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Innovative solutions for food security and energy transition through sustainable fertilizer production techniques

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Abstract

Global challenges in food security, energy transition, and sustainable agriculture necessitate innovative approaches to address intertwined socioeconomic and environmental issues. The demand for food continues to rise with population growth, while the agricultural sector faces mounting pressures from climate change, resource depletion, and escalating energy costs. Simultaneously, the transition to renewable energy is reshaping global energy systems, prompting the need for agricultural solutions that are both energy-efficient and environmentally sustainable. Fertilizer production, a cornerstone of modern agriculture, is energy-intensive and a significant contributor to greenhouse gas emissions. Thus, transitioning toward sustainable fertilizer production techniques is paramount in achieving food security and supporting the energy transition. This review explores innovative solutions that integrate renewable energy sources, such as solar, wind, and biomass, into fertilizer manufacturing processes, thereby reducing carbon footprints and improving energy efficiency. It also examines advancements in precision agriculture technologies and bio-based fertilizers, which minimize nutrient waste and environmental impacts while enhancing soil health. Furthermore, the study highlights the potential of circular economy principles, such as recycling organic waste and recovering nutrients, to create sustainable fertilizer systems. By narrowing the focus, the paper emphasizes scalable, region-specific strategies that align with global sustainability goals, particularly in energy-deficient and climate-vulnerable regions. Collaborative efforts involving policymakers, researchers, and industry stakeholders are critical to driving innovation and fostering the adoption of these technologies. The findings underline that sustainable fertilizer production is a pivotal element in securing global food systems and achieving a balanced energy transition, ultimately contributing to climate resilience and ecological balance.

Keywords: Food Security; Energy Transition; Sustainable Fertilizer; Renewable Energy; Circular Economy; Precision Agriculture.

1. Introduction

1.1. Overview of Global Food Security and Energy Transition Challenges

Food security and sustainable energy are foundational to global development and human well-being. With the world population projected to reach 9.7 billion by 2050, ensuring sufficient food production has become increasingly urgent [1]. Fertilizers play a pivotal role in enhancing agricultural productivity by replenishing essential nutrients in the soil. However, the growing demand for fertilizers poses significant challenges in terms of resource allocation and environmental impact [2].

The energy-intensive nature of fertilizer production highlights the need for sustainable energy transitions. Currently, the reliance on fossil fuels, particularly natural gas, for synthesizing ammonia—the primary precursor in nitrogen-

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based fertilizers—contributes significantly to greenhouse gas emissions [3]. Transitioning to renewable energy sources such as green hydrogen, solar, and wind power offers an opportunity to decarbonize fertilizer production processes while addressing the global energy crisis.

The dual challenge of ensuring food security and achieving energy sustainability requires innovative solutions that integrate modern agricultural practices with clean energy technologies. Sustainable fertilizer production represents a critical intersection of these goals, with the potential to support resilient food systems and mitigate environmental degradation [4]. Addressing these intertwined challenges demands a multidisciplinary approach that encompasses policy reform, technological innovation, and collaboration among stakeholders.

This article delves into the complexities of these challenges, examining innovative methods for sustainable fertilizer production and their implications for global food security and energy transitions.

1.2. Current State of Fertilizer Production

Conventional fertilizer production techniques rely heavily on the Haber-Bosch process for ammonia synthesis. While this method revolutionized agriculture by enabling large-scale fertilizer production, it is energy-intensive, consuming approximately 1-2% of global energy annually [5]. The reliance on natural gas as the primary feedstock exacerbates the environmental impact, with the fertilizer industry accounting for nearly 3% of global CO₂ emissions [6].

Phosphate and potassium fertilizers also rely on resource-intensive mining and processing methods, contributing to soil degradation and water pollution. These processes are further limited by finite reserves of phosphate rock and potash, raising concerns about the long-term availability of these critical resources [7].

Despite its effectiveness in boosting crop yields, the conventional approach to fertilizer production fails to address sustainability challenges. The environmental costs, including high carbon emissions and pollution, underscore the urgent need for innovative alternatives. Recent advancements in green technologies, such as electrochemical ammonia synthesis and the use of bio-based fertilizers, offer promising avenues for mitigating these issues [8]. However, these technologies remain in the early stages of development and require significant investment to achieve scalability and commercial viability.

The shift toward sustainable practices in fertilizer production is essential for reducing environmental harm and aligning with global energy transition goals.

1.3. Scope and Objectives of the Article

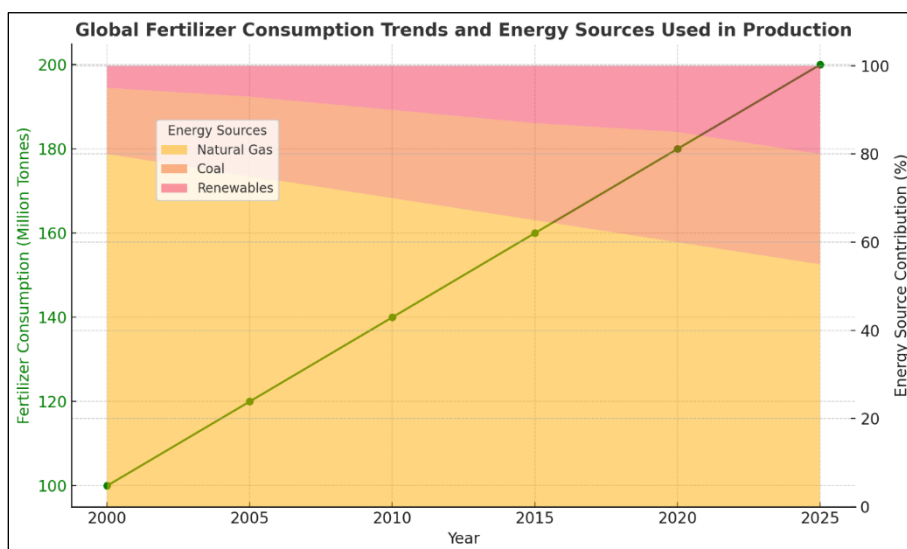


Figure 1 Summarizing global fertilizer consumption trends and the energy sources used in production illustrating the scope of the problem and highlight the opportunities for innovation. By addressing these objectives, this article seeks to contribute to the ongoing discourse on sustainable development and energy transitions in agriculture

The primary purpose of this article is to explore innovative techniques for sustainable fertilizer production that address the intertwined challenges of food security and energy transition. Fertilizers are indispensable for modern agriculture, but their current production processes pose significant sustainability issues. By examining emerging technologies and practices, this article aims to provide a roadmap for transitioning to more sustainable fertilizer production systems.

