livestock feed additives, among other emissions-reducing technologies. This would involve advocating for harmonized standards, certifications, and accounting methodologies with multilateral organizations such as WTO and various UN agencies and is related to the previous recommendation on Codex Planetarius, where such standards would be agreed upon, and once agreed upon, products that meet the Codex Planetarius would be conferred the presumption of compliance by the WTO, facilitating trade in green and low-emission agricultural products.

8 Conclusion

The breakthrough objective for the food and agriculture sector is to make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030 (IEA 2022).

It is well known that the agrifood sector is particularly vulnerable to climate change, with losses and damages occurring throughout the value chain. To minimize the impacts of climate change, it is crucial to stay within the 1.5°C to 2°C temperature goals set by the Paris Agreement. Achieving this requires immediate and deep reductions in emissions across all sectors, including the agrifood sector, which accounts for almost one-third of all GHG emissions (IPCC 2023), within a broader framework of just transitions that safeguards the interests of smallholder producers, particularly those in the global South who are most at risk.

The agriculture chapter of the 2022 Breakthrough Agenda Report identified seven technological areas and approaches to achieve breakthroughs in the agriculture sector. The agriculture chapter of the 2023 Breakthrough Agenda Report provided detailed analysis of these seven technological areas and approaches by documenting the latest scientific advancements in each one and evaluating how these fare across the four principles outlined earlier. This year, we have focused on a subset of the agrifood system, exploring four concrete technologies and approaches for reducing emissions from fertilizers and limiting enteric emissions from livestock. The reason for focusing on a subset of technologies and approaches was to tackle the two most important sources of GHG emissions within the agrifood sector, that is, fertilizers and livestock, and to provide recommendations for international action that are more granular in nature and can be easily translated into high impact international priority action for 2024–2025.

The recommendations, like those of the previous two years, focus on five sets of actions, namely, finance; knowledge sharing; metrics and standards; support for RD&D; and trade and markets, with specific and detailed recommendations for sub-actions under each of these. Put together, these recommendations, when translated into appropriate high-ambition priority actions in 2024–2025, will set in motion actions that can potentially contribute to emissions reductions, particularly in high-income countries, and emissions reductions without compromising food and nutrition security, particularly in LMIC contexts. The key to achieving the desired results will depend on the ambition set in the priority actions based on the recommendations of this report. While translating the recommendations to priority actions, it will be important to remember that agriculture and agrifood systems are hugely diverse and none of the recommendations can be applied in a uniform way. Therefore, the focus must be on triggers that incentivize movement toward low-emission food systems, with each country charting its own roadmap based on its own unique national circumstances.

Finally, the report mapped the extensive landscape of existing efforts at international cooperative actions aligned to the four breakthrough goals, and the center stage that agrifood systems are taking within the climate discussions. These show that there is increasing intention to align actions in this sector toward a low-emissions pathway, but also that those actions are falling short of what is needed. More ambitious actions to take food systems to a low-emissions pathway, without compromising the food and nutrition security of the most vulnerable, needs to be at the top of the agenda in the next few years.

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Annex 1: Non-exhaustive list of international initiatives across the agrifood system, 2021–2024

Annex 2: Progress against priority actions formulated in the 2023 Agriculture Breakthrough Agenda Report


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