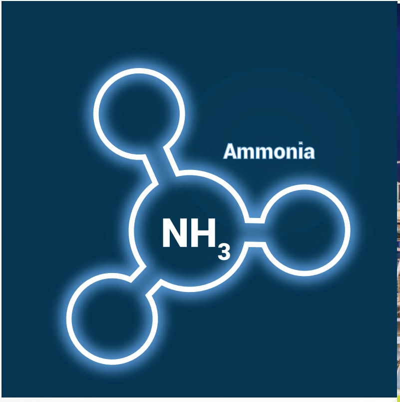
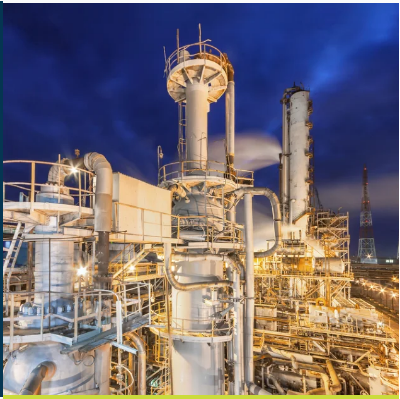
VASUDHA
FOUNDATION
Green ways for a good earth!

Fast-tracking Decarbonisation in Fertiliser Production through Green Hydrogen Innovations

January 2024





H_2

Authors- Jaideep Saraswat, Nikhil Mall, Varun B.R., Tushar Katiyar

Reviewers- Srinivas Krishnaswamy, Raman Mehta

Editorial & Design- Aman Kumar, Swati Bansal, Priya Kalia

About Vasudha Foundation

Vasudha Foundation is a non-profit organisation set up in 2010. We believe in the conservation of Vasudha, which in Sanskrit means the Earth, the giver of wealth, with the objective of promoting sustainable consumption of its bounties. Our mission is to promote environment-friendly, socially just and sustainable models of energy by focusing on renewable energy and energy-efficient technologies as well as sustainable lifestyle solutions. Through an innovative approach and data- driven analysis, creation of data repositories with cross-sectoral analysis, along with outreach to ensure resource conservation, we aim to help create a sustainable and inclusive future for India and Mother Earth.

Disclaimer

Copyright

Contents

List of Tables

List of Figures

Executive Summary

According to the United Nations, the global population is projected to reach 8.5 billion by 2030 and 9.7 billion by 2050. Meeting the food demands of this growing population requires a nearly 60 percent increase in overall food production from current levels. In this context, modernised agricultural technologies and advanced chemical fertilisers have a key role to play. These fertilisers provide essential nutrients Nitrogen (N), Phosphorus (P), and Potassium (K) that are crucial for promoting plant development. Nitrogen fosters vegetative growth, phosphorus enhances root development and flowering, and potassium fortifies resistance to environmental challenges, ranging from extreme weather conditions to pest attacks.

So far, the rise in food production has been accompanied by a corresponding increase in fertiliser production, though it comes with a notable drawback in the form of increased emissions. In 2018, ammonia production alone contributed to 11.9 percent of total Industrial Processes and Product Use (IPPU) emissions in India. Thus, meeting national climate targets necessitates the decarbonisation of the fertiliser sector. This involves greening the electricity used in the production process, eliminating emissions from heat production, and ensuring that the processing of materials for production does not release harmful emissions.

In this report we look into the production pathways of the majorly produced fertilisers in India – Urea, DAP, and complex fertilisers (NPK). We then delve into the sustainable fertiliser production routes. Two categories of production leading to low-carbon fertilisers, and renewable fertilisers are examined. Further, as Urea is the most produced fertiliser in India with over 60 percent of share in total fertiliser production, we look into the possible pathways of green urea production. The key component being the source of carbon-dioxide (CO_2), 'Green' urea is thus dependent on the source of non-fossil-based CO_2, and can be derived primarily via two routes – biomass, and Direct Air Carbon Capture (DAC).

Green ammonia and biomass are two low-hanging fruits identified in enabling sustainable fertiliser production pathways in India. A cost comparison between grey and green ammonia highlighted the volatility of grey ammonia owing to price shocks of natural gas. The cost of grey ammonia has precedence of exceeding the estimated cost of green ammonia **(INR 295.77/kg).** Further, an analysis of the currently available surplus biomass in India, revealed that there is a potential of **~80 LMT of ammonia production capacity in India to be harnessed.** Given the total ammonia imports hover around 20.1 LMT, this builds a case for developing a biomass feedstock value chain to support production of green urea via carbon-neutral biomethane.

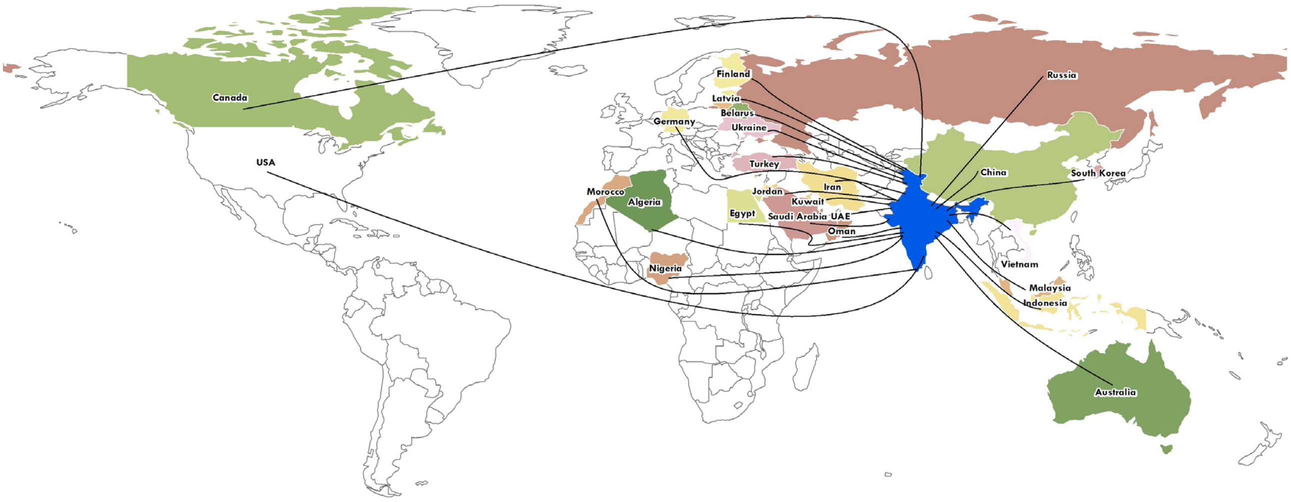
The report additionally examines case studies involving nitrogenous fertilisers that are not urea-based, exploring their potential prospects going forward. Finally, the report provides key recommendations derived from the study. The recommendations are divided into strategies for decarbonising existing fertiliser production units and ensuring that new units achieve a net-zero status. Additionally, there are suggestions to promote the adoption of green fertilisers by farmers, emphasising the mandate for maintaining stable fertiliser procurement prices and ensuring ease of applicability for farmers at all times.