The first objective is to analyse the limitations of conventional fertilizer production methods, particularly their dependence on fossil fuels and their environmental consequences. The second objective is to evaluate innovative approaches, such as green ammonia synthesis using renewable energy and the integration of bio-based fertilizers, for their potential to decouple fertilizer production from carbon-intensive energy sources [9].

Another key goal is to bridge the gap between global food security and energy transition priorities. This requires assessing how sustainable fertilizer production can enhance agricultural productivity while reducing environmental harm and contributing to the broader goal of carbon neutrality.

2. Sustainable fertilizer production techniques

2.1. Innovations in Nitrogen-Based Fertilizer Production

2.1.1. Electrochemical Processes for Ammonia Synthesis

The Haber-Bosch process, while transformative, is highly energy-intensive and responsible for a significant portion of the global CO₂ emissions attributed to agriculture. As a result, low-carbon alternatives such as electrochemical ammonia synthesis have gained attention as sustainable replacements [6]. Electrochemical methods use renewable electricity to convert nitrogen and water into ammonia under ambient conditions, significantly reducing the reliance on fossil fuels and the associated carbon footprint [7].

These methods leverage advanced catalytic systems, including transition metal-based catalysts and nitrogenase-inspired enzymatic pathways, to enhance nitrogen activation and ammonia production rates. The development of solid oxide electrolysis cells (SOECs) has further improved the efficiency of these processes by enabling high-temperature operations that optimize reaction kinetics [8]. Emerging research has demonstrated the feasibility of combining electrochemical systems with novel electrode designs to increase production efficiency while reducing energy input requirements [9].

Despite their potential, challenges such as scalability and durability of catalytic materials remain significant barriers. The integration of advanced nanomaterials as catalysts and the optimization of reaction conditions are ongoing research areas aimed at overcoming these obstacles [10]. Electrochemical ammonia synthesis represents a promising pathway toward decarbonized fertilizer production, aligning with global sustainability goals.

2.1.2. Integration of Renewable Energy Sources

Integrating renewable energy sources into fertilizer manufacturing offers another significant opportunity to reduce the environmental impact of nitrogen-based fertilizers. Solar and wind energy, in particular, have proven effective in powering ammonia synthesis processes by supplying green hydrogen through water electrolysis [11]. The hydrogen obtained is then reacted with atmospheric nitrogen in modified ammonia production systems, creating a pathway to completely decouple fertilizer production from fossil fuels [12].

Case studies have illustrated the success of pilot projects utilizing renewable energy for ammonia synthesis. For example, solar-powered ammonia plants in Australia and wind-powered facilities in Denmark have demonstrated energy-efficient and low-emission production cycles, setting benchmarks for future industrial-scale applications [13]. Hydrogen-based approaches, including proton exchange membrane (PEM) electrolyzers, have also shown significant promise in replacing natural gas as a feedstock, with studies reporting up to 90% reductions in greenhouse gas emissions compared to conventional methods [14].

The integration of renewable energy in ammonia production not only reduces carbon emissions but also contributes to energy security by diversifying energy sources. However, widespread adoption requires significant investment in renewable infrastructure and improvements in the storage and transportation of green hydrogen. By addressing these challenges, renewable energy integration can facilitate a more sustainable fertilizer industry.

2.2. Phosphorus Recovery and Recycling Techniques

Phosphorus is an essential macronutrient in agriculture, playing a critical role in root development and crop yield. However, natural phosphorus reserves are finite, with most sources concentrated in geopolitically sensitive regions, raising concerns about long-term availability [15]. This makes phosphorus recovery and recycling from alternative sources a key focus of sustainable fertilizer production.

Technologies for phosphorus recovery often target waste streams, such as municipal wastewater and agricultural runoff, which contain significant quantities of phosphorus in soluble or particulate forms. Struvite crystallization is one of the most widely implemented techniques, wherein magnesium, ammonium, and phosphate ions are precipitated into solid struvite crystals. These crystals can be harvested and used as slow-release fertilizers, providing a circular solution for nutrient management [16].

Thermal processes, such as pyrolysis of organic waste, offer another avenue for phosphorus recovery by converting organic matter into biochar enriched with phosphorus. This biochar can be applied directly to soils, improving nutrient availability while enhancing soil structure [17]. Advances in membrane-based separation technologies have further improved the efficiency of phosphorus recovery from liquid waste streams, reducing energy consumption and operational costs [18].

While promising, these techniques face challenges in scalability and economic feasibility. High initial capital costs and logistical barriers, such as transporting waste materials to recovery facilities, hinder widespread adoption. However, policy incentives and technological innovations can accelerate the implementation of phosphorus recovery solutions, ensuring the sustainability of global food systems.

2.3. Potassium Alternatives and Sustainable Sourcing

Potassium is another critical nutrient in fertilizers, supporting plant water regulation, enzyme activation, and photosynthesis. However, traditional potassium extraction methods, such as mining potash from underground deposits, are energy-intensive and environmentally damaging [19]. Moreover, potassium reserves are geographically concentrated, making supply chains vulnerable to geopolitical tensions and trade restrictions.

Recent innovations have focused on alternative sources of potassium, such as seawater and mining byproducts. Seawater contains potassium in dissolved form, and advances in desalination and ion-exchange membrane technologies have enabled the selective extraction of potassium ions. Pilot studies have demonstrated the feasibility of harvesting potassium from seawater with minimal environmental impact, though the high energy requirements of desalination remain a challenge [20].

