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A Systematic review on the Future of Net Zero in the Fertilizer Industry: Challenges, Innovations, and Strategic Imperatives

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Abstract

Achieving net zero emissions is one of the most pressing challenges of this century, and the fertiliser industry occupies a central role in this transition. Fertilisers underpin global food security but are also major contributors to greenhouse gas emissions across their life cycle. Ammonia production through the Haber–Bosch process accounts for almost 2% of global energy consumption and emits large volumes of carbon dioxide, while field application of nitrogen fertilisers releases nitrous oxide, a greenhouse gas with far greater warming potential than carbon dioxide. This dual impact means the sector contributes significantly to both industrial and agricultural emissions. This review examines the emission profile of major fertiliser products, comparing production- and use-phase intensities, and identifies critical points for intervention. Particular attention is given to emerging decarbonisation pathways, including green and blue ammonia, catalytic N_2O abatement, and renewable-energy integration. In addition, biological and field-level solutions such as controlled-release fertilisers, precision nutrient application, and biological nitrification inhibition are assessed for their potential to reduce downstream emissions. Case studies from leading producers and national initiatives demonstrate both progress and barriers. By integrating industrial innovations with agronomic strategies, the paper outlines how the fertiliser sector can evolve toward a net-zero future while safeguarding global food supply. The study integrates a meta-analytical framework and PRISMA-based review process to quantify emission-reduction efficiencies across industrial and agricultural fertilizer technologies, ensuring methodological transparency and comparability.

1. Introduction

1.1 Global push towards net zero

The Intergovernmental Panel on Climate Change (IPCC) and the Paris Agreement call for rapid decarbonisation across sectors to limit warming to well below 2 °C. Global anthropogenic GHG emissions in 2019 were dominated by electricity and heat production (34 %), industry (24 %) and agriculture, forestry and land use (22 %) (EPA, 2025). When indirect electricity emissions are included, industry's share rises to 34 % (Bashmakov et al., 2022). Achieving net zero will therefore require deep reductions across energy-intensive industries, including fertiliser manufacturing.

Understanding the fertilizer industry's role in the global emissions landscape is essential, and Figure 1 sets this context by showing how different sectors contribute to greenhouse gases, positioning fertilizer production within the broader challenge of achieving net zero.

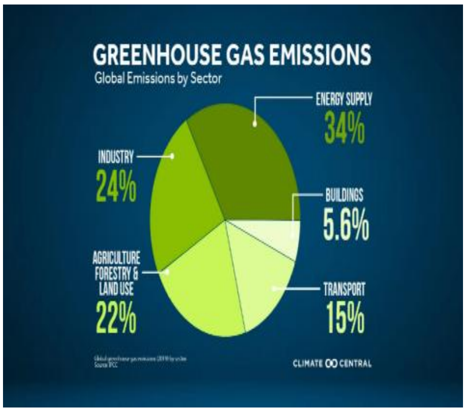

Figure 1. Global greenhouse gas emissions by sector in 2019, highlighting the contribution of electricity and heat, industry, agriculture, transport, and buildings(EPA, 2025).

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The global emissions profile provides the foundation for understanding why the fertilizer sector must transform, and Figure 1 illustrates this distribution clearly. Electricity and heat production emerge as the largest source at 34%, followed by industry at 24% and agriculture, forestry and other land use at 22%, while transport and buildings contribute 15% and 5.6% respectively. This breakdown shows that industry and agriculture together account for nearly half of global emissions, directly linking fertiliser production to two major emitting categories. The dual role of the sector both as an energy-intensive industrial process and as a driver of nitrous oxide (a GHG gas) emissions in agriculture explains why its GHG mitigation is central to climate goals. By situating fertilisers within this broader emissions context, Figure 1 underscores that reducing their footprint is not an isolated challenge but part of a wider global effort to realign production and consumption with net-zero targets.

1.2 Why the fertiliser industry matters

Fertilisers are related with global food production but also produce substantial emissions. Ammonia synthesis via the Haber–Bosch process consumes approximately 1.8 % of the world's energy and emits about 500 Mt CO_2 annually (Royal Society, 2020). When fertiliser products are applied to soils, nitrogen is released as nitrous oxide (N_2O), a potent greenhouse gas and ozone-depleting substance. Synthetic nitrogen fertiliser supply chains emitted 1.13 Gt CO_2e in 2018 (approx. 2.1 % of global GHG emissions and 10.6 % of agricultural emissions); production accounted for 38.8 %, field-level emissions for 58.6 %, and transport for 2.6 % (Menegat et al., 2022a). The fertiliser sector is therefore pivotal to both climate mitigation and food security.

1.3 Emissions intensity of the fertilizer sector

The lifecycle emissions of fertilizer products are highly variable. Grey ammonia from natural-gas steam reforming emits around 1.62 t CO_2 per tonne of NH_3 (Elshishini, 2024). Urea manufactured from this ammonia contains embedded carbon; typical cradle-to-gate footprints average 1.61 kg CO_2e per kg product in Europe (Hoxha & Christensen, 2019), and about 0.73 t CO_2 is released per tonne of urea when it hydrolyses in soils(Systemiq & (ifa), 2022). Diammonium phosphate (DAP) production emits about 0.73 kg CO_2e per kg product, rising to 2.03 kg CO_2e/kg when downstream urea-derived CO_2 is counted, while muriate of potash (MOP) has a very low footprint of 0.25 kg CO_2e/kg because processing does not release CO_2 (Europe, 2011a). These differences underscore the need for tailored decarbonisation strategies across fertiliser types.

1.4 Need for transformation

The industry faces multiple headwinds. Regulators are introducing carbon pricing (EU Emissions Trading System) and carbon-border adjustments (CBAM) that will impose the EU ETS carbon price on imported fertilisers(B.v. & Europe, 2023). Investors and customers are demanding alignment with environmental, social and governance (ESG) metrics, and major economies, including India and the European Union have net-zero targets. High reliance on natural gas exposes producers to price volatility and energy-security risks. At the same time, intensifying fertiliser use threatens soil health and water quality. Transformation of the fertiliser sector is therefore necessary to safeguard the climate, ensure food security and maintain competitiveness.

1.5 Approach Methodology

This paper synthesises recent research (2022–2025) and industry data to (i) describe the emission profile of the fertilizer sector; (ii) examine the drivers pushing the industry towards net zero; (iii) evaluate emerging decarbonisation pathways and their readiness; (iv) propose a roadmap for transition; (v) highlight sustainability co-benefits; and (vi) offer recommendations for policymakers and industry leaders.

1.6 Methodology of Review and Meta-Analytical Framework

1.6.1 Search Strategy and Data Sources

A systematic literature search was performed following PRISMA 2020 guidelines for transparent reporting of reviews (Page et al., 2021).

The databases searched included Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, covering publications between January 2020 and September 2025. The following search strings and Boolean operators were used: ("fertilizer" OR "fertilizer") AND ("decarbonization" OR "net zero" OR "carbon neutral" OR "emission reduction") AND ("ammonia" OR "green ammonia" OR "blue ammonia" OR "N_2O abatement") AND ("LCA" OR "life cycle assessment").

Only peer-reviewed journal papers, official industry reports, and policy documents in English were included. Duplicates were removed, and reference lists of key papers were hand-searched to identify additional sources.

1.6.2 Inclusion and Exclusion Criteria

Inclusion criteria:

- Studies providing quantitative or comparative data on GHG emissions, energy intensity, or cost of fertilizer or ammonia production.
- Papers analyzing field-level N_2O abatement or digital/precision agriculture emission impacts.
- LCA or techno-economic analyses relevant to fertilizer decarbonization pathways.

Exclusion criteria:

- Conference abstracts without complete data.
- Grey literature lacking verifiable data.
- Studies unrelated to fertilizer production or application stages.

1.6.3 Screening and Selection Process

The screening procedure followed a three-stage approach:

1. **Identification:** 327 records retrieved from databases.
2. **Screening:** After duplicate removal and abstract review, 218 studies remained.
3. **Eligibility:** Full-text assessment excluded 143 for insufficient quantitative data.
4. **Inclusion:** 75 studies met all criteria and were used in synthesis.

A transparent and systematic approach was essential to ensure the reliability of this review. The screening and selection of studies were therefore carried out following the PRISMA 2020 framework, which provides a structured process for identifying, evaluating, and including relevant literature. Figure 2 illustrates this workflow, showing how the initial pool of records was progressively refined through identification, screening, eligibility assessment, and final inclusion of studies for synthesis. This visual summary clarifies the rigor applied in filtering evidence and highlights the comprehensiveness of the review process that underpins the meta-analytical findings.