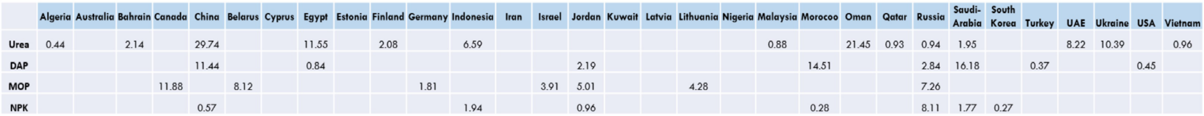
1

Introduction

Globally, India is the second-largest consumer of fertilisers and its third-largest manufacturer. In FY 1990-91, the annual production stood at 222.3 Lakh Metric Tonne (LMT)[1]. Three decades hence, the fertiliser production in the country has nearly doubled with 436.6 LMT[1] recorded in FY 2021-22, as a result of concerted policy efforts. The major fertilisers produced in India are Urea, Di-ammonium Phosphate (DAP), and Complex Fertilisers, with Urea constituting over 60 percent of the production. Presently, there are 33 large-size urea manufacturing units, and 21 units producing DAP and complex fertilisers[2]. Despite significant production infrastructure, India imported 182.28 LMT of fertilisers to meet the consumption demand in FY 2021-22[3]. The import dependency across various nations is illustrated in Figure 1, which captures India's fertiliser import for the year FY 2020-21. The total demand for fertilisers is expected to grow at a faster rate, with estimates suggesting a total requirement of 573 LMT[4] by 2030 in India.

In India, Nitrate fertilisers occupy a 75.27 percent[1] share in its overall fertiliser production. Nitrogen is a critical element





	Algeria	Australia	Bahrain	Canada	China	Belarus	Cyprus	Egypt	Estonia	Finland	Germany	Indonesia	Iran	Israel	Jordan	Kuwait
Urea	0.44		2.14		29.74			11.55		2.08		6.59				
DAP					11.44			0.84							2.19	
MOP				11.88		8.12					1.81			3.91	5.01	
NPK					0.57							1.94			0.96	

	Latvia	Lithuania	Nigeria	Malaysia	Morocoo	Oman	Qatar	Russia	Saudi-Arabia	South Korea	Turkey	UAE	Ukraine	USA	Vietnam
Urea				0.88		21.45	0.93	0.94	1.95			8.22	10.39		0.96
DAP					14.51			2.84	16.18		0.37			0.45	
MOP		4.28						7.26							
NPK					0.28			8.11	1.77	0.27					

Figure 1: India's country-wise fertiliser imports for FY2020-21[5]

for crop growth. Ammonia forms the key link to fixating atmospheric nitrogen in the soils and is thus an essential part of fertiliser production. Globally, about 70 percent[6] of all ammonia produced is utilised in fertiliser production. Further, ammonia production is an energy-intensive process consuming about 2 percent of the total global final energy consumption (in FY2021). Currently, ammonia production is heavily dependent on fossil-fuels. Natural gas-based steam reforming, and coal gasification form the primary modes of ammonia production. This has resulted in global direct emissions amounting to 450 $MtCO_2$,[6] as recorded in FY2021.

In light of India's NDCs which aim to reduce emissions intensity of its GDP by 45 percent by 2030 from the 2005 level[7], there is a need to support the fertiliser sector to abate emissions and adopt sustainable production pathways. Ammonia production solely contributes to about 1 percent of India's economy-wide emissions[8]. Hydrogen, which is one of the key inputs to produce ammonia, provides an opportunity to drive decarbonisation in fertiliser production, by greening the hydrogen produced to derive ammonia. India has been a pioneer in extending support to the hydrogen ecosystem with supporting regulations such as the launch of the National Green Hydrogen Mission 2021, and the roll-out of the National Green Hydrogen Policy, 2022. A detailed Hydrogen mission document was also released in 2023. Further, the G20 New Delhi Leader's Declaration also commits to support the acceleration of production, utilisation, as well as the development of transparent and resilient global markets for hydrogen produced from zero and low-emission technologies and its derivatives such as ammonia[9].

1.1 Scope of Study

The fertiliser sector value chain is represented in Figure 2. The value chain begins with the extraction and processing of key minerals, followed by the transportation of these raw materials such as Phosphates, Nitrogen, and Potash to the manufacturing plants. Post-manufacturing, the products are distributed to the retailers who blend the materials in the desired proportions to suit the crop type and demand. Various energy-consuming processes are involved at each stage of the value chain. For example, Nitrogen which is a key element for fertiliser manufacturing is separated from the air via prominent industrial methods such as membrane nitrogen generators, and pressure swing adsorption (PSA) nitrogen generators[10]. However, nitrogen generators with a specific energy consumption of 0.549 kWh/kg[11] are relatively less energy-intensive when compared with energy requirements at the fertiliser production stage. The energy intensity of Ammonia production using fossil fuel as feedstock (brown ammonia) stands at 8kWh/kg[12]. Thus, the focus of this study is primarily on fertiliser production where the prospects of integrating green hydrogen are probed as a key vector to abate emissions in this sector.

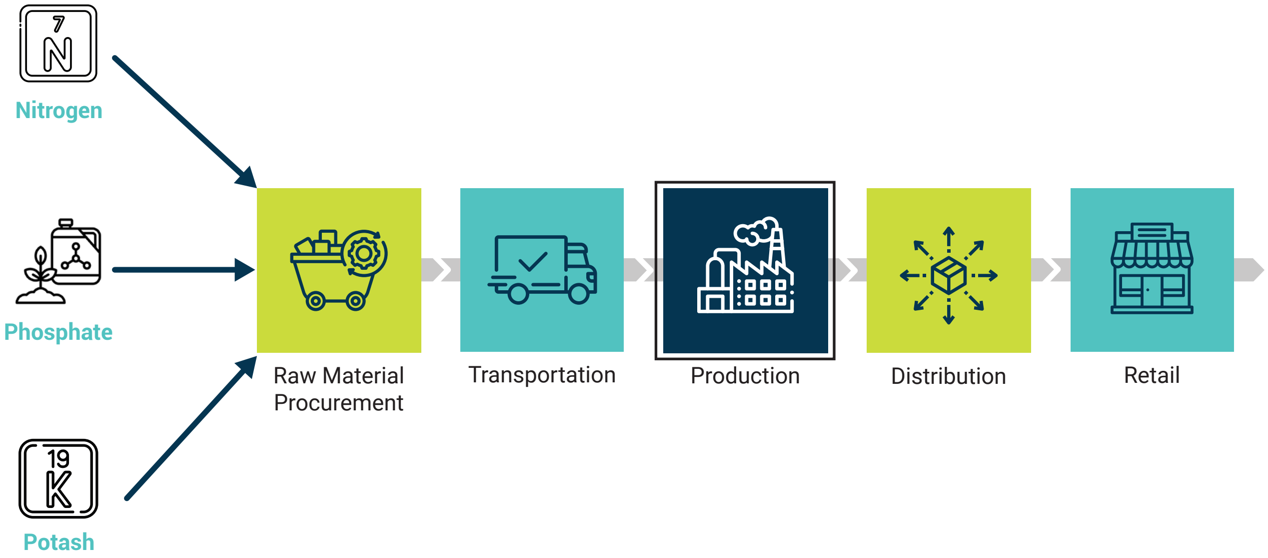


Figure 2: Schematic representation of the fertiliser sector value chain[13]

2

Key Facets Concerning Fertiliser Production

2.1 Overview of Different Fertiliser Types

In India, three broad categories of fertilisers are produced – Straight Nitrogenous, Straight Phosphatic, and Complex Fertilisers (NP/NPK). The various types of fertilisers are listed in Table 1, along with their grade, which quantifies the nutrient content present by percent weight in the corresponding fertiliser product.