Mining byproducts, such as feldspar and mica, also offer a sustainable source of potassium. These silicate minerals contain potassium in insoluble forms, which can be extracted through chemical processes, including acid leaching and thermal treatment. Research has shown that potassium extraction from these sources can be cost-competitive with traditional methods, especially when combined with waste valorization strategies that utilize byproducts from other industries [21].

In addition to these innovations, researchers are exploring the use of microbial solutions to enhance potassium availability in soils. Certain soil microbes, such as *Bacillus* species, can solubilize potassium from insoluble sources, reducing the reliance on synthetic fertilizers. By adopting these alternative potassium sourcing strategies, the fertilizer industry can reduce its environmental footprint while enhancing resource security.

2.4. Bio-Fertilizers and Organic Alternatives

Bio-fertilizers and organic alternatives represent environmentally friendly solutions to conventional fertilizers, leveraging natural processes to improve soil fertility. Bio-fertilizers use microbial solutions, such as nitrogen-fixing bacteria, phosphorus-solubilizing microbes, and potassium-mobilizing organisms, to enhance nutrient availability in the soil. For instance, *Rhizobium* species form symbiotic associations with leguminous plants, fixing atmospheric nitrogen and reducing the need for synthetic nitrogen fertilizers [22].

Compost-based nutrients, derived from organic waste materials, provide another alternative to synthetic fertilizers. Composting not only recycles organic waste but also enriches soils with essential nutrients and organic matter, improving soil structure and water retention capacity. Studies have shown that compost-based fertilizers can significantly enhance crop yields while reducing greenhouse gas emissions compared to conventional fertilizers [23].

The adoption of bio-fertilizers and organic alternatives aligns with the principles of circular agriculture, minimizing waste and promoting sustainable resource use. However, their effectiveness can be variable depending on soil conditions and crop types, necessitating tailored application strategies. As research continues to optimize these solutions, bio-fertilizers and organic alternatives are poised to play a vital role in sustainable agricultural systems.

Table 1 Comparison of Traditional and Innovative Fertilizer Production Methods

Method	Efficiency	Cost	Environmental Impact
Traditional Fertilizers	Moderate	Low (high externalities)	High emissions, pollution risk
Electrochemical Ammonia Synthesis	High	High (decreasing with scale)	Low emissions, minimal pollution
Bio-Fertilizers	Moderate	Moderate	Low emissions, improves soil health
Renewable Energy Integration	High	High (initial investment)	Very low emissions, renewable resource use

3. Environmental and economic implications

3.1. Environmental Benefits of Sustainable Fertilizer Techniques

Sustainable fertilizer production offers substantial environmental benefits, addressing critical challenges associated with conventional methods. One of the most significant advantages is the reduction in greenhouse gas (GHG) emissions. Traditional fertilizer production processes, such as the Haber-Bosch method, are energy-intensive, relying heavily on fossil fuels and emitting significant quantities of CO₂ [11]. In contrast, innovations such as electrochemical ammonia synthesis powered by renewable energy drastically lower carbon footprints. Studies have shown that green ammonia production can achieve a 70-90% reduction in emissions compared to conventional methods [12].

Beyond GHG reductions, sustainable techniques mitigate water and soil contamination. Conventional fertilizers often result in nutrient leaching and runoff, leading to eutrophication in water bodies and loss of biodiversity [13]. Techniques like controlled-release fertilizers and bio-fertilizers address this issue by providing nutrients in a more efficient and targeted manner, reducing the risk of runoff. For instance, bio-fertilizers enriched with microbial solutions enhance nutrient uptake by plants, minimizing excess application and its environmental consequences [14].

Soil health also benefits from sustainable practices. Organic alternatives, such as compost-based fertilizers, improve soil structure and microbial activity, promoting long-term fertility [15]. By transitioning to sustainable fertilizer techniques, the agricultural sector can significantly reduce its ecological footprint, contributing to global sustainability goals.

3.2. Economic Viability and Market Adoption

The economic viability of sustainable fertilizer techniques is a critical factor influencing their adoption in the agricultural sector. While traditional methods have historically been cost-effective due to established infrastructure and economies of scale, the increasing environmental and regulatory costs are shifting the balance in favor of innovative solutions [16].

Cost comparisons reveal that, while sustainable techniques such as electrochemical ammonia synthesis and phosphorus recovery technologies currently require higher capital investment, they offer long-term cost advantages. For instance, renewable energy-powered systems reduce dependence on volatile fossil fuel markets, resulting in greater economic stability for fertilizer producers [17]. Additionally, innovations in potassium extraction from seawater and mining byproducts have demonstrated cost-competitiveness when integrated into existing industrial processes [18].

Scaling sustainable fertilizer production presents significant opportunities for market growth. Governments and international organizations are increasingly providing financial incentives, such as subsidies and tax credits, to encourage the adoption of green technologies [19]. Public-private partnerships play a pivotal role in this transition, facilitating investments in research, development, and infrastructure to lower production costs.

However, widespread market adoption requires addressing challenges such as knowledge gaps among farmers and the perceived risks of transitioning to newer technologies. Educational initiatives and demonstration projects can help build

trust and understanding of sustainable practices, accelerating their uptake across the agricultural value chain [20]. By fostering economic incentives and addressing market barriers, sustainable fertilizer techniques can become a mainstream solution for modern agriculture.

3.3. Policy and Regulatory Frameworks

Global policies and regulatory frameworks are essential for supporting the widespread adoption of sustainable fertilizer techniques. International agreements, such as the Paris Agreement, emphasize the importance of reducing agricultural emissions, providing a strong impetus for transitioning to green technologies in fertilizer production [21]. National policies, such as the European Union's Green Deal, have set ambitious targets for decarbonizing agriculture, including fertilizer production, by promoting the use of renewable energy and circular nutrient management [22].