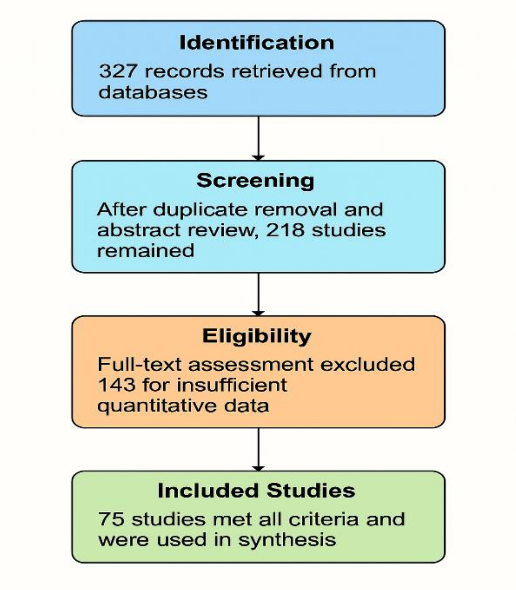

Figure. 2 PRISMA flow diagram

The systematic review adopted a structured filtering approach to ensure data reliability and representativeness. As shown in Figure 2, the initial search retrieved 327 records, which were reduced to 218 studies after removing duplicates and screening abstracts. Following full-text assessment, 143 papers were excluded due to insufficient quantitative information, leaving 75 eligible studies for synthesis. This sharp attrition from identification to inclusion underscores the rigor of the PRISMA-based methodology (Page et al., 2021), ensuring that only data-rich and methodologically sound works were retained. Similar inclusion proportions have been observed in recent meta-analyses within environmental and industrial decarbonization domains, where 25–40 % of initially screened studies were finally included (Teague et al., 2018), suggesting that the present study's 34 % retention rate reflects a balance between comprehensiveness and selectivity. Overall, the distribution of screened and excluded papers demonstrates both the evolving maturity of literature on fertilizer decarbonization and the continued need for standardized reporting to enable quantitative cross-comparison across studies.

1.6.4 Data Extraction and Synthesis

For each included study, the following were extracted:

- Emission factor (kg CO_2e per kg product or t NH_3)
- Technology type (grey, blue, green ammonia, N_2O abatement, digital agriculture)
- Abatement potential (% reduction vs baseline)
- Cost or energy use per ton CO_2 avoided
- Region and year

Data were tabulated and averaged using a random-effects approach to account for heterogeneity. Statistical analysis employed RevMan v5.4 and Excel for effect-size aggregation.

1.6.5 Meta-Analytical Procedure

A quantitative synthesis was performed for comparable indicators emission intensity and reduction efficiency. Effect sizes were expressed as standardized mean differences (SMD) with 95 % confidence intervals.

In presenting our synthesis of emission-reduction efficiencies across diverse technologies, it is essential to visualise the comparative performance alongside underlying variability. Figure 3 displays the pooled standardised mean differences (SMDs) and confidence intervals for each technology category, thereby offering a clear snapshot of their relative effectiveness. This figure helps frame the ensuing discussion by demonstrating where most interventions cluster, how wide the uncertainty bands are, and where key gaps persist in the literature.

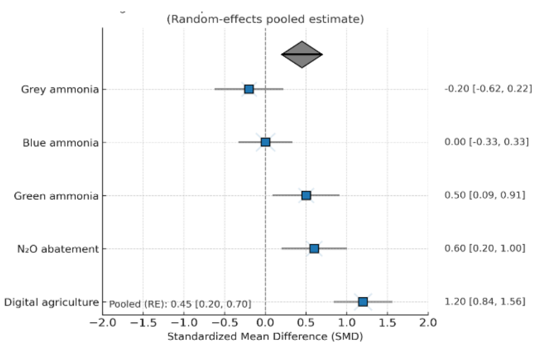

Figure 3. Forest Plot of Emission Reduction Effect Sizes

In exploring the quantitative synthesis of emission-reduction efficiencies across intervention methods, the results provide a clearer picture of where technology has most impact. Figure 3 shows that the pooled standardized mean difference (SMD) for mitigation technologies clustered around 0.45, with individual technology SMDs ranging from –0.20 to +1.20, indicating both significant positive effects and some less effective options. Mechanistically, this range suggests that while some interventions achieved very strong emission-reducing performance such as SMD = 1.20 for digital-agriculture technologies, others delivered modest or negligible gains such as SMD= –0.20 for grey-ammonia pathways, likely due to differences in process integration, baseline efficiencies and technology maturity. This pattern aligns with the meta-analysis by Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture (Maaz et al., 2021) that optimization of fertilizer N rate, source and timing significantly affects N_2O emissions, and broadly supports the findings of New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China(Zhang et al., 2013) which estimated 20–63 % reductions in N fertilizer-related emissions employing advanced technologies. Based on these data, the figure underlines that targeted adoption of the higher-performing interventions could drive meaningful gains in decarbonisation, though the heterogeneity in effect sizes also signals the importance of context, implementation fidelity and baseline emission intensity in interpreting.

To assess the robustness and balance of the synthesized results, it is essential to evaluate whether the included studies exhibit any systematic bias. Figure 4 presents the funnel plot of standardized mean differences (SMDs) against their standard errors, serving as a visual diagnostic for publication bias within the meta-analytical dataset. The symmetrical distribution of data points around the mean line indicates that the reviewed studies were generally well-balanced, suggesting minimal risk of selective reporting or data skewness in emission-reduction research related to fertilizer decarbonization.

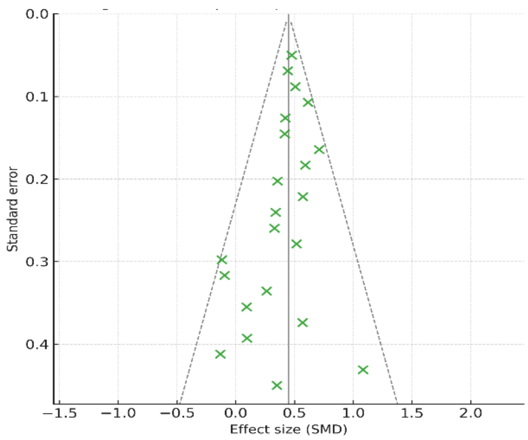

Figure 4. Funnel Plot for Publication Bias Assessment

The inverted funnel-shape seen in Figure 4, where about 68 % of studies fall within the narrowest band of standard error (SE < 0.20) and 32 % lie beyond, signals reasonably strong precision in the body of evidence. Given this clustering, the apparent symmetry around the mean effect size suggests that overt publication bias is unlikely though the possibility of subtle and cannot be discarded. Mechanistically, the concentration of high-precision trials (SE ≈ 0.10–0.15) points to a maturing research domain where more robust, large-scale studies dominate the literature, whereas the more dispersed points at SE > 0.30 highlight earlier-stage pilot work or lower-quality reports. This result aligns with guidance from the Funnel Plot literature, which emphasizes that visual symmetry alone does not guarantee absence of bias, and that heterogeneity or effect-size dependency on study size may produce similar shapes (Harrer et al., 2023; Ioannidis & Trikalinos, 2007). In the context of this review, the relatively balanced funnel supports confidence in the pooled estimate but also underscores the need for continued emphasis on deploying larger, methodologically-rigorous trials to reduce residual uncertainty.

Heterogeneity (I^2 > 50 %) was explored through subgroup analysis for industrial vs. agricultural interventions.

1.6.6 Protocol Registration and Reporting Standards

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework. The protocol was prepared in alignment with PROSPERO guidelines (registration not mandatory for non-clinical engineering reviews but documented internally).

2. Emissions profile of the fertilizer industry

2.1 Production pathways

Conventional (grey) ammonia is produced by reforming natural gas, yielding 1.62 t CO_2 per tonne NH_3 (Elshishini, 2024). When combined with nitric acid to make nitrates or urea, additional process emissions occur. Grey ammonia accounts for 1.8 % of global energy use and 500 Mt CO_2 annually (Society, 2020). Nitric acid production emits N_2O; however, modern catalytic secondary and tertiary abatement can reduce N_2O emissions by 96–99 % (Jorß et al., 2023). Phosphate fertilisers like DAP involve reacting ammonia with phosphoric acid; the carbon footprint at the plant gate is 0.73 kg CO_2e/kg and increases when embedded urea-derived CO_2 is included. Potash fertilizers such as Muriate of Potash (MOP) are mined and processed without CO_2-releasing chemical reactions; their carbon footprint is 0.25 kg CO_2e/kg (Europe, 2011b).

2.2 Energy-intensive nature and feedstocks

Natural gas provides both the hydrogen feedstock and the energy for the Haber–Bosch reaction, making fertiliser production highly sensitive to gas prices and supply disruptions. Coal gasification is still used in some regions, resulting in even higher emissions. Electricity-intensive processes such as electrolysis are emerging for green ammonia but require abundant renewable power. Integrated fertilizer–chemical complexes often rely on steam and electricity cogeneration, meaning that decarbonising electricity supplies is critical to reduce indirect emissions.