Table 1: Types of fertilisers produced in India[14]

Fertiliser type	Fertiliser product	Grade
Straight Nitrogenous	Ammonium Sulphate	20.6% N
	Calcium Ammonium Nitrate	25% N
	Ammonium Chloride	25% N
	Urea	46% N
Straight Phosphatic	Single Super Phosphate	16% P2O5
	Triple Super Phosphate	46% P2O5
Complex Fertilisers	Urea Ammonium Phosphate	24-24-0 (N-P-K)
		28-28-0 (N-P-K)
		14-35-14 (N-P-K)
	Ammonium Phosphate Sulphate	16-20-0 (N-P-K)
		20-20-0 (N-P-K)
	Diammonium Phosphate (DAP)	18-46-0 (N-P-K)
	Mono Ammonium Phosphate (MAP)	11-52-0 (N-P-K)
	Nitro Phosphate	20-20-0 (N-P-K)
		23-23-0 (N-P-K)
	Nitro Phosphate with Potash	15-15-15 (N-P-K)
	Other NPKs	17-17-17 (N-P-K)
		14-28-14 (N-P-K)
		19-19-19 (N-P-K)
		10-26-26 (N-P-K)

Geographic Presence of Fertiliser Production Units

As illustrated in Figure 3, Uttar Pradesh has the largest share (~19 percent) in fertiliser production facilities, followed by Gujarat and Andhra Pradesh[15]. Correspondingly, these states also possess the maximum number of fertiliser production plants – 9, 5, and 4 respectively . India's total fertiliser production capability stands at 419.11 LMT[11] as of FY 2022-23[15].

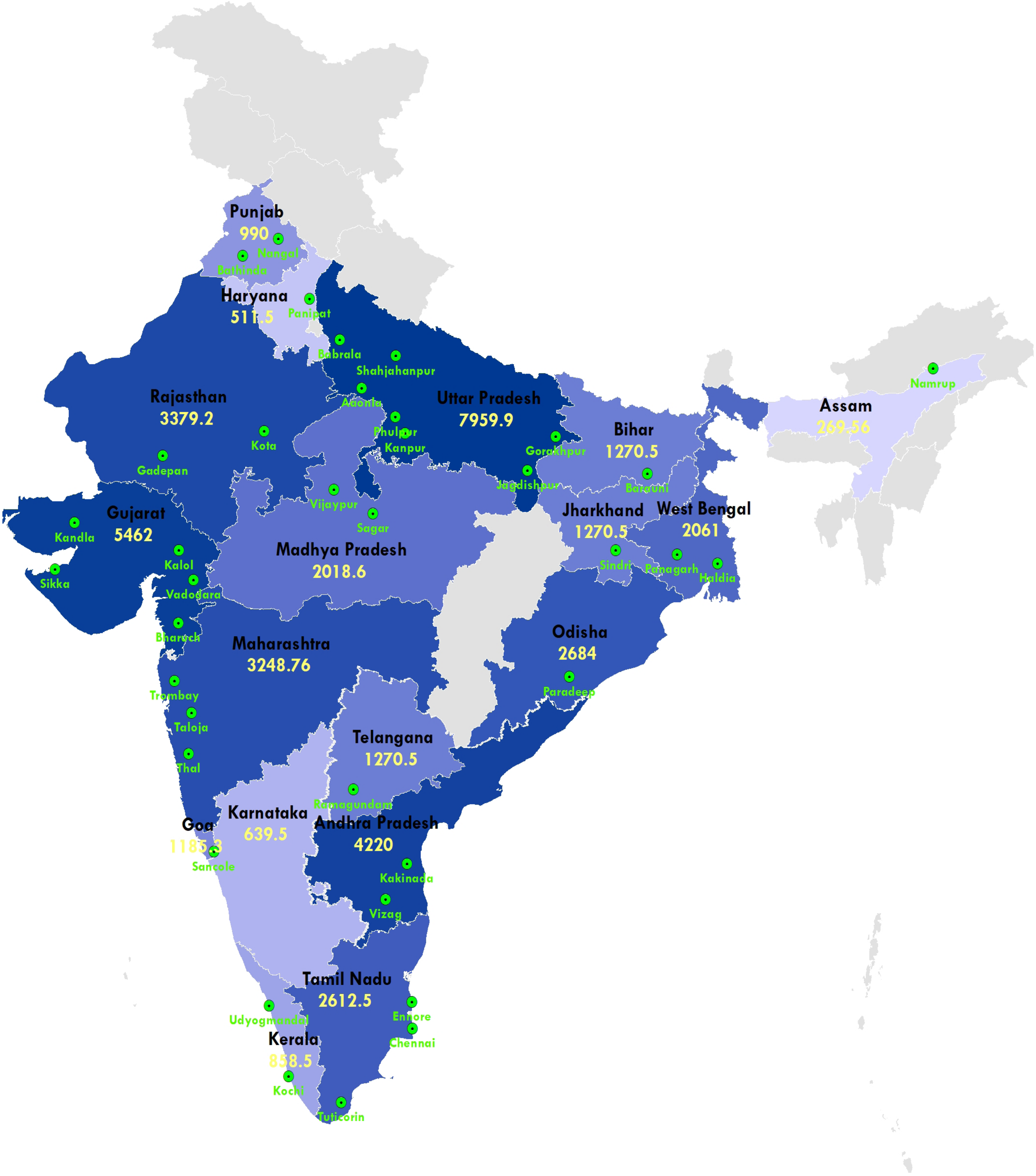


Figure 3: State-wise fertiliser production units in India (in thousand metric tonnes)[15]

Demand Scenario of Major Fertilisers in India

Over the past decade, the production of major fertilisers in India has shown an increasing trend, indicative of progressive demand. For example, Urea production has grown at a CAGR of 1.42 percent from 227.15 LMT in FY 2013-14 to 250.71 LMT in FY 2021-22[14]. This growth has been attributed to a favourable policy environment that has facilitated investments across the sector. Table 2 captures the quantum of production of Urea, DAP, and other complex fertilisers across the public, private, and cooperative segments in FY 2021-22.

Table 2: Production of major fertilisers in India[15]

Type of Sector	2021-22		
	Urea (in Lakh Metric Tonnes)	DAP (in Lakh Metric Tonnes)	Complex Fertilisers (in Lakh Metric Tonnes)
Public Sector	63.84	-	14.23
Cooperative sector	65.68	26.87	16.48
Private sector	121.19	15.34	52.56
Total	250.71	42.21	83.27

The consumption of fertilisers has been growing steadily owing to demand-side attributes such as increasing population, increased area under irrigation, rising average minimum support price, and supply-side factors such as government subsidies, and expenditure on importing fertiliser. India's population is expected to reach 1.5 billion[16] by 2030, and will constitute ~17.5 percent of the world's population. To support the growing demand, Figure 4 showcases the projected growth in fertiliser consumption up to 2030 which is expected to reach 573.2 lakh tonnes. Concomitantly, fertiliser usage per hectare is expected to increase to 277.27 kg/ha[17] by 2030.