Regulatory incentives, such as carbon pricing and subsidies for green ammonia plants, encourage industry stakeholders to adopt sustainable practices. For instance, countries like Germany and Japan have introduced funding programs to support the development of green hydrogen infrastructure, a key component of decarbonized fertilizer production [23]. Similarly, policies promoting phosphorus recovery from waste streams, such as nutrient trading schemes in the United States, incentivize innovative approaches to nutrient recycling [24].

However, significant regulatory challenges remain. Many developing nations lack the policy frameworks and financial resources necessary to support large-scale adoption of sustainable fertilizer techniques. Inconsistent enforcement of environmental regulations and limited access to green technologies further hinder progress in these regions [25].

Overcoming these challenges requires global cooperation and knowledge sharing. International organizations, such as the Food and Agriculture Organization (FAO) and the United Nations Environment Programme (UNEP), can play a key role in providing technical assistance and facilitating technology transfer to developing countries [26]. By addressing regulatory gaps and aligning policies with global sustainability goals, a robust framework can be established to accelerate the adoption of sustainable fertilizer techniques.

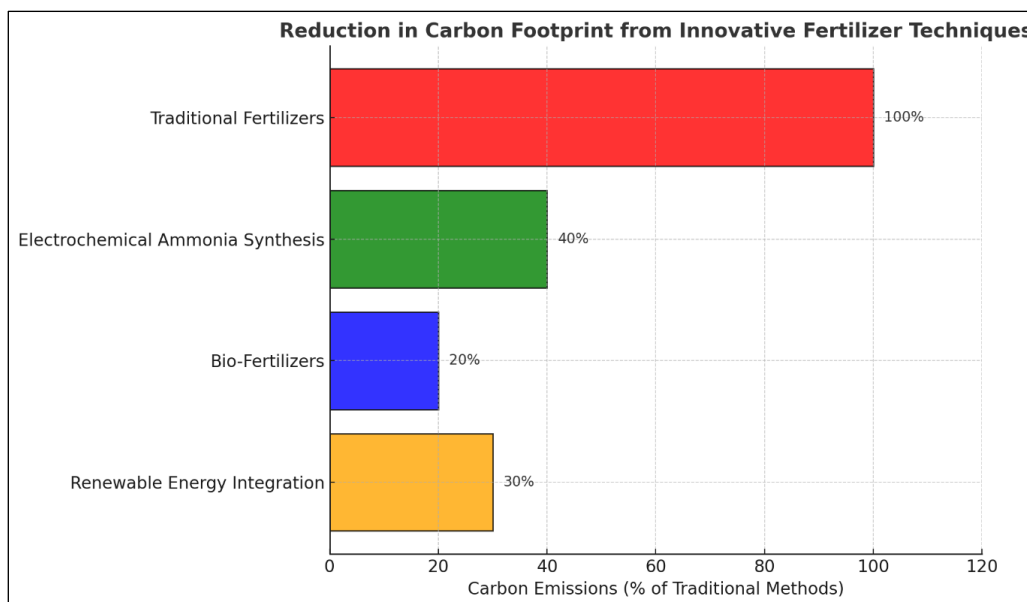


Figure 2 illustrating the reduction in carbon footprint from innovative fertilizer techniques will be included here to visually depict their environmental benefits.

4. Addressing food security through sustainable practices

4.1. Linking Fertilizer Innovation to Agricultural Productivity

Sustainable fertilizers have demonstrated a transformative impact on agricultural productivity, addressing both yield gaps and environmental challenges. Case studies from various regions underline their potential. For instance, the use of bio-fertilizers enriched with nitrogen-fixing microbes increased rice yields by 25% in Southeast Asia, showcasing their ability to replace traditional nitrogen fertilizers without compromising productivity [17]. Similarly, controlled-release

fertilizers have enhanced maize yields in Sub-Saharan Africa by up to 30%, reducing nutrient loss and improving resource efficiency [18].

Regional analysis highlights the critical role of fertilizers in bolstering food security. In South Asia, where nutrient-deficient soils are prevalent, the adoption of phosphorus-enriched fertilizers has significantly improved wheat and pulse productivity, contributing to dietary diversification and caloric sufficiency [19]. Meanwhile, innovative potassium recovery techniques, such as those applied in Brazil, have enhanced soybean and sugarcane yields, supporting the region's role as a global agricultural exporter [20].

The linkage between fertilizer innovation and agricultural productivity is particularly evident in areas where traditional methods have failed to meet the demands of growing populations. Sustainable fertilizers not only enhance crop yields but also promote soil health, ensuring long-term agricultural viability. However, challenges such as inconsistent adoption rates and varying regional soil conditions underscore the need for tailored solutions that align with local agronomic practices.

4.2. Improving Accessibility for Smallholder Farmers

Smallholder farmers account for a significant portion of global agricultural output, yet they often face barriers to accessing fertilizers due to high costs and limited availability. Reducing these barriers is essential for ensuring equitable agricultural development. Subsidies and microfinance programs have proven effective in lowering cost barriers. For example, fertilizer subsidy programs in Malawi increased smallholder access to inputs, boosting maize yields by 40% and improving food security at the community level [21].

Community-level initiatives also play a critical role in improving accessibility. Farmer cooperatives in India and East Africa have facilitated bulk procurement and distribution of fertilizers, enabling small-scale farmers to purchase inputs at reduced costs [22]. Capacity-building programs that provide training on sustainable fertilizer use further enhance adoption. For instance, training sessions in Uganda demonstrated how smallholder farmers could incorporate bio-fertilizers into their cropping systems, reducing input costs while improving yields [23].

Moreover, localized production of bio-fertilizers offers a cost-effective alternative. By utilizing agricultural waste and microbial cultures, communities can produce fertilizers tailored to local soil conditions, reducing dependency on imported inputs. Expanding such initiatives requires investment in infrastructure, education, and extension services to bridge knowledge and resource gaps. Addressing accessibility challenges for smallholder farmers will significantly contribute to global food security by unlocking their productivity potential.