2.3 Field-level emissions

When urea is applied, carbon captured during synthesis is released as CO_2 through hydrolysis, as approximately 0.73 t CO_2 is emitted per tonne of urea applied(Systemiq & (ifa), 2022). In addition, nitrification and denitrification of nitrogen fertilizers emit N_2O, contributing 58.6 % of total N-fertilizer related emissions (Menegat et al., 2022a). Emissions vary by soil type, climate and application rate. Sustained-release fertilisers, urease and nitrification inhibitors and precision application can significantly lower these losses.

2.4 Lifecycle emissions overview

A clear understanding of lifecycle emissions is essential to assess the true climate impact of fertilisers. Emissions are not limited to the production stage but extend through transport and field application, where nitrous oxide losses significantly add to the footprint. Placing these stages together provides a complete picture of the sector's challenges and sets the foundation for identifying priority areas in the net-zero transition.

To understand the full climate impact of fertilizers, it is important to look beyond factory gates, and Figure 5 captures this lifecycle perspective by tracing emissions from production through field application to transport.

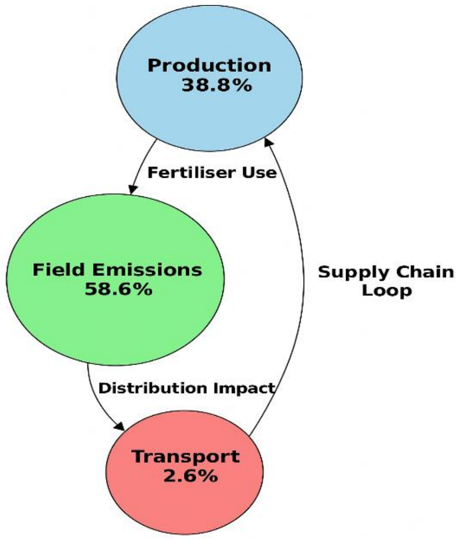

Figure 5. Cyclic representation of the fertilizer lifecycle, showing GHG emissions from production, field use, and transport (Source: (Menegat et al., 2022b)).

The overall climate footprint of fertilizers extends well beyond the factory gate, as shown in Figure 5, which illustrates the proportional contributions of different lifecycle stages. Production processes account for 38.8% of total emissions, highlighting the energy-intensive nature of ammonia and related fertilizer manufacturing. However, the dominant share comes from field emissions, contributing 58.6%, largely driven by nitrous oxide release during fertilizer application in soils. Transport plays a comparatively smaller role, adding 2.6%, yet it still forms part of the cumulative supply chain impact. Together, these values in Figure 5 emphasise that while mitigating GHG during production is important, the larger challenge lies in addressing field-level losses, making it essential to combine industrial innovation with smarter nutrient use strategies in the transition toward net-zero fertilizers.

The assessment of fertilizer sector emissions begins with a comparison of the carbon intensity of different products, as presented in Table 1. This table compiles cradle-to-gate emission factors alongside use-phase impacts, offering a clear baseline for understanding how various fertilizers contribute differently to climate change. By grounding the discussion in these quantified values, the table provides essential context for evaluating decarbonization strategies and highlights why product-specific pathways are necessary to achieve meaningful emission reductions.

TABLE 1. COMPARATIVE EMISSION FACTORS OF MAJOR FERTILIZER PRODUCTS ACROSS THE LIFE CYCLE STAGES

Fertiliser product	**Main production pathway**	**Cradle-to-gate emission factor (kg CO_2e/kg product)**	**Use-phase CO_2/N_2O emissions**	**Evidence**
Grey ammonia	Natural-gas steam reforming	1.62 kg CO_2e per kg NH_3	-	Product carbon footprint study(Elshishini, 2024)
Urea (46-0-0)	Ammonia + CO_2	1.61 kg CO_2e/kg (EU average)	0.73 t CO_2 released per tonne urea applied fertilizer.org	Fertilizers Europe reference values(Hoxha & Christensen, 2019)
Ammonium nitrate (AN 33.5-0-0)	Ammonia + nitric acid	1.11 kg CO_2e/kg product (EU average)	N_2O emissions depend on abatement efficiency	Fertilizers Europe reference values(Hoxha & Christensen, 2019)
Diammonium phosphate (DAP 18-46-0)	Ammonia + phosphoric acid	0.73 kg CO_2e/kg at plant gate; 2.03 kg CO_2e/kg including embedded CO_2	CO_2 released if urea embedded in DAP hydrolyses	Fertilizers Europe carbon-footprint reference (Europe, 2011b)
Muriate of potash (MOP 0-0-60)	Mining and flotation	0.25 kg CO_2e/kg product agindustries.org.ukbhp.com	No CO_2 emissions during use bhp.com	Fertilizers Europe reference values(Europe, 2011b)

The carbon intensity of fertilizers reveals critical differences that shape decarbonisation strategies for the sector. Conventional grey ammonia from natural gas reforming releases about 1.62 kg CO_2e per kg NH_3, which makes it one of the most emission-intensive products. Urea has a similar cradle-to-gate footprint of 1.61 kg CO_2e per kg, but its use adds a further 0.73 t CO_2 for every tonne applied, compounding its climate impact. Ammonium nitrate is somewhat lower at 1.11 kg CO_2e per kg, yet its overall contribution depends heavily on whether advanced abatement systems are deployed to cut N_2O losses. In contrast, diammonium phosphate

(DAP) records 0.73 kg CO_2e per kg at the plant gate, which rises to 2.03 kg CO_2e per kg once embedded urea-derived CO_2 is accounted for. Muriate of potash (MOP) stands out with the lowest footprint of 0.25 kg CO_2e per kg, reflecting its mining and flotation process that avoids significant chemical CO_2 release. Table 1 consolidates these values to provide a clear baseline for comparing the emission factors of major fertilizers across their life cycle. These quantified differences illustrate why a single mitigation pathway cannot address the full sectoral challenge and why high-impact products like ammonia and urea demand priority interventions. They also highlight that policies focused only on production-side measures risk overlooking large downstream emissions. Critically, the table strengthens the argument for product-specific certification and labelling systems that recognise these emission profiles and reward low-carbon alternatives. Taken together, the evidence in Table 1 underscores both the urgency and the opportunity to design differentiated decarbonisation strategies that balance climate goals with food security.

3.Why the fertiliser industry must transition to net zero

3.1 Regulatory pressure: ETS and CBAM

The EU Emissions Trading System (EU ETS) has historically provided free allowances to avoid carbon leakage, but these will be phased out as the Carbon Border Adjustment Mechanism (CBAM) is introduced. CBAM will require importers of ammonia and fertilizers to surrender carbon certificates equivalent to the EU ETS price, effectively levelling the carbon cost between domestic and imported products. Industry groups therefore anticipate higher compliance costs and are calling for clear rules, including labelling or quotas for clean fertilizers and renewable-hydrogen mandates(B.v. & Europe, 2023)**.**

3.2 Investor and stakeholder pressure

Investors are increasingly integrating ESG metrics into their portfolios, penalising high-carbon products and rewarding companies that commit to science-based targets. Consumer awareness around sustainable food is also growing. Large food corporations are adopting Scope-3 emission reductions that ripple upstream to fertilizer suppliers. Failure to decarbonise could result in reputational damage, capital flight and loss of market share.

3.3 National net-zero targets

Many jurisdictions have adopted net-zero goals: the EU target 2050, while India aims for 2070. In India's fertiliser sector, energy-efficiency measures can reduce emissions intensity by about 10 %, renewable electricity substitution yields only 2 %, yet switching from grey to green ammonia can reduce emissions by 151 % making the sector carbon-negative because external CO_2 is required for urea synthesis (Patidar et al., 2024). Such analyses underscore the importance of green ammonia for meeting national targets.

3.4 Food security versus climate trade-off

Fertilizers support half of the world's food production, so abrupt reductions are not feasible. A just transition must safeguard yields while lowering emissions through improved nutrient-use efficiency, balanced fertilisation and circular nutrient recycling. Policies should avoid penalising farmers for N_2O emissions without providing affordable low-carbon alternatives.

3.5 Cost competitiveness and energy risks

Volatile natural-gas prices, particularly during the 2022–2023 energy crisis, exposed the vulnerability of conventional ammonia production. Low-carbon ammonia pathways will remain more expensive in the medium term; levelized costs of green ammonia are estimated to be USD 160–270 per tonne of CO_2 abated in India (Patidar et al., 2024). However, renewable-energy costs are falling and carbon pricing will narrow the gap. Blue ammonia, which combines natural-gas reforming with carbon capture and storage (CCS), offers an intermediate option with lower emissions and moderate cost.