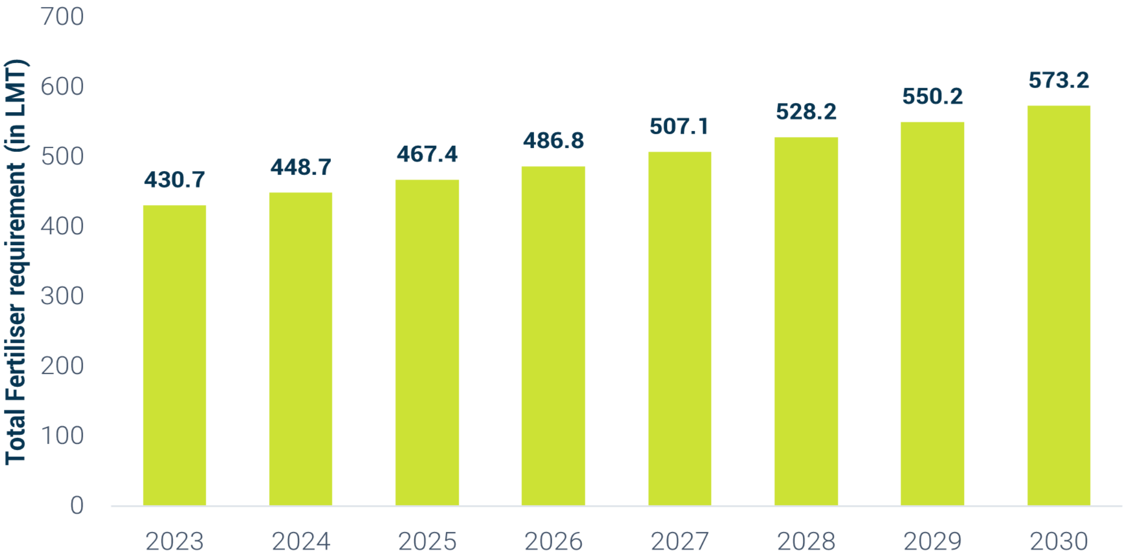


Figure 4: Total fertiliser requirement up to 2030[18]

Fertiliser imports in India

Due to limited domestic natural gas availability, India resorts to substantial imports of ammonia, including direct fertilisers like urea and DAP. The country currently imports around 2.6 million tons of ammonia[19] annually and directly imports urea and DAP, in addition to domestic ammonia production. Further, rock phosphate which is a key raw material in DAP and NPK fertiliser production is majorly import-dependent (~ 90 percent). Figure 5 shows the recent import trend of Urea, DAP and NPK. All three fertilisers have seen a rise in imports. Urea imports are the highest among fertilisers, and have grown at a CAGR of 11.2 percent, indicative of the growing demand in India.

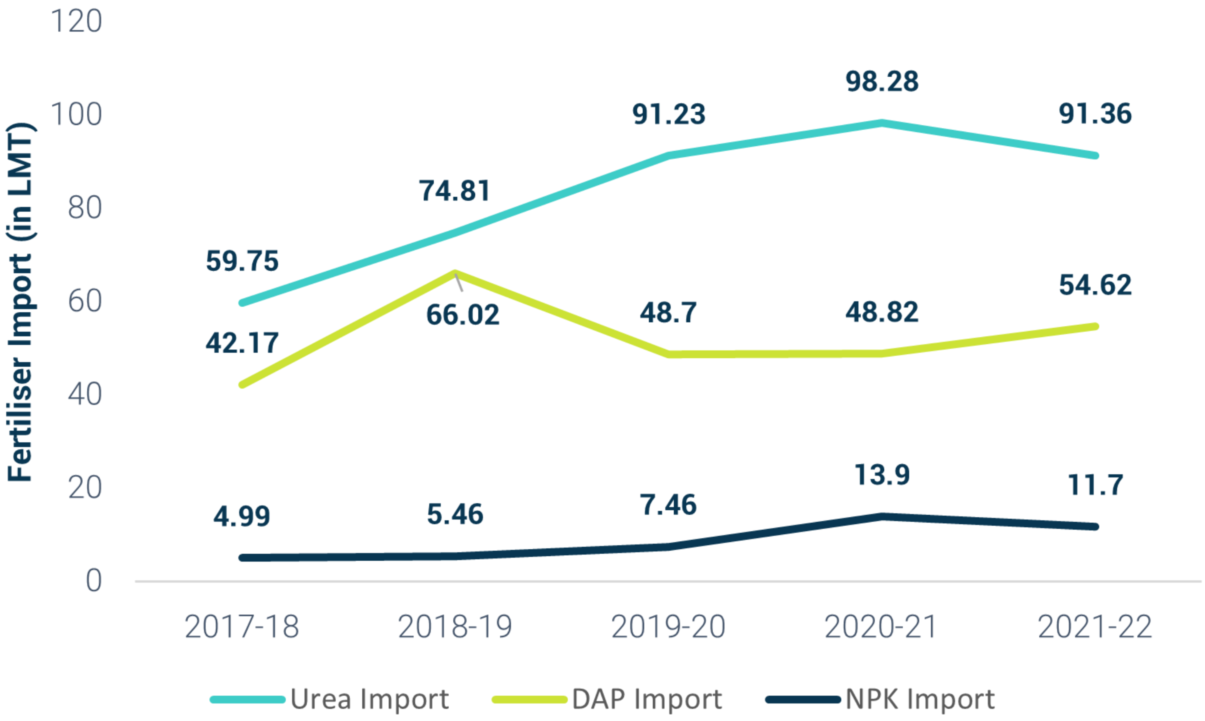


Figure 5: Import trend of urea, DAP, and NPK[15]

Government intervention to improve self-sufficiency

Under India's *Aatmanirbhar* initiative, the Department of fertilisers is working towards ramping production in phospherite deposits spread across various geographies such as Rajasthan, Lalitpur in Uttar Pradesh, and Hirapur in Madhya Pradesh. On similar lines, the government plans to revive urea manufacturing plants to increase production capacities in this year. Recently, the Talcher fertiliser plant in Odisha was commissioned[20].

Additionally, neem coating on urea has been initiated[21] to restrict its usage in other industries involved in the production of resins, glues, medical supplements, etc.

2.2 Global Scenario of Fertiliser Sector

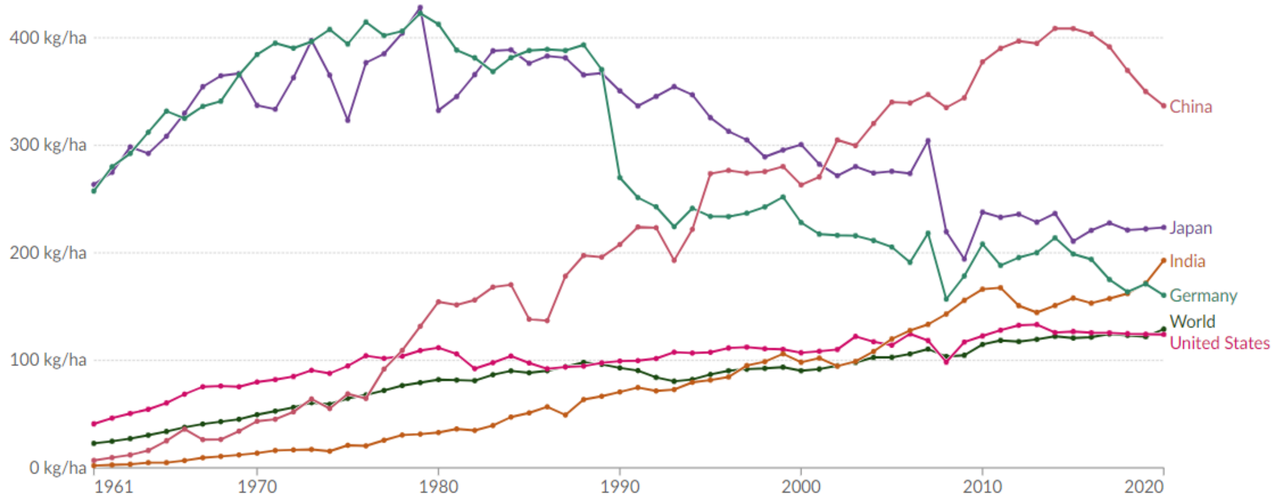


Figure 6: Fertiliser use per hectare of cropland[22]