4.3. Role of Precision Agriculture in Fertilizer Application

Precision agriculture is revolutionizing fertilizer application by optimizing resource use and minimizing waste. Technologies such as variable rate application (VRA) systems enable farmers to apply fertilizers based on specific soil and crop needs, improving efficiency and reducing environmental impact [24]. For example, sensor-based VRA systems in Europe have shown a 15% reduction in fertilizer use while maintaining or enhancing crop yields [25].

AI and IoT technologies play a pivotal role in smart farming solutions, further enhancing fertilizer application. Machine learning algorithms analyse soil data, weather conditions, and crop health to generate precise recommendations for fertilizer use. IoT devices, such as soil moisture sensors and drone-based monitoring systems, provide real-time data to farmers, enabling timely interventions [26]. These technologies not only reduce fertilizer waste but also lower production costs, making agriculture more sustainable and profitable.

While precision agriculture has gained traction in developed regions, its adoption in developing countries remains limited due to high costs and technological barriers. Expanding access to affordable precision tools and fostering public-private partnerships can help bridge this gap, ensuring that farmers worldwide benefit from these innovations. By integrating precision agriculture into fertilizer application strategies, the agricultural sector can achieve higher efficiency and sustainability.

4.4. Addressing Regional Disparities in Fertilizer Distribution

Fertilizer distribution disparities remain a significant challenge, particularly in developing countries where access to fertilizers is often limited by logistical, economic, and policy constraints. Sub-Saharan Africa, for instance, accounts for less than 2% of global fertilizer consumption, despite its vast agricultural potential [27]. High transportation costs, weak

supply chains, and limited infrastructure contribute to this disparity, preventing farmers from accessing the inputs necessary for improving productivity [28].

Strategies for equitable distribution include strengthening supply chains and leveraging digital platforms to improve accessibility. Mobile applications that connect farmers with suppliers have shown promise in reducing inefficiencies. In Nigeria, digital platforms like AgroMall have streamlined fertilizer procurement and distribution, increasing access for rural farmers [29]. Investments in infrastructure, such as storage facilities and transportation networks, also play a crucial role in overcoming regional challenges.

Policy interventions, including targeted subsidies and trade agreements, are essential for ensuring equitable access to fertilizers. For example, regional partnerships in East Africa have reduced trade barriers for agricultural inputs, facilitating cross-border fertilizer distribution and lowering costs for farmers [30].

Addressing these disparities requires a holistic approach that combines infrastructure development, technological innovation, and policy support. By improving fertilizer distribution systems, developing countries can unlock their agricultural potential, contributing to global food security and sustainable development.

Table 2 Global Disparities in Fertilizer Use and Agricultural Productivity

Region	Fertilizer Use (kg/ha)	Agricultural Productivity (tonnes/ha)	Food Security Status
Sub-Saharan Africa	16	1.8	Low: High reliance on imports
South Asia	125	3.2	Medium: Growing demand, regional variability
Europe	140	5.0	High: Stable production and exports
North America	130	5.8	High: Surplus production and exports
Latin America	90	4.5	Medium: Strong exports but regional inequalities

5. Energy transition and fertilizer production

5.1. Role of Green Hydrogen in Fertilizer Production

Hydrogen is a critical feedstock for ammonia synthesis, the foundation of nitrogen-based fertilizers. Conventional methods rely on hydrogen derived from natural gas, contributing significantly to carbon emissions. Green hydrogen, produced through the electrolysis of water powered by renewable energy, offers a sustainable alternative [25]. By replacing fossil fuels with green hydrogen, the fertilizer industry can significantly reduce its carbon footprint while meeting global ammonia demand.

Emerging technologies are revolutionizing green hydrogen production, making it more efficient and scalable. Proton exchange membrane (PEM) and alkaline electrolyzers are leading innovations, with efficiencies exceeding 70% in some systems [26]. Solid oxide electrolyzers, which operate at high temperatures, further enhance efficiency by utilizing waste heat from industrial processes [27]. Advances in renewable energy integration, such as coupling electrolyzers with solar and wind farms, have also reduced the cost of green hydrogen production.

While challenges such as high capital costs and energy storage limitations persist, initiatives like hydrogen valleys—regional hubs integrating hydrogen production and utilization—are accelerating adoption. Pilot projects in Europe and Asia demonstrate the viability of green hydrogen for decarbonizing ammonia synthesis at scale [28]. As green hydrogen becomes more accessible, its role in fertilizer production will be pivotal in achieving global energy transition goals.

5.2. Integration of Circular Economy Principles

Circular economy principles emphasize waste minimization and resource reutilization, offering transformative potential for fertilizer production. Waste-to-energy solutions are a key aspect, converting agricultural and industrial waste into energy and nutrients. Technologies such as anaerobic digestion convert organic waste into biogas, which can

power fertilizer plants or be upgraded to biomethane for direct application in ammonia synthesis [29]. This dual-purpose approach reduces reliance on fossil fuels while addressing waste management challenges.

Reusing agricultural byproducts in fertilizer manufacturing is another cornerstone of the circular economy. For example, crop residues and animal manure can be processed into bio-fertilizers, enriching soils with essential nutrients while reducing the need for synthetic inputs. Innovations in pyrolysis and gasification have further enhanced the efficiency of converting organic waste into nutrient-rich biochar and syngas, providing additional energy sources for fertilizer production [30].

Circular models also extend to nutrient recovery from wastewater and agricultural runoff. Phosphorus and nitrogen recovery technologies, such as struvite crystallization, close the nutrient loop, reducing environmental pollution and enhancing resource efficiency [31]. Implementing circular economy principles in fertilizer production not only promotes sustainability but also aligns with global waste reduction and energy transition goals.

5.3. Hybrid Energy Systems in Fertilizer Plants

Hybrid energy systems, combining renewable and conventional energy sources, offer a pragmatic solution for enhancing operational efficiency in fertilizer production. These systems integrate solar, wind, and biomass energy with conventional natural gas or grid electricity, ensuring continuous operation and reducing dependency on fossil fuels [32].