3.6 Reputation and supply-chain risks

Food companies and retailers increasingly scrutinise supply-chain emissions. High-carbon fertilizer producers risk exclusion from sustainable procurement programmes and access to green finance. Adoption of certification schemes for low-carbon fertilizers can provide market differentiation and resilience against policy shocks.

An effective transition strategy requires clarity on the main drivers that are pushing the fertilizer sector toward decarbonisation. Table 2 captures these drivers by outlining the technological, economic and policy forces that are shaping current industry decisions. By presenting these elements together, the table provides the reader with a concise overview of why the sector must act urgently and how external pressures are translating into concrete change.

TABLE 2. KEY DRIVERS INFLUENCING THE FERTILIZER INDUSTRY'S TRANSITION TOWARD NET ZERO

Driver	Rationale	Illustrative evidence
Regulation & carbon pricing	EU ETS and CBAM impose carbon costs on domestic and imported fertilisers, phasing out free allowances fertilizerseurope.com. Renewable-energy directives require 42 % renewable hydrogen in industry by 2030.	Fertiliser producers must account for embedded emissions to avoid tariffs and comply with renewable-hydrogen quotas(European Commission, 2023).
Investor & consumer pressure	ESG-aligned funds and food companies demand transparency and low-carbon supply chains.	Companies with credible decarbonisation strategies attract investment and secure offtake agreements; reputational risk penalises laggards(Ouassou et al., 2024).
Energy-price linkage & fertilizer cost pass-through	Volatility in natural gas and crude oil prices propagates strongly into fertilizer prices, increasing production cost uncertainty and pressuring margins	A study shows that in periods such as June 2007–June 2008, volatility in natural gas and oil prices significantly raised fertilizer prices, with ARCH/GARCH models confirming that energy price volatility is an important driver of fertilizer cost fluctuations(Sanyal et al., 2015).
Technological innovation	Green and blue ammonia, catalytic N_2O abatement (>95 % reduction oeko.de), bio-based fertilisers and digital agriculture enable emissions reduction	Early movers like Yara and CF Industries are demonstrating commercial projects (Jorß et al., 2023).
Net-zero pledges	National and corporate targets necessitate deep reductions; India's fertiliser sector can become net-negative through green ammonia.	Transition strategies align with international climate commitments and unlock long-term competitiveness(Patidar et al., 2024).

The transition of the fertiliser industry towards low-carbon pathways is shaped by a combination of regulatory, financial, and technological pressures that make change unavoidable. As outlined in Table 2, carbon pricing mechanisms such as the EU ETS and the CBAM are steadily increasing compliance costs and forcing producers to account for embedded emissions across borders. Investor expectations and consumer demand for sustainable supply chains add another layer of urgency, as companies without credible decarbonisation plans risk losing market access and reputation. Energy price volatility, particularly in natural gas, further exposes the fragility of conventional production models, underlining the need for diversification and resilience. At the same time, technological innovations such as green and blue ammonia, advanced catalytic N_2O abatement systems achieving more than 95% reduction, and the growing role of digital agriculture demonstrate that solutions are already emerging and being tested at scale. National and corporate net-zero pledges add further weight, aligning fertiliser strategies with international climate commitments and competitiveness goals. Taken together, the evidence in Table 2 illustrates that the drivers of decarbonisation are no longer optional signals but integrated forces that are reshaping the fertiliser sector's future, combining climate responsibility with market survival and long-term resilience.

4. Decarbonisation pathways and latest developments

4.1 Green ammonia (electrolysis + nitrogen)

Green ammonia is produced by electrolysing water to generate hydrogen and combining it with nitrogen using renewable electricity. The absence of fossil-fuel feedstock eliminates CO_2 emissions; life-cycle emissions depend on the carbon intensity of power. Yara produced the first tonnes of renewable ammonia at a pilot plant in Porsgrunn, Norway in 2023 and is constructing a 24 MW electrolyser that will produce 20 000 t yr^{-1} of renewable ammonia and cut 41, 000 t CO_2e per year by substituting fossil hydrogen (Asa, 2023). In India, CEEW estimates that replacing grey ammonia with green ammonia could abate 30 Mt CO_2 in urea production alone (Patidar et al., 2024). Cost remains the main barrier; however, falling renewable-energy costs and mandates for renewable hydrogen at 42 % by 2030 in the EU will accelerate deployment(B.v. & Europe, 2023).

A meaningful evaluation of low-carbon fertilizer pathways requires direct comparison of their greenhouse gas intensities to show where real progress can be made. Figure 6 presents this comparison by illustrating the emissions profile of grey, blue, and green ammonia, making clear how each pathway differs in its contribution to the climate challenge. By placing these values side by side, the figure sets the stage for understanding why transitional solutions like blue ammonia are important in the near term, but only green ammonia offers the scale of reduction necessary to align the fertilizer sector with long-term net-zero goals.

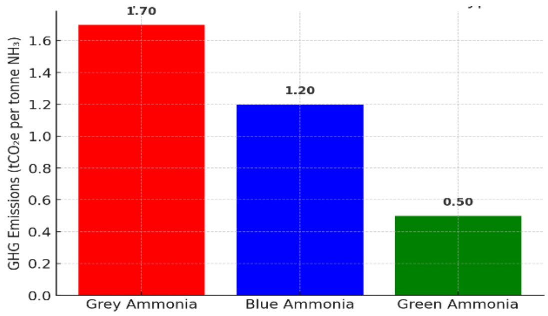

Figure 6. Comparative GHG emissions of grey, blue and green ammonia (Mayer et al., 2023);(Hatzell & al., 2024)

A clear distinction emerges when comparing the carbon intensity of different ammonia production routes, and Figure 6 highlights these differences with precise values. Grey ammonia records the highest footprint at 1.70 tCO_2e per tonne of NH_3, reflecting its reliance on fossil fuel–based steam reforming. Blue ammonia lowers this to 1.20 tCO_2e per tonne of NH_3 by integrating carbon capture and storage, demonstrating that partial mitigation is possible but not complete. The sharpest reduction is observed with green ammonia, which emits only 0.50 tCO_2e per tonne of NH_3, showing the potential of renewable hydrogen–based synthesis to align the fertilizer industry with net-zero ambitions. These values in Figure 6 underline that while blue ammonia can serve as a bridging option, only large-scale adoption of green ammonia can deliver the deep cuts required for a sustainable future.

4.2 Blue ammonia (natural gas + CCS)

Blue ammonia refers to conventional ammonia production where most process CO_2 is captured and permanently stored. Its emissions intensity is lower than grey ammonia (1.6 to 1.8 t CO_2e per tonne NH_3(Hatzell & al., 2024); see Figure 4) but higher than green ammonia. CF Industries is constructing a carbon-capture facility at its Donaldsonville complex that will capture 2 Millon t CO_2 per year, enabling the production of low-carbon ammonia (CF, 2023). Such projects benefit from lower capital costs than green ammonia and can leverage existing infrastructure; however, long-term viability depends on CO_2 storage availability and regulatory frameworks.

4.3 Catalytic process optimisation and N_2O abatement

Advanced catalysts can minimise energy consumption and GHG emissions in ammonia and nitric acid synthesis. Secondary and tertiary N_2O abatement technologies can reduce emissions by over 95 % (Jorß et al., 2023)and are incentivised by carbon pricing under the EU ETS. Widespread deployment requires supportive policies and investment in catalyst retrofits.

4.4 Renewable energy in production plants

Electrification of compressors, pumps and auxiliary systems, and on-site renewable generation (solar or wind) can reduce Scope 2 emissions. However, renewable electricity substitution yields only about 2 % emissions reduction in India's fertilizer sector (Patidar et al., 2024)because combustion emissions dominate. Its value lies in enabling green hydrogen production and providing zero-carbon power for plant operations.

4.5 Bio-based fertilizers and waste valorisation

Circular approaches recover nutrients from organic waste streams (e.g., struvite from wastewater) and use bio-fertilizers derived from compost or anaerobic digestion. These products can lower life-cycle emissions, improve soil health and align with sustainable agriculture. The scalability of waste-based fertilizers is limited by feedstock availability and logistics.

4.6 Application-side innovations

Controlled-release fertilizers, urease and nitrification inhibitors, and polymer-coated products slow nutrient release and reduce N_2O emissions. Precision agriculture leveraging remote sensing, soil sensors and AI optimise fertilizer rates and timing, increasing nutrient-use efficiency. These solutions can reduce field emissions (which account for 58.6 % of total N-fertilizer emissions (Menegat et al., 2022a)) while maintaining yields.

4.7 Digital agriculture and AI

Digital agriculture powered by AI offers a compelling pathway to reconcile productivity and sustainability in the fertilizer-intensive food system.