Fertilisers have played an essential role in feeding a growing global population. It is estimated that just under half of the people alive today are dependent on synthetic fertilisers[22]. Figure 6 describes fertiliser use per hectare of cropland for the top 5 GDPs along with the global average. Global fertiliser use has seen a 42.7 percent increase since the turn of the century. Both China and India have witnessed a sharp increase in the amount of fertiliser used over the past 30 years, signifying their growing economies. In 2022, ammonia production witnessed an estimated 1 percent decline to 182.2 Mt, while phosphoric acid production exhibited a 2 percent increase, reaching 84.8 Mt after facing difficulties in 2021[23]. In contrast, global potassium chloride production is estimated to have declined by 15 percent to 62.1 Mt compared to 2021, but when assessed against 2019 levels, 2022 production demonstrated a 6 percent decrease, signifying a notable reduction from the peak years of 2020 and 2021 in potash supply[23].

Fertiliser capacity is projected to increase further in the coming years. Table 3 describes the projected growth in fertiliser capacity between 2022 and 2027. An additional 25.4 Mt of fertiliser capacity is expected to be added by 2027.

Table 3: World Fertiliser Capacity Growth 2022-27[23]

Fertiliser Capacity (in Mt)	2022	2027 (projected)
Nitrogen	190.7	201.6
Phosphate	61.7	69.1
Potash	63.3	70.4

H_2 & Electrolyser Status

In alignment with the growth of fertiliser production, there was a historic peak in 2022 in global hydrogen demand, totalling 95 Mt, indicating a nearly 3 percent year-on-year increase[24]. Despite robust growth in major consumption regions, Europe experienced a decline in industrial activity due to elevated natural gas prices. Electrolysers constitute a pivotal technology for generating low-emission hydrogen through renewable or nuclear electricity. While electrolysis capacity for dedicated hydrogen production has exhibited growth, the pace moderated in 2022, witnessing 130 MW of new capacity, a 45 percent reduction from the preceding year[24]. Nonetheless, electrolyser manufacturing capacity surged by over 25 percent, reaching nearly 11 GW per year in 2022[24]. China, spearheading both electrolysers deployment and manufacturing capacity, accounts for 40 percent of global capacity. Despite these advancements, meeting the Net Zero Emissions by 2050 (NZE) target necessitates a substantial acceleration, targeting over 550 GW of installed electrolysis capacity by 2030. Ambitious expansion plans, aiming for 155 GW/year of manufacturing capacity by 2030, have been announced by electrolyser manufacturers, yet only 8 percent of this capacity has achieved Final Investment Decision (FID)[24].

Pricing

The global fertiliser industry has witnessed notable fluctuations in recent years, influenced by various factors such as conflicts, climate variations, and economic disruptions. This period has seen a surge in fertiliser prices, particularly for nitrogen, phosphorous, and potassium fertilisers. Benchmark prices for nitrogen-based urea tripled since 2020, reaching USD 678/tonne in September 2022[25]. Simultaneously, diammonium phosphate (DAP), a key phosphorous fertiliser, experienced almost a threefold increase, reaching USD 752/tonne over the same period[15]. While potash prices remained relatively stable until 2022, the benchmark spot price surged to USD 563/tonne in March 2022[24]. Figure 7 highlights the rapid increase in fertiliser prices observed in the last two years.

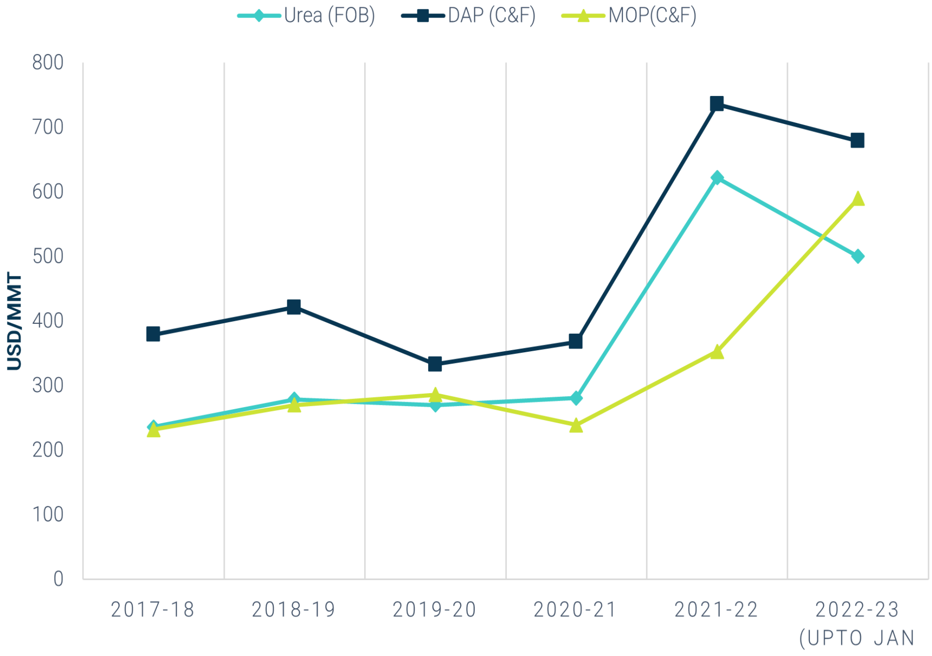


Figure 7:Trend in International Prices of Major Fertilisers[15]

2.3 Overview of Existing Fertiliser Production Processes

In this section, we delve into the production processes of the three major fertilisers produced in India – Urea, DAP, and Complex fertilisers (NPK). Ammonia and its derivatives constitute key raw materials in the production of these major fertilisers.

Urea

Urea is most commonly produced by reacting carbon dioxide and ammonia. Owing to the requisite raw materials, urea production is generally co-located in an ammonia production plant, where carbon-dioxide is derived as a by-product. Figure 8 illustrates a schematic representation of the urea production process. The process is initiated by reacting liquid ammonia and carbon-dioxide in the synthesis tower, where two primary reactions take place. First, ammonia and carbon-dioxide undergo an exothermic reaction to form ammonium carbamate. This product is then passed to the second stage of the synthesis tower, where it is dehydrated to yield urea and water, in an endothermic reaction. The overall reaction remains exothermic. Along with water, there are other impurities such as unreacted ammonia, and ammonium carbamate. Subsequent stages involve carbamate decomposers aimed at eliminating the corrosive carbamate, which can potentially damage process equipment. This can be achieved through a stripping process where CO_2 serves as the stripping agent. In the final processing steps, the urea solution undergoes vacuum decomposition and is then directed through a prilling tower to yield granulated urea as the end product, with less than 1 percent biuret formation.