A prominent example is the Yara-Pilbara plant in Australia, which integrates solar energy with natural gas for ammonia synthesis. This hybrid approach has achieved a 20% reduction in carbon emissions while maintaining production efficiency [33]. Similarly, facilities in India are exploring biomass co-firing, using agricultural waste to complement natural gas in fertilizer production, thereby reducing greenhouse gas emissions and lowering production costs [34].

Hybrid systems also mitigate the intermittency challenges of renewable energy sources. By leveraging conventional energy during peak demand or periods of low renewable generation, these systems ensure uninterrupted operation. Battery storage solutions further enhance the reliability of hybrid systems, storing excess renewable energy for later use [35].

The adoption of hybrid energy systems represents a transitional step toward fully renewable fertilizer production. By combining the reliability of conventional energy with the sustainability of renewables, these systems provide an immediate pathway for reducing the environmental impact of fertilizer manufacturing.

5.4. Global Initiatives Driving Energy Transition

Global collaborations among governments, industries, and non-governmental organizations (NGOs) are driving the energy transition in fertilizer production. Initiatives such as Mission Innovation and the Clean Energy Ministerial have established platforms for international cooperation on green ammonia production and hydrogen technologies [36]. Governments are providing significant funding to support research and development in these areas. For example, the European Union has allocated over €1 billion under the Horizon Europe program for projects related to hydrogen and fertilizer decarbonization [37].

Public-private partnerships are also accelerating innovation. Collaborations between fertilizer companies and renewable energy providers have resulted in pilot projects that demonstrate the feasibility of low-carbon production methods. In Norway, Yara International has partnered with Ørsted to develop a green ammonia plant powered entirely by renewable energy [38].

NGOs and non-profits are playing a crucial role in advocating for policy reforms and raising awareness about sustainable fertilizer production. Initiatives such as the Green Hydrogen Catapult aim to scale green hydrogen production globally by fostering collaboration among industry leaders and policymakers [39].

Despite these efforts, challenges such as unequal access to funding and technological disparities persist, particularly in developing regions. Expanding global initiatives to include underrepresented countries will ensure that the benefits of the energy transition are equitably distributed, fostering sustainable agricultural development worldwide.

6. Socioeconomic benefits and challenges

6.1. Empowering Rural Communities

Decentralized fertilizer production systems have the potential to empower rural communities by creating jobs and fostering economic resilience. Traditional fertilizer supply chains often bypass rural areas, leaving farmers reliant on costly imports. Decentralized systems, such as small-scale bio-fertilizer plants, address this gap by producing fertilizers locally using agricultural waste or renewable energy sources. This approach generates direct employment opportunities in production, distribution, and maintenance while stimulating local economies [30]. For instance, pilot projects in India employing village-scale bio-fertilizer units have created up to 50 jobs per plant, enhancing income stability for rural households [31].

Skills development and education initiatives are crucial for maximizing the benefits of decentralized fertilizer production. Training programs focusing on sustainable agricultural practices, bio-fertilizer production, and equipment maintenance can build technical capacity within rural communities. Organizations such as the Food and Agriculture Organization (FAO) have launched capacity-building workshops in Sub-Saharan Africa, equipping farmers with the knowledge to adopt and manage bio-fertilizer systems effectively [32]. Additionally, vocational education initiatives in Latin America have supported rural youth in acquiring skills for employment in renewable energy-powered fertilizer plants [33].

Decentralized production systems not only create jobs but also empower communities by reducing dependency on external suppliers. By fostering local ownership and capacity, these systems contribute to long-term socioeconomic development and food security in rural areas.

6.2. Balancing Economic Growth and Environmental Goals

Achieving a balance between economic growth and environmental sustainability is a critical challenge for the fertilizer industry. Strategies for aligning industrial growth with sustainability targets involve integrating green technologies and circular economy principles into fertilizer production processes. For example, replacing fossil fuel-based hydrogen with green hydrogen in ammonia synthesis reduces carbon emissions without compromising production efficiency [34].

Case studies highlight successful implementations of such strategies. In Norway, Yara International's green ammonia plant uses renewable energy to produce fertilizers, achieving significant reductions in greenhouse gas emissions while maintaining profitability [35]. Similarly, in Brazil, nutrient recovery technologies have been integrated into sugarcane processing facilities, enabling the production of bio-fertilizers from agricultural byproducts. This approach not only reduces environmental pollution but also enhances the economic viability of sugarcane farming [36].

Government support and public-private partnerships play a key role in balancing growth and sustainability. Policies promoting renewable energy integration and waste recovery in fertilizer production create incentives for industries to adopt green practices. For instance, carbon credit schemes in the European Union have encouraged fertilizer manufacturers to invest in low-carbon technologies [37]. By adopting strategies that prioritize both economic and environmental goals, the fertilizer industry can achieve sustainable growth, contributing to global food security and climate change mitigation.

6.3. Barriers to Adoption and Solutions

The adoption of sustainable fertilizer production technologies faces several barriers, including financial, technical, and infrastructural challenges. High initial capital costs for technologies such as green hydrogen electrolyzers and advanced nutrient recovery systems often deter widespread implementation, particularly in developing regions [38]. Additionally, the lack of technical expertise and skilled labor limits the effective operation and maintenance of sustainable production facilities [39].

Infrastructure constraints, such as inadequate transportation networks and limited access to renewable energy sources, further exacerbate adoption challenges. For instance, in Sub-Saharan Africa, weak supply chains hinder the delivery of raw materials and distribution of finished fertilizers, increasing costs for producers and farmers alike [40].

Overcoming these barriers requires a multi-faceted approach. Financial challenges can be addressed through subsidies, tax incentives, and international funding mechanisms. The Global Environment Facility (GEF), for example, has funded projects in Asia to establish green ammonia plants, reducing financial risks for investors [41]. Technical barriers can be mitigated through training programs and knowledge-sharing initiatives. Partnerships between academic institutions

and fertilizer manufacturers, such as those established in Europe, have facilitated the transfer of expertise to developing regions [42].