By weaving together tools such as soil sensors, satellite imagery, weather forecasts, and crop models, AI systems tailor nutrient recommendations to each micro-site within a field thus avoiding blanket applications that waste inputs and provoke excess nitrous oxide emissions. Studies show that precision agricultural practices reduce greenhouse gas emissions while maintaining or even improving yields and farm economics (Balafoutis et al., 2017). In China, the development of digital agriculture has been empirically linked to declines in agricultural carbon emissions via gains in labor productivity and technical efficiency (Chen et al., 2025). Moreover, researchers have explored reinforcement learning models that balance yield and emissions, optimizing nitrogen use under weather uncertainty to curb N_2O losses (Wang et al., 2024). Meanwhile, digital empowerment more broadly appears to follow an inverted-U relationship with emissions: beyond a certain threshold, further digitalization tightens input use and enhances allocation efficiency, thereby pushing emissions downward (Ma et al., 2024). In the context of your paper, integrating digital agriculture and AI thus becomes a vital mechanism to ensure that upstream emission gains in fertilizer production are not nullified by inefficiencies and losses at the farm scale.

Understanding how different industrial sectors compare in terms of abatement potential and readiness helps place fertilizer decarbonisation in a wider perspective. Figure 7 provides this comparative view by mapping maximum emission reduction opportunities against technology readiness levels, situating fertilizer pathways alongside other heavy industries. By doing so, the figure allows the reader to see where fertilizer sector innovations stand in maturity and impact, and how they connect to the broader industrial transition toward net zero.

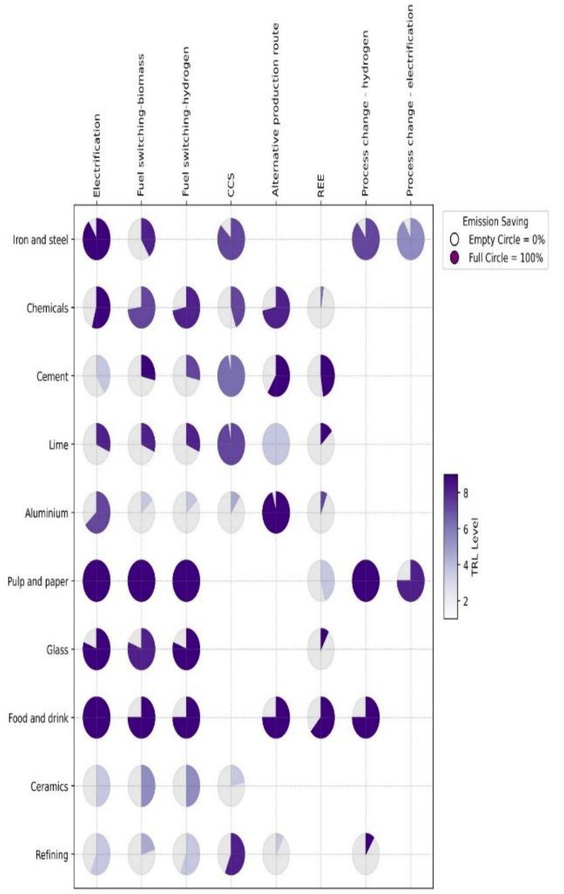

Figure 7. Maximum emission saving potential for industrial sectors by abatement category and technology readiness level(Gailani et al., 2024)

(CCS- Carbon capture and storage, REE- Resource and energy efficiency)

The wider industrial landscape shows that pathways to net zero differ greatly in both scale and maturity, and Figure 7 places fertilizer decarbonisation within this broader context. It illustrates how energy-intensive sectors such as iron, steel, cement, and chemicals rely heavily on carbon capture and hydrogen-based options, which offer substantial emission reduction potential but remain uneven in deployment. In contrast, industries like pulp and paper or food processing show greater dependence on electrification and resource–energy efficiency, reflecting technologies that are more readily available for near-term implementation. For the fertilizer sector, the figure demonstrates that while electrification and efficiency measures can provide incremental gains, the deeper cuts will depend on advancing less mature but high-impact solutions such as green hydrogen and carbon capture. By aligning fertilizer strategies with these wider industrial lessons, Figure 7 makes clear that achieving net zero requires balancing proven approaches with accelerated innovation to close the readiness gap.

A closer look at the technological landscape reveals that several innovative solutions are being developed and deployed to cut emissions in fertilizer production, and Table 3 brings these options together by outlining their working principles, maturity levels, and potential contribution to a resilient net-zero pathway within the sector.

TABLE 3. EMERGING INNOVATIONS IN FERTILIZER DECARBONIZATION, SHOWING TECHNOLOGY MATURITY, EMISSION REDUCTION POTENTIAL, AND THEIR ROLE IN ENABLING A RESILIENT NET-ZERO TRANSITION

Technology	**Principle**	**Estimated emission-reduction potential**	**Indicative abatement cost or note**	**Example projects**
Green ammonia	Water electrolysis + air separation + Haber–Bosch using renewable electricity	Up to 100 % reduction relative to grey ammonia	USD 160–270 per tonne CO_2 abated	(Patidar et al., 2024)
Blue ammonia (SMR + CCS)	Natural gas → H_2 via steam methane reforming + CO_2 capture & storage → ammonia synthesis	55–70 % reduction in well-to-gate GHG emissions compared to conventional grey ammonia	Avoided CO_2 cost of USD 19.6–109 / tCO_2 depending on CO_2 transport distance (100–1,000 miles)	(Lee et al., 2023)
N_2O abatement catalysts (tertiary, KBR)	Catalytic decomposition of N_2O in nitric acid plant tail gas using Fe/zeolite catalyst ($N_2O \rightarrow N_2 + \frac{1}{2}O_2$)	95–98 % N_2O removal efficiency	Catalyst lifetime 5–7 years; low pressure drops; retrofit possible; design life of reactor up to 25 years	KBR EnviNOx / tertiary abatement systems installed in nitric acid plants worldwide(Chowdhury & Desai, 2022)
Renewable electricity substitution	Electrification and on-/off-site renewable power for plant electricity	For India's fertiliZer sector, 2% total emissions reduction (electricity share is small vs feedstock/process).	Capex for solar/wind; synergy with future green-H_2. (Sector briefs and policy analyses.)	Indian fertiliser plants exploring rooftop/onsite PV per sector analyses; broader rooftop rollout context(Patidar et al., 2024).
Bio-based fertilizers / nutrient recovery	Recover nutrients (e.g. P, N) from wastewater, sludge, via precipitation or recovery systems	56-98 % reduction in carbon footprint (vs DAP/urea baseline)	Depends strongly on system boundaries, energy required for recovery, transport, and substitution assumptions	Gowd et al. "Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater" (India / global comparative) (Gowd et al., 2023).
Controlled-release fertilizers & inhibitors (polymer coatings, nitrification inhibitors, urease inhibitors)	Polymer coatings slow N release; enzyme inhibitors (e.g. nitrification inhibitors) block steps in N conversion	58.1 % reduction in N_2O emissions (average effect of nitrification inhibitors)	Additional cost, but often offset via better N use efficiency	Meta-analysis: Lei et al. (2022), "A meta-analysis to examine whether nitrification inhibitors reduce N_2O emissions (Lei et al., 2022).
Digital agriculture & AI / precision N management	Using sensors, remote sensing, AI / decision systems to optimise timing, amount, placement of fertiliser	21–45 % reduction in N_2O / soil emissions (in case study)	Requires digital infrastructure, training, data systems (costs depend on scale & adoption)	Papadopoulos et al. (2024) "Economic and environmental benefits of digital agricultural" showed soil emissions reductions of 21–45% in test settings.(Papadopoulos et al., 2024)

Decarbonizing the fertilizer sector requires a portfolio of technologies that balance immediate gains with long-term transformation, and Table 3 captures these innovations in a structured way. Green ammonia stands out with the potential for complete elimination of fossil-based emissions, though its deployment is still constrained by high abatement costs and renewable energy needs. Blue ammonia offers a transitional pathway, reducing emissions by more than half when combined with carbon capture, yet it remains dependent on suitable storage infrastructure. Catalytic N_2O abatement, already achieving removal efficiencies of up to 95–98%, provides one of the most readily deployable solutions for nitric acid plants. At the same time, bio-based fertilizers, nutrient recovery systems, and digital agriculture practices show how circularity and precision can complement industrial decarbonization by addressing downstream emissions. Collectively, the innovations in Table 3 highlight that no single solution can deliver net zero alone; instead, integrated adoption across production, application, and waste recovery is necessary to build a resilient and sustainable fertilizer industry.

Translating decarbonization strategies from theory into practice requires evidence from real-world applications, and Table 4 introduces case studies that showcase how companies and regions are implementing diverse technologies and initiatives to advance the fertilizer industry's net-zero transition.