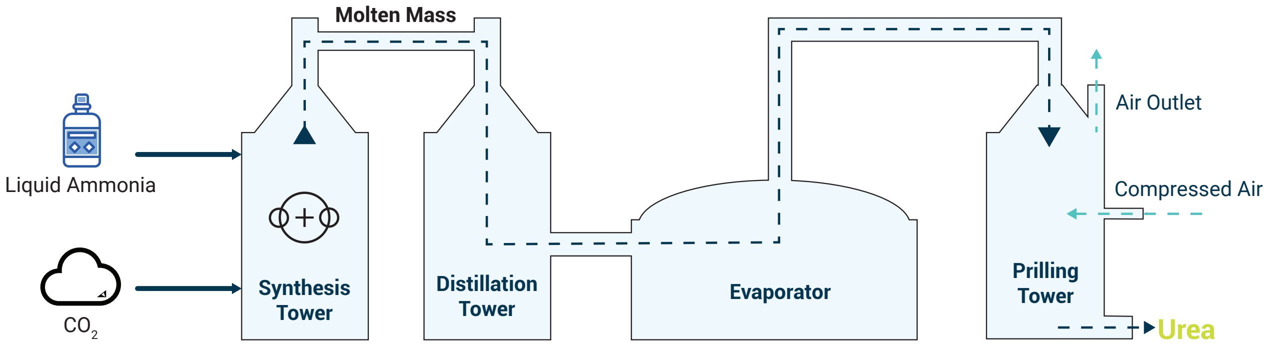


Figure 8: Schematic representation of Urea Production Process[26]

Di-Ammonium Phosphate

In the presence of sulphuric acid and steam, phosphoric acid is partially neutralised with anhydrous ammonia in the pre-neutraliser stage to form a slurry mixture of mono and di-ammonium phosphates. As illustrated in Figure 9, the slurry is then pumped to a rotary granulator-reactor where it is further reacted with anhydrous ammonia. This results in a solid granular diammonium phosphate mixture having a range of particle sizes which is then passed through a dryer. The dried granular diammonium phosphate mixture is introduced to screeners to separate undersize and oversized granular particles, and particles which have a size in the range of 2 mm to 4 mm are collected[27]. The off-sized granular particles are milled and sent back to the granulator-reactor to repeat the process until the desired DAP granules are obtained.

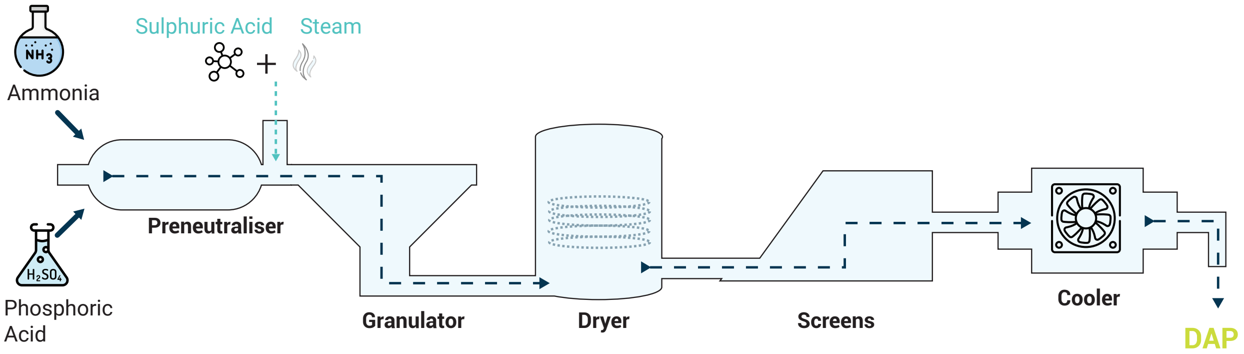


Figure 9: Schematic representation of DAP production process[28]

Complex Fertilisers

As listed in Figure 10, the raw materials are portioned according to the market demand and soil health specific to the region of demand, and introduced into the crusher, where they are transformed into a uniform powder and mixed. This is done to prevent the agglomeration of fertilisers rendering them unfit for granulation. The product is then conveyed to the granulator, where the powder is combined to form granules constituting the input materials. The resulting granules are then conveyed into the dryer to rid the granules of excess moisture. This aids in increasing particle strength, avoiding fertiliser caking, and facilitating easy transportation and storage. The resulting granules are then passed through a cooler to prevent absorption of moisture which may lead to agglomeration. The granules are then screened to be segregated to attain the desired particle size of the final product and move onto the packaging stage.

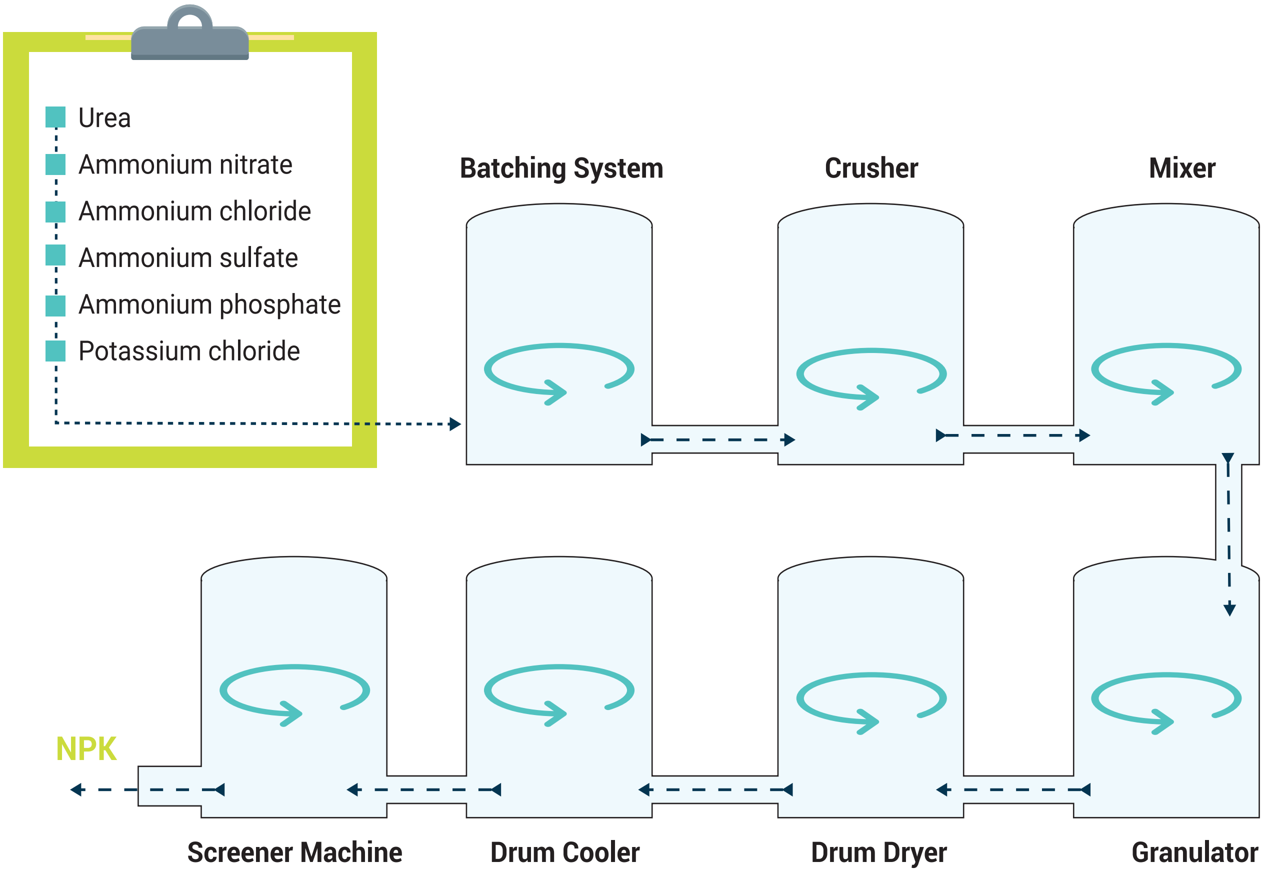


Figure 10: Schematic representation of NPK production process[29]