Policy interventions are also crucial. Governments can create enabling environments by implementing regulations that mandate sustainable practices and provide support for infrastructure development. Collaboration between stakeholders—industries, policymakers, and non-governmental organizations—can ensure that sustainable fertilizer technologies become accessible and scalable. By addressing these barriers, the global fertilizer industry can transition toward more sustainable practices.

Table 3 Socioeconomic Benefits and Challenges of Sustainable Fertilizer Production

Aspect	Benefits	Challenges
Job Creation	Increased employment in rural communities via decentralized systems	Limited opportunities in regions with low adoption
Skills Development	Training programs enhancing technical expertise in sustainable practices	Lack of widespread educational initiatives for farmers
Environmental Impact	Reduction in GHG emissions and improved soil health	High costs of transitioning from conventional to sustainable methods
Economic Growth	Enhanced market opportunities with sustainable fertilizer technologies	Balancing profitability with environmental commitments
Technology Barriers	Access to advanced production methods fosters innovation	High costs of advanced technologies for smallholder farmers
Infrastructure Challenges	Improved local facilities through investments in renewable energy systems	Limited logistics and energy access in developing regions

7. Future directions and recommendations

7.1. Emerging Technologies and Research Opportunities

Emerging technologies are driving innovation in fertilizer production, offering opportunities to enhance efficiency and sustainability. Advanced materials and catalysts are at the forefront of these developments. Research into nanostructured catalysts, such as transition metal nitrides and oxides, has shown promise in improving the efficiency of ammonia synthesis under mild conditions. These catalysts enable better nitrogen activation, reducing energy requirements and emissions compared to traditional methods [43]. Additionally, bio-inspired catalysts, modelled after nitrogenase enzymes found in microorganisms, are opening new avenues for green ammonia production through ambient-pressure electrochemical processes [44].

Artificial intelligence (AI) is revolutionizing fertilizer production by optimizing manufacturing processes. AI-powered models analyse real-time data from production plants to identify inefficiencies and recommend adjustments, reducing energy consumption and operational costs. For example, predictive maintenance algorithms have been deployed in ammonia plants to minimize downtime and improve equipment longevity [45]. AI is also being used to optimize feedstock ratios, reactor conditions, and energy inputs, ensuring maximum output with minimal environmental impact [46].

Moreover, the integration of digital twin technologies, which create virtual replicas of physical production systems, is enabling real-time monitoring and experimentation. These technologies allow researchers to test innovative production methods virtually, accelerating the development and implementation of sustainable solutions.

Continued investment in research and development (R&D) is essential for scaling these innovations. Collaborative efforts between academic institutions, industries, and governments are needed to overcome technical challenges and translate laboratory breakthroughs into commercial applications.

7.2. Global Collaboration for Sustainable Solutions

Global collaboration is vital for addressing the challenges associated with sustainable fertilizer production. International cooperation in research and development accelerates innovation by pooling resources, expertise, and funding. Initiatives like the Global Fertilizer Research Alliance have brought together researchers and industry leaders from multiple countries to develop low-carbon technologies and share best practices [47].

Public-private partnerships play a critical role in scaling these technologies. Governments provide policy support and funding, while private companies bring technical expertise and market access. For instance, the partnership between Yara International and Ørsted has enabled the development of a large-scale green ammonia plant powered entirely by renewable energy, setting a benchmark for global sustainability efforts [48].

Collaboration among non-governmental organizations (NGOs) and international bodies, such as the United Nations Food and Agriculture Organization (FAO), has also been instrumental in promoting sustainable practices. These organizations facilitate knowledge transfer to developing regions, ensuring that technological advancements benefit farmers and industries worldwide. Additionally, cross-border initiatives, such as the European Green Deal, have fostered regional cooperation in decarbonizing agriculture, including fertilizer production [49].

To achieve meaningful progress, it is essential to establish frameworks that promote equitable participation in these collaborations. Developing nations often face barriers to accessing advanced technologies, underscoring the need for inclusive initiatives that address regional disparities. By fostering global cooperation, the fertilizer industry can accelerate its transition to sustainable practices and contribute to global food security.

7.3. Policy Recommendations for a Sustainable Future

Strong policy frameworks are critical for supporting the energy transition in fertilizer production. Governments must prioritize the development and enforcement of global policies that incentivize sustainable practices. For instance, implementing carbon pricing mechanisms can encourage industries to reduce emissions by adopting green technologies [50]. Similarly, establishing mandates for renewable energy integration in fertilizer manufacturing can drive the shift away from fossil fuels [51].