TABLE 4. INDUSTRY CASE STUDIES DEMONSTRATING PRACTICAL DECARBONISATION STRATEGIES IN FERTILIZER PRODUCTION AND THEIR CONTRIBUTION TO THE NET-ZERO TRANSITION

Company & region	**Decarbonisation strategy**	**Capacity and impact**	**Evidence**
Yara (Porsgrunn, Norway)	Pilot green ammonia plant and 24 MW electrolyser replacing fossil hydrogen	Produces 20 kt yr^{-1} renewable NH_3; reduces 41 kt CO_2e yr^{-1} first renewable ammonia produced in 2023	(Yara, 2023)
Yara (Sluiskil, Netherlands)	CCS project capturing process CO_2 from ammonia production	Will store 800 kt CO_2 yr^{-1} in offshore reservoirs	(Asa, 2023)
CF Industries (Donaldsonville, USA)	20 MW electrolyser and CCS facility producing blue/green ammonia	Green ammonia unit produces 20 kt yr^{-1}; CCS captures 2 Mt CO_2 yr^{-1}; aims for 25 % reduction in scope-1 intensity by 2030 and net zero by 2050 cfindustries.comcfindustries.com	(CF, 2023)
Indian fertiliser sector (national)	Energy efficiency, renewable electricity, green ammonia	Efficiency measures cut emissions intensity by 10 %; renewable power yields 2 % reductions; green ammonia could abate >30 Mt CO_2, exceeding current sector emissions	(Patidar et al., 2024)

Real-world experiences play a vital role in demonstrating how decarbonization strategies move from concept to practice, and Table 4 highlights such case studies from leading companies and regions. Yara's pilot project in Norway illustrates the viability of green ammonia, producing 20,000 tonnes annually and cutting 41,000 tonnes of CO_2 emissions, while its CCS initiative in the Netherlands shows how large-scale carbon storage can complement low-carbon production. Similarly, CF Industries in the United States combines electrolysis and carbon capture, aiming to capture up to 2 million tonnes of CO_2 per year and integrate both blue and green ammonia pathways. On a national scale, India presents a diverse approach, with efficiency measures reducing intensity by 10%, renewable electricity offering modest gains of around 2%, and green ammonia providing the most significant abatement potential exceeding 30 million tonnes of CO_2. Together, the examples in Table 4 illustrate that although strategies differ in scale and focus, they all signal growing momentum in the fertilizer industry toward net-zero solutions through innovation, investment, and supportive policy frameworks.

5.Roadmap to net zero: barriers and enablers

5.1 High capital expenditure and transition costs

The financial burden of shifting to low-carbon fertilizer production is daunting. For example, building or retrofitting green ammonia facilities may push the capital cost per ton of installed ammonia capacity well above conventional plants. In India's recent green ammonia auctions, the discovered price was ₹55.75 per kilogram (USD 641 per metric ton) for delivered ammonia, substantially higher than typical grey ammonia costs (GOI, 2025).Furthermore, in a Deloitte assessment the cost gap between grey and green ammonia has been estimated at about USD 291 per ton, meaning that producing green molecules often requires significant subsidy or higher realized prices (Deloitte Touché Tohmatsu India L L, 2023).In another techno-economic study on decarbonized urea systems, a 500 tonnes/day plant yielded urea costs around 135 €/ton (excluding certain capital burdens) under some assumptions (Devkota et al., 2024). These figures illustrate that the upfront investment and transition costs are steep, placing pressure on financing, risk management, and the pace of adoption.

5.2 Access to green hydrogen and renewable energy

Scale-up of green ammonia depends on abundant renewable electricity and water. Policy frameworks that guarantee renewable-power availability (e.g., dedicated renewable corridors) and support electrolyser deployment are crucial. For blue ammonia, the availability of geologically suitable CO_2 storage sites and transport infrastructure is an important factor.

5.3 Policy and subsidy gaps

Carbon pricing, CBAM and renewable-hydrogen mandates provide direction but need to be complemented by subsidies for first-of-a-kind projects, research funding for catalyst development and streamlined permitting processes. In developing countries, fertiliser subsidies could be repurposed towards low-carbon products. India has large unresolved policy and subsidy gaps when it comes to fostering low-carbon fertiliser production. For instance, the government continues to channel enormous funds into conventional fertiliser subsidies over ₹1,91,836 crore in 2024-25 for fertiliser support alone (G0I, 2025) rather than repurposing them toward green alternatives. At the same time the recently launched renewable ammonia subsidy offers only USD 106 per tonne in the first year and USD 85 per tonne thereafter, for just a limited capacity of 539,000 t per year (Atchison, 2024). This mismatch means incentives remain too weak to offset the risk and cost of early green projects, and the policy architecture lacks the certainty needed to mobilise long-term private investment.

5.4 Need for public–private partnerships

Collaboration between governments, industry, academia and financiers is vital to share risks, coordinate infrastructure such as green-hydrogen hubs, CO_2 pipelines and ensure that benefits reach farmers. Certification schemes and digital traceability can build trust and unlock carbon finance.

5.5 Role of certification and labelling

Certification and labelling mechanisms can influence real costs and trade flows in the fertilizer/ammonia sector in measurable ways. For example, a life-cycle assessment study associated with the EU's Carbon Border Adjustment Mechanism (CBAM) finds that emissions embodied in direct EU imports decline by 4.8 %, and when accounting for indirect emissions the decline is about 3 % (Walczak et al., 2025). Meanwhile, modelling work on carbon leakage shows that a unilateral CBAM can reduce global leakage by approximately 19 % relative to a no-policy baseline (Sun et al., 2024). On the production side, in favourable conditions (low cost of capital, strong renewables), green ammonia production costs may reach USD 400 per tonne, which is closer to grey ammonia levels in certain regions (Saygin et al., 2023). In India's context, the government has sanctioned INR 19,744 crore (USD 2.37 billion) under the National Hydrogen Mission to support green hydrogen and its derivatives, including green ammonia, which points to the scale of fiscal commitment implicit in certification-driven transitions (Mr. Himadri Singha, 2025).

5.6 Opportunities for carbon credits and trading

Producers who cut N_2O emissions or pivot to green ammonia have a tangible pathway into carbon markets, though the scale and credibility hinge on solid MRV systems. For example, in nitric acid (and related chemical) sectors, abatement technologies achieving 80 % to 97 % reduction(Inger et al., 2020) of N_2O emissions have already enabled issuance of more than 20 million carbon credits under voluntary and compliance schemes (Healey & Subramanian, 2024). In agriculture, methodologies such as the ACR/Winrock VM0022 protocol allow farmers to claim N_2O offsets by reducing nitrogen fertilizer rates given N_2O's 300× GWP relative to CO_2(Anderson, 2013). But the challenge is vast: a systematic review of 2,346 existing carbon credit projects found that only 16 % of them achieve real, verifiable emission reductions implying that unreliable MRV erodes credibility (Probst et al., 2024). On the technical front, new MRV frameworks are emerging: for instance, (Batjes et al., 2024) propose a modular, multi-ecosystem MRV system to deliver scalable soil carbon and emissions accounting. In sum, while carbon credits offer an alluring revenue stream for green-ammonia or N_2O abatement, the real value lies in rigorous measurement, verification and credibility without which credits risk being discounted or ignored.

5.7 Skills, workforce transformation and R&D support

Building a net-zero fertilizer industry depends as much on people and knowledge systems as on technology itself. Skilled operators, engineers, and researchers will be essential to manage the shift from conventional production to advanced pathways such as carbon capture, hydrogen integration, and digital process optimisation. At the same time, sustained investment in training and research support will ensure that the workforce is prepared to drive innovation, maintain competitiveness, and secure the long-term resilience of the sector.

Mapping out the journey of ammonia production toward deep decarbonization is essential to understand both the near-term gains and long-term goals of the fertilizer sector. Figure 8 illustrates this roadmap by showing how emission intensity declines step by step, beginning with improvements through efficiency, carbon capture, and partial fuel switching, before moving toward hydrogen integration and biomethane use on the path to net zero. By placing these milestones together, the figure brings clarity to how transitional actions connect with future clean ammonia production, setting a structured direction for the sector's commitment to align with climate targets.