2.4 Sustainable Fertiliser Production

Ammonia is key to fertiliser production as illustrated in Figure 11. Currently, Ammonia is produced through the Haber-Bosch Process where nitrogen and hydrogen are combined. Hydrogen derived from natural gas via the process of Steam Methane Reforming forms the primary mode of production.

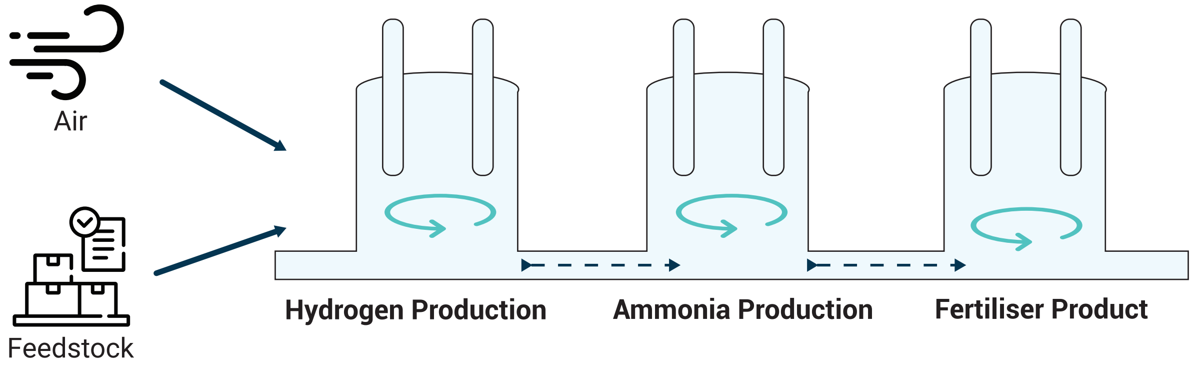


Figure 11: Conventional fertiliser production chain[30]

However, this process is emission-intensive with a direct CO_2 intensity of 1.8 tCO_2/tNH_3[31]. Table 4 captures the energy needs and accompanying emission intensities of the prominent technologies used to produce 1 tonne of ammonia. Renewable production technologies such as Electrolysis indicate a higher net energy intensity when compared with the traditional production route of Natural Gas SMR. However, with the use of renewable electricity, the direct CO_2 emissions are avoided, and thus positioning it as a sustainable production route.

Alternative sustainable production technologies[32] revolve around the feedstock used to produce hydrogen. Some of the technology options revolve around the replacement of natural gas as a feedstock with bio-methane, carbon capture and storage (CCS), and electrolysis[30]. Further, this buckets ammonia production into low-carbon (CCS, Bio-methane) and renewable (large-scale electrolysis) pathways.

Table 4: Energy needs to produce 1 tonne of Ammonia via various production routes[31]

Production route	Net Energy Intensity (GJ/ tNH_3)	Direct CO_2 intensity (tCO_2/tNH_3)
Coal Gasification	36.1	3.2
Natural gas SMR	27.6	1.8
Natural gas Auto-Thermal Reforming (ATR)	28.9	1.6
Coal with CCS	41.2	0.2
SMR with CCS	30	0.1
ATR with CCS	29.4	0.1
Electrolysis	34.4	0
Biomass Gasification	36.5	0
Methane Pyrolysis	47.3	0

Low-carbon fertilisers

In this pathway, the CO_2 released in the upstream stages is repurposed for use in the downstream stages, thus minimising the release of CO_2 to the atmosphere. The conventional hydrogen production with CCS qualifies under this type. As Figure 12 showcases, the carbon-dioxide produced during hydrogen production process is captured and stored for utilisation in other downstream processes.

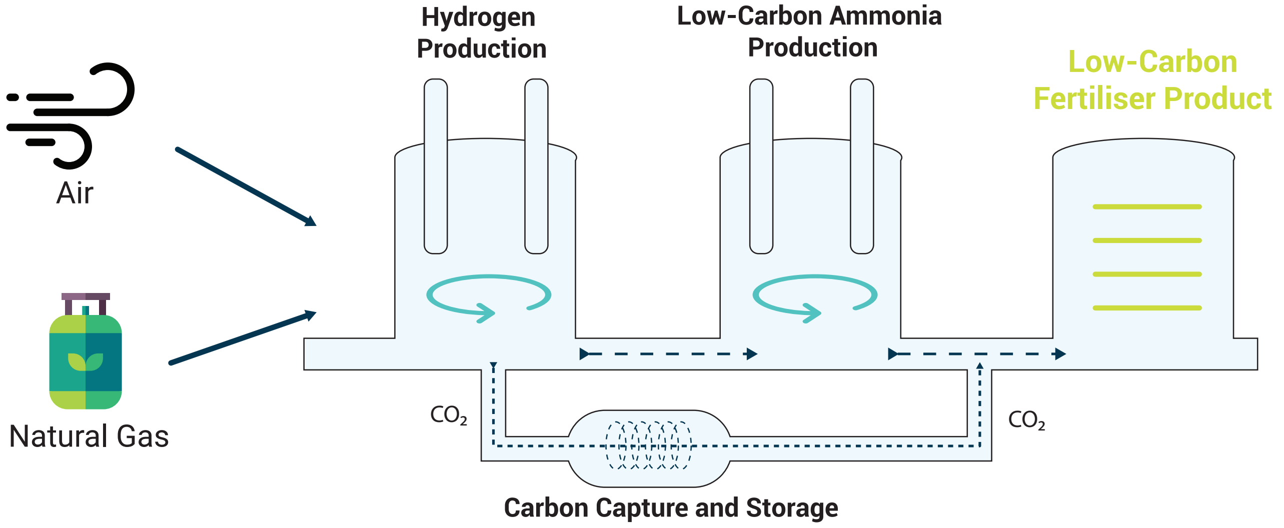


Figure 12: Low-carbon fertiliser production integrated with CCS technology[30]

Similarly, as biomass utilises atmospheric carbon-dioxide for its growth, the conversion to biomethane and use as a suitable replacement for natural gas, makes the process devoid of fossil-based carbon-dioxide. As seen in Figure 13, the process is overall carbon-neutral albeit a few losses, making it a low-carbon pathway.