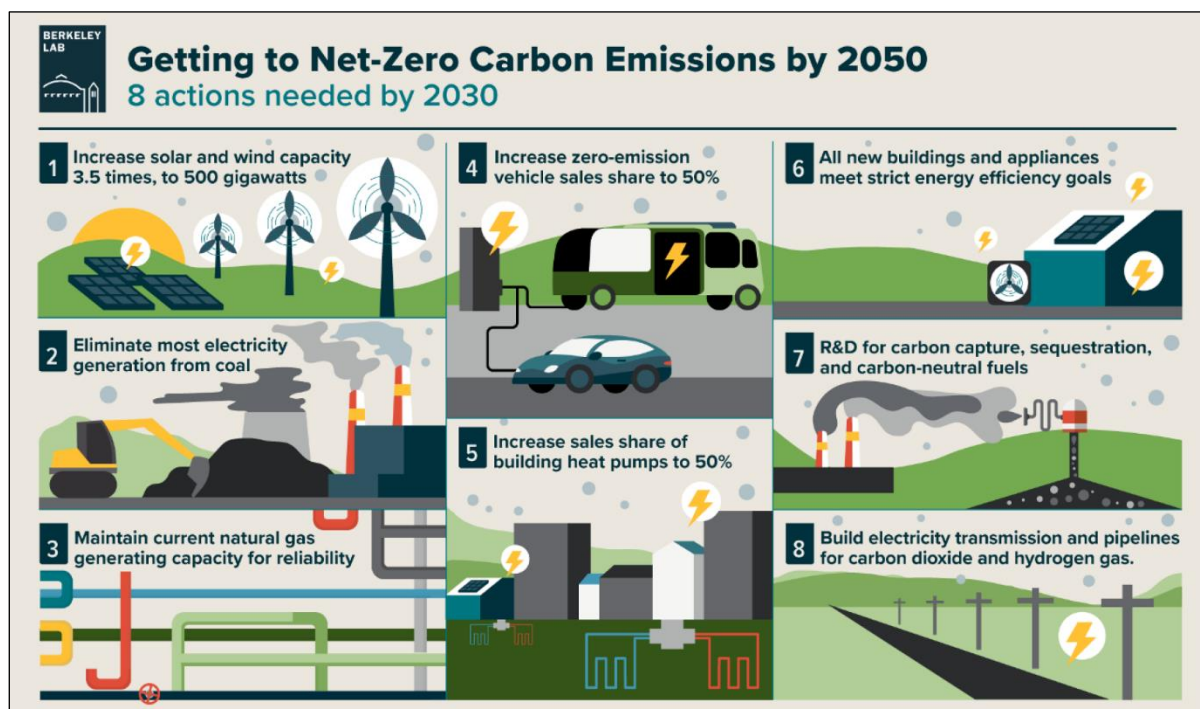


Figure 3 showcasing a roadmap for achieving global energy transition goals.

Incentives play a key role in encouraging industries to adopt sustainable practices. Subsidies and tax breaks for renewable energy-powered production systems, as well as grants for R&D in advanced catalysts and bio-fertilizers, can reduce the financial burden of transitioning to greener methods [52]. Public investments in infrastructure, such as

hydrogen production facilities and nutrient recovery systems, are also essential for creating an enabling environment for sustainable fertilizer production.

International policy alignment is necessary to ensure a coordinated approach to sustainability. Frameworks such as the Paris Agreement provide a basis for global action, but stronger commitments are needed to address the specific challenges of decarbonizing agriculture and fertilizer production [53]. Regional trade agreements that eliminate tariffs on sustainable fertilizer technologies can further facilitate their adoption.

Additionally, policy reforms must address barriers faced by smallholder farmers and developing nations. Programs that promote technology transfer and capacity-building can ensure that the benefits of sustainable fertilizer production are equitably distributed [55]. By aligning policies with sustainability targets, governments and industries can foster a resilient agricultural sector that supports both environmental and economic goals [54].

8. Conclusion

Sustainable fertilizer production stands at the intersection of addressing global food security and tackling environmental challenges. With a rapidly growing population and increasing demand for agricultural productivity, fertilizers remain indispensable in ensuring adequate food supply. However, the environmental costs of conventional production methods, including high greenhouse gas emissions, resource depletion, and soil and water contamination, underscore the urgent need for transformative approaches.

8.1. Key Innovations and Their Impact

Innovations in sustainable fertilizer production are pivotal in decoupling agriculture from its reliance on fossil fuels and unsustainable practices. Advances in green hydrogen production and its integration into ammonia synthesis offer a clear pathway for reducing emissions and achieving energy efficiency. Electrochemical processes, leveraging renewable energy and advanced catalysts, demonstrate immense potential in revolutionizing nitrogen-based fertilizers by enabling low-carbon production.

Similarly, circular economy principles, such as waste-to-energy technologies and nutrient recovery from agricultural runoff, are reshaping the production landscape. These approaches not only minimize waste but also promote resource efficiency and reduce dependency on finite reserves. Precision agriculture, supported by AI and IoT, complements these innovations by optimizing fertilizer application, reducing waste, and ensuring that nutrients are delivered effectively to crops.

8.2. Addressing Barriers and Challenges

Despite the promise of these innovations, several barriers persist in achieving widespread adoption. High capital costs, limited access to technology, and weak supply chains remain significant obstacles, particularly in developing regions. However, targeted policies, public-private partnerships, and international collaboration offer viable solutions to these challenges. Subsidies, tax incentives, and capacity-building programs can lower adoption costs and enhance technical expertise. Furthermore, investments in infrastructure and digital technologies can improve access and scalability for smallholder farmers and underrepresented regions.

8.3. The Role of Global Collaboration

The transition to sustainable fertilizer production cannot be achieved in isolation. Global collaboration among governments, industries, academic institutions, and NGOs is essential. Initiatives such as the Global Fertilizer Research Alliance and regional frameworks like the European Green Deal exemplify how coordinated efforts can drive progress. By fostering knowledge exchange, technology transfer, and inclusive participation, these collaborations ensure that advancements benefit both developed and developing nations.

8.4. Future Directions and Policy Recommendations

Looking ahead, the role of policy is critical in accelerating the adoption of sustainable practices. Strengthening global policies, such as implementing carbon pricing and mandating renewable energy integration, will incentivize industries to transition to low-carbon technologies. Tailored incentives for innovation, including funding for R&D and infrastructure development, will further catalyze progress. Additionally, addressing regional disparities in fertilizer access and production is imperative. Programs that support decentralized production systems, enhance local capacity, and promote circular economy models can empower rural communities and reduce inequalities. Precision agriculture

and digital solutions must also be made accessible to smallholder farmers, ensuring their active participation in the sustainability transition.

8.5. A Sustainable Future for Fertilizers

By aligning innovations in technology, collaboration, and policy, the fertilizer industry can redefine its role in global agriculture. Sustainable fertilizer production not only addresses pressing environmental concerns but also fosters economic growth, empowers communities, and enhances food security. These efforts must be holistic and inclusive, recognizing the interconnectedness of environmental, economic, and social goals. The journey toward sustainable fertilizers is not without challenges, but the opportunities for positive change are immense. Through collective action, investment, and innovation, the global agricultural sector can transition to a more resilient, equitable, and sustainable future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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