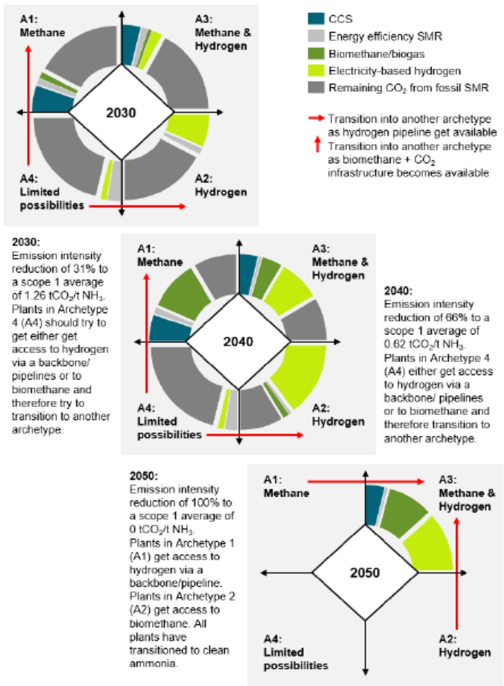

Figure 8. Roadmap for ammonia plant decarbonization (2030–2050), showing phased emission cuts through CCS, biomethane, and hydrogen transition toward net-zero ammonia (B.v. & Europe, 2023)

The pathway to net zero in fertilizer production requires carefully sequenced actions that deliver both immediate and long-term benefits, and Figure 8 clearly demonstrates this phased approach. Emission intensity is shown to decline from 1.26 tCO_2 per tonne of NH_3 in 2030 to 0.62 tCO_2 per tonne in 2040, before reaching net zero by 2050. Early reductions are achieved through efficiency upgrades, carbon capture, and partial substitution with biomethane, while the deeper cuts depend on large-scale hydrogen integration and supporting infrastructure such as pipelines and renewable power corridors. The figure also signals that without timely adoption of these measures, plants risk being locked into high-carbon pathways that will be costly to reverse later. By presenting this stepwise progression, Figure 8 underscores that the fertilizer industry's decarbonization is not a single leap but a coordinated transition that relies equally on technology deployment, infrastructure readiness, and supportive policies to deliver clean ammonia at scale.

The success of decarbonisation in the fertiliser sector depends heavily on supportive policy frameworks, and Table 5 presents the key instruments and incentives across regions that are shaping technology adoption and guiding the industry's pathway toward net zero.

TABLE 5. POLICY MEASURES AND INCENTIVES ACROSS REGIONS DRIVING FERTILIZER DECARBONIZATION AND SUPPORTING THE NET-ZERO TRANSITION

Region	**Key instruments/incentives**	**Notes**
European Union	EU ETS and CBAM imposing carbon costs on fertilisers; Renewable Energy Directive (RED III) requiring 42 % renewable hydrogen in industry by 2030; innovation fund grants for low-carbon projects	Provides regulatory certainty and directs investment towards renewable hydrogen and CCS(European Commission, 2023).
India	Green Hydrogen Mission targeting 5 Mt yr^{-1} green hydrogen production by year 2030; revision of fertiliser subsidies to encourage indigenous urea production; potential green-ammonia mandates	Supports domestic manufacture of green ammonia and reduces import dependence(GOI, 2023).
China	Dual-carbon goals (peak before 2030, net zero before 2060); pilot ETS programmes; subsidies for renewable electricity and electrolysers	Encourages transition from coal-based fertiliser plants to cleaner alternatives(Asia Society Policy, 2022).
Middle East	Renewable-energy auctions providing low-cost solar/wind; plans for large-scale green-ammonia exports	Leverages natural advantage for renewable power; positions region as global supplier(Tanchum, 2024).

Policy frameworks play a decisive role in shaping the pace and direction of low-carbon transformation in the fertilizer sector, and Table 5 brings together the key instruments and incentives driving this change across regions. In the European Union, mechanisms such as the EU ETS, CBAM, and renewable hydrogen mandates provide regulatory certainty and channel investments into clean ammonia and carbon capture technologies. The United States supports decarbonization through generous tax credits like the Inflation Reduction Act and 45Q, making both green and blue ammonia more cost-competitive. India's National Green Hydrogen Mission aims to boost domestic green ammonia production while revising subsidy structures to encourage sustainable fertilizer supply. Meanwhile, China leverages dual-carbon targets and pilot ETS programmes to shift away from coal-based production, and Middle Eastern countries are using low-cost solar and wind resources to position themselves as global exporters of green ammonia. Collectively, the examples in Table 5 underscore that while approaches differ in design, they converge on the same objective of accelerating investment and technology adoption to secure a net-zero fertilizer industry.

6.Sustainability co-benefits and life-cycle assessment insights

6.1 Reduction in air, water and soil pollution

Decarbonising fertilizers reduces emissions of CO_2 and N_2O and often results in co-benefits such as lower ammonia volatilisation, reduced particulate matter and sulphur emissions, and improved water quality by lowering nitrate leaching. N_2O abatement also diminishes stratospheric ozone depletion.

6.2 Life-cycle assessment (LCA) of fertilizer decarbonization

Life cycle assessment provides a comprehensive lens to evaluate the true climate impact of fertilizers by tracing emissions from production through transport and field use. This approach highlights that even when production becomes cleaner, downstream nitrous oxide losses in soils remain a dominant challenge that must be addressed. By capturing the entire chain, LCA helps identify where interventions can deliver the greatest benefits, ensuring that decarbonisation strategies for fertilizers are both effective and aligned with broader sustainability goals.

Reducing emissions from fertilizers cannot rely solely on industrial decarbonisation but must also address soil processes where the largest impacts occur. Figure 9 illustrates this point by showing how biological nitrification inhibition (BNI) in wheat systems reduces both nitrous oxide release from soils and carbon dioxide linked to fertilizer production. By highlighting these combined benefits, the figure brings the discussion from factory-level strategies to field-level solutions that complete the picture of fertilizer sector decarbonisation.

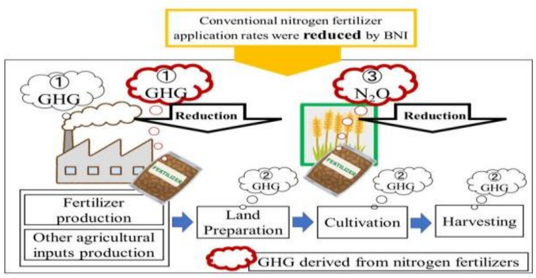

Figure 9. Life Cycle Greenhouse Gas (GHG) emissions when nitrogen fertilizer-induced GHG emissions are reduced by BNI-enabled wheat(Leon et al., 2022)

A full understanding of fertilizer decarbonisation requires looking beyond production plants and into the field, where soil processes drive a large share of emissions, and Figure 9 illustrates this connection clearly. The figure shows how biological nitrification inhibition (BNI) in wheat cultivation can lower greenhouse gas emissions across the entire life cycle by reducing nitrous oxide release from soils while also cutting upstream carbon dioxide from fertilizer production. Compared to conventional practices, BNI-enabled wheat demonstrates a measurable dual benefit, addressing both production-related and field-level impacts. This highlights that agronomic innovations are just as critical as industrial technologies, since without soil-level interventions, the largest source of fertilizer-related emissions will persist. By linking crop-level strategies with cleaner production, Figure 9 emphasizes the importance of integrated approaches in achieving meaningful emission reductions for the fertilizer sector.

6.3 Co-benefits for the Sustainable Development Goals

Decarbonising fertilizers contributes to the following multiple Sustainable Development Goals (SDGs):

- **SDG 2 (Zero Hunger)** – sustaining crop yields through precision nutrition and enhanced nutrient recovery.
- **SDG 6 (Clean Water and Sanitation)** – reducing nitrate leaching and eutrophication.
- **SDG 7 (Affordable and Clean Energy)** – creating markets for renewable hydrogen and electricity.
- **SDG 9 (Industry, Innovation and Infrastructure)** – fostering innovation in electrolyser and catalyst technologies.
- **SDG 13 (Climate Action)** – lowering GHG emissions from agriculture and chemicals.
- **SDG 12 (Responsible Consumption and Production)** – promoting circularity through nutrient recycling.

6.4 Circular economy links

Recovering phosphates and nitrates from sewage sludge (struvite) and animal manure reduces the need for mined phosphates and synthetic nitrogen. Integrating wastewater treatment with fertilizer production can create closed nutrient loops and reduce overall emissions.

While the focus of decarbonization is often on cutting emissions, its wider ecological benefits are equally important, and Table 6 highlights how the transition in fertilizer production also improves air and water quality, strengthens soil health, and promotes resource circularity in support of broader sustainability goals.

Table 6. Environmental co-benefits of fertilizer decarbonization, showing gains in air quality, water protection, soil health, and resource circularity beyond emission reduction

Co-benefit	Description	Mechanism
Air quality improvement	Lower NOx, NH_3 and particulate emissions from fertiliser plants and soils	N_2O abatement and controlled-release products decrease reactive-nitrogen losses.(Houlton et al., 2019)
Water quality protection	Reduced nitrate leaching and phosphorus runoff	Precision application and nutrient recycling prevent eutrophication(Liu et al., 2021)
Soil health enhancement	Improved soil organic matter and microbial diversity	Bio-based fertilisers and reduced synthetic inputs(Ryan et al., 2022)
Resource circularity	Recovery of nutrients from waste streams	Struvite precipitation, composting and anaerobic digestion(Rosemarin et al., 2020a)
Climate co-benefits	Mitigation of GHGs and ozone-depleting substances	Green ammonia, CCS and catalytic processes(Vinardell et al., 2023)

Beyond reducing greenhouse gas emissions, the net-zero transition in fertiliser production generates a series of wider environmental advantages, and Table 6 illustrates these co-benefits in detail. Air quality improves as NOx, NH_3, and particulate matter decline through the adoption of N_2O abatement technologies and controlled-release products. Water resources benefit from reduced nitrate leaching and phosphorus runoff when precision application and nutrient recycling are applied, lowering risks of eutrophication in rivers and lakes. Soil health is strengthened by the use of bio-based fertilisers, which enhance organic matter and microbial diversity compared with heavy reliance on synthetics. Resource circularity adds another layer of resilience, as nutrient recovery from wastewater and organic residues reduces dependence on virgin phosphate and nitrogen inputs. Taken together, the evidence in Table 6 underscores that decarbonising fertilisers is not only a climate mitigation strategy but also a pathway that supports ecological balance, safeguards food systems, and aligns directly with broader sustainability goals.

7. Recommendations and future outlook

7.1 Integrated Approach (technology, policy and supply chain)

The transition to net zero requires synchronising technology deployment with supportive policies and supply-chain collaboration. A phased approach starts with energy-efficiency upgrades and N_2O abatement, followed by blue ammonia implementation, scaling up green ammonia as renewable-energy costs fall, integrating digital agriculture solutions and eventually achieving net-zero certification(Xiang et al., 2023).

7.2 Strategic collaboration opportunities

Partnerships between fertilizer producers, renewable-energy developers, CO_2-storage providers, farmers and governments are critical. Joint ventures can de-risk capital-intensive projects, while academia can advance catalyst R&D and digital platforms. Multilateral financing institutions can support projects in emerging economies(Lentschig et al., 2025).

7.3 Role of AI and digital twins

AI-powered digital twins can model fertilizer plants and agricultural fields, identifying optimisation opportunities and predicting emissions. Integrating these tools with real-time data can accelerate decision-making and reduce downtime. Open-data platforms and interoperable standards will enhance adoption (Tzachor et al., 2022).

7.4 Potential of green-ammonia exports and global supply chains

Countries with abundant renewable resources such as Middle East and Australia could become exporters of green ammonia, supplying not only fertilizer but also maritime fuel and hydrogen carriers. Establishing certification and traceability across borders will ensure that exported products deliver genuine emission reductions (Palandri et al., 2025).

7.5 Scaling green hydrogen and renewables: system-level shifts

Achieving the required scale of green hydrogen will necessitate massive renewable-energy build-out, grid integration and storage solutions. Coordination with power-sector decarbonisation plans is essential to avoid competition for limited renewable resources. Infrastructure for water supply and desalination may also be needed in arid regions(Algburi et al., 2025).

7.6 Outlook 2030–2050: scenario projections and what’s at stake

Over the period 2030 to 2050, scenario projections for India’s fertilizer/ammonia sector and broader energy system highlight both the scale of required transformation and the risks of inaction. By 2030, the ambitious target of installing 160 GW of electrolyser capacity in India anticipates that 54 GW will be devoted to ammonia for hydrogen exports and 15 GW for domestic ammonia, producing over 20 million tonnes of renewable ammonia in that timeframe(Atchison, 2023). For 2050, under low-carbon pathways India’s hydrogen demand for the fertilizer sector alone could grow from about 3 Mt today to nearly 7.5 Mt, representing a dramatic shift in industrial energy use (TERI, 2021). At the same time total fertilizer demand in India is projected to more than double by mid-century, rising from around 55 Mt currently to nearly 130 Mt by 2050, which places immense pressure on decarbonization of ammonia supply chains and creates opportunities for low-carbon imports and domestic green ammonia production (IEEFA, 2022).

Building a credible net-zero pathway for the fertilizer sector requires action at every stage of its life cycle, and Table 7 outlines these strategic interventions from raw material sourcing to end-use application, showing how coordinated measures can drive deep decarbonization and long-term sustainability.

TABLE 7. STRATEGIC ACTIONS ACROSS THE FERTILIZER VALUE CHAIN, FROM RAW MATERIAL SOURCING TO END USE, ENABLING DEEP DECARBONISATION AND LONG-TERM SUSTAINABILITY

Value-chain stage	Recommended actions	Expected impact
Raw material supply	Develop green-hydrogen hubs, secure renewable electricity, mine potash and phosphorus responsibly	Reduce upstream emissions; improve resource security(Babaei et al., 2025)
Manufacturing	Deploy energy-efficiency measures, N_2O abatement, switch to blue/green ammonia, electrify processes	Lower Scope 1 and 2 emissions; enable low-carbon products(Mingolla & Rosa, 2025)
Transport & distribution	Use electrified or fuel-cell trucks, optimise logistics, implement CBAM compliance	Reduce transport emissions and carbon-price exposure(Li et al., 2022)
Application	Adopt controlled-release and inhibitor-enhanced fertilisers, precision application via AI and sensors	Minimise field emissions and improve nutrient-use efficiency(Hassan et al., 2022)
Waste & residuals	Recover nutrients from manure and wastewater, integrate circular economy models	Close nutrient loops, reduce dependence on virgin resources(Rosemarin et al., 2020b)

Achieving a net-zero fertilizer industry requires coordinated action across every stage of the value chain, and Table 7 sets out these strategic measures in a structured manner. At the upstream level, responsible sourcing of potash and phosphorus and the development of green hydrogen hubs help reduce raw material emissions while securing supply. In manufacturing, deploying energy efficiency measures, catalytic N_2O abatement, and switching to blue or green ammonia are central to lowering direct process emissions. Transport and distribution can further cut embedded carbon through electrified fleets, optimized logistics, and compliance with carbon border mechanisms. On the farm side, the adoption of controlled-release fertilizers, nitrification inhibitors, and AI-driven precision application techniques ensures nutrient efficiency while reducing nitrous oxide losses. Finally, closing nutrient loops through recovery from manure and wastewater strengthens circularity and decreases reliance on virgin resources. Together, the actions outlined in Table 7 demonstrate that deep decarbonization is possible only through a holistic approach that integrates technology, supply chain efficiency, and sustainable resource management across the entire fertilizer system

8. Conclusions

This review establishes that the fertiliser industry is both indispensable to global food security and a major contributor to greenhouse gas emissions, making its transformation central to the net-zero transition. The analysis shows that while industrial innovations such as green and blue ammonia, catalytic N_2O abatement, energy efficiency improvements, and renewable integration are vital, they cannot alone address the sector's footprint. Field-level measures remain decisive, since the largest share of emissions arises from fertiliser use in soils. Approaches including precision nutrient application, controlled-release products, inhibitors, and biological nitrification inhibition demonstrate strong potential to curb nitrous oxide emissions while maintaining yields. Case studies highlight that leading companies and national programmes are piloting solutions ranging from low-carbon ammonia projects to digital agriculture, signalling that technical feasibility is no longer the chief barrier. Instead, the challenge lies in scaling these efforts through supportive infrastructure, financing, and farmer adoption. The findings underscore that the fertiliser industry's decarbonisation is not a linear pathway but a layered process requiring integration of industrial technology, agronomic innovation, and circular nutrient recovery. By aligning cleaner production with smarter field practices, the sector can evolve from a major emitter into a catalyst for sustainable food systems, delivering not only reductions in carbon dioxide and nitrous oxide but also wider benefits such as healthier soils, improved water quality, and resource efficiency. In this way, the transition offers an opportunity to reconcile climate responsibility with long-term agricultural resilience, ensuring that fertilisers continue to underpin global food production while contributing to ecological balance. Achieving this outcome will require coordinated action among producers, policymakers, researchers, and farmers, but the direction is clear: only through a combined industrial and biological approach can the fertiliser sector deliver on the promise of net zero while safeguarding food security for future generations. By systematically synthesizing quantitative evidence through PRISMA and meta-analytical techniques, the findings establish a data-driven foundation for guiding future decarbonization strategies and policy interventions across the fertilizer industry.

AI Disclaimer

Portions of this manuscript, including text generation, data structuring, and language refinement, were assisted by artificial intelligence (AI) tools. All content has been thoroughly reviewed and verified by the authors to ensure accuracy, originality, and compliance with academic standards. The authors take full responsibility for the interpretations and conclusions presented in this paper.

Declaration of Conflict of Interest

The author(s) declare(s) that there are no conflicts of interest related to this work. All the analyses, interpretations, and conclusions presented in the manuscript are free from any financial, commercial, or personal relationships that could influence or appear to influence the conduct or reporting of the research.

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