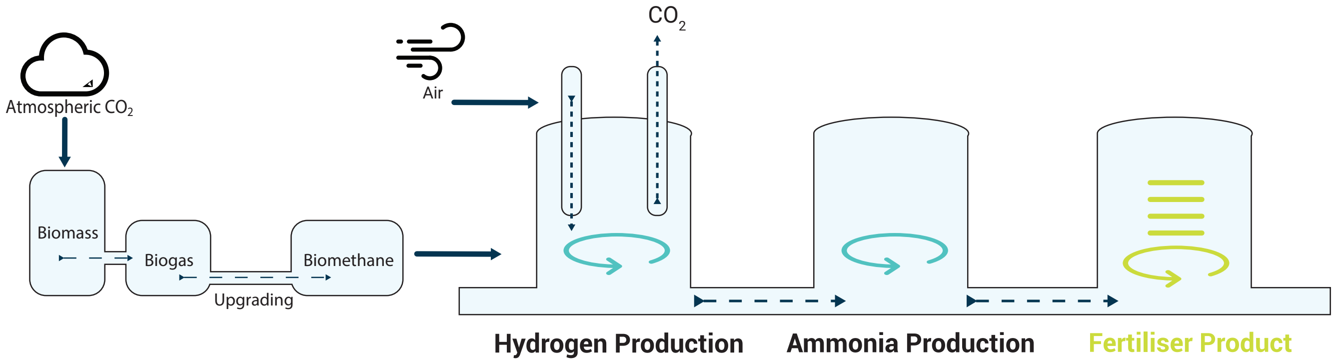


Figure 13: Low-carbon fertiliser production via utilisation of biomethane[30]

Renewable fertilisers

In this pathway, the need for CO_2 is eliminated by use of renewable production processes such as electrolysis where air, water, and electricity are the sole inputs required. Use of renewable electricity further ensures that grid-level upstream emissions are also eliminated. As seen in Figure 14, green hydrogen is directly used to produce green ammonia which results in the renewable fertilisers.

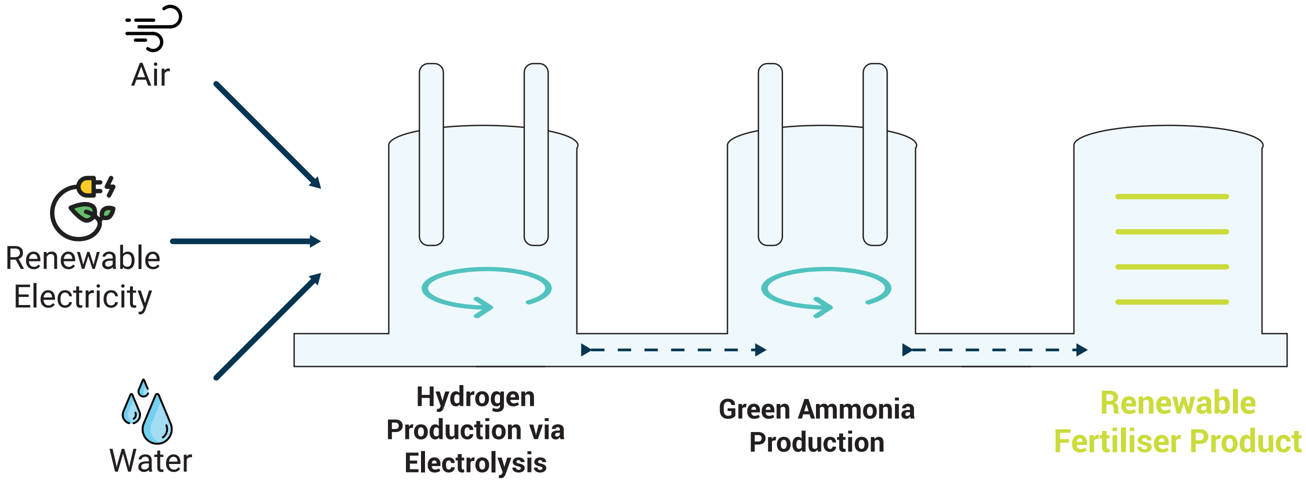


Figure 14: Renewable fertiliser production via electrolysis[13]

However, the renewable pathway that produces green ammonia can directly be used only for the production of complex fertilisers, and not urea. While the sustainable discourse revolves around carbon abatement, production of Urea requires the reaction of ammonia with carbon dioxide. Generally, the CO_2 produced in ammonia production is utilised in urea production. In the case of green ammonia, there is a need for external supply of CO_2 to produce urea. Synthesising urea from non-fossil-based sources of CO_2 is considered as a carbon-neutral pathway, as the CO_2 is captured and utilised in downstream production processes. Carbon-neutral or 'Green' urea is thus dependent on the source of non-fossil-based CO_2, and can be derived primarily via two routes – biomass, and Direct Air Carbon Capture (DAC).

Green urea production via biomass

Biomass is a renewable feedstock owing to its zero net carbon footprint. Atmospheric CO_2 used for growth is used to produce biogas which is synthesised to release CO_2 that is utilised into a downstream urea production process, as shown in Figure 15. However, biomass has wide variation in its composition, rendering varied quality of biomass feedstocks. Further, the energy content in biomass is relatively lower, and the corresponding yield of hydrogen is also lower. Three important factors determine the quality of biomass, and thereby the quantity required – moisture, energy, and mineral content. Thus, it is necessary to optimise the feedstock requirement with the production technologies, and the end-use requirement.

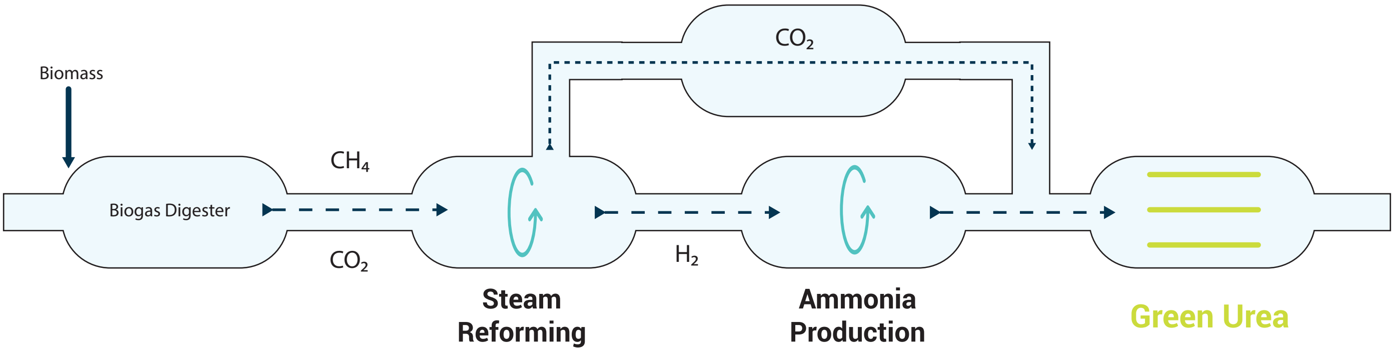


Figure 15: Green urea production route via biomass[33]

Green urea production via DAC

DAC refers to the process of extracting CO_2 from ambient air by using materials known as sorbents. It has benefits over other technology routes for CO_2 capture such as lesser land area and water consumption. It is also more acceptable as a global deployment measure as it does not compete for agricultural lands and bioresources, which are scarce. The green ammonia produced via renewable pathways and the CO_2 released from the DAC unit are sent to the urea synthesis plant, resulting in green urea as shown in Figure 16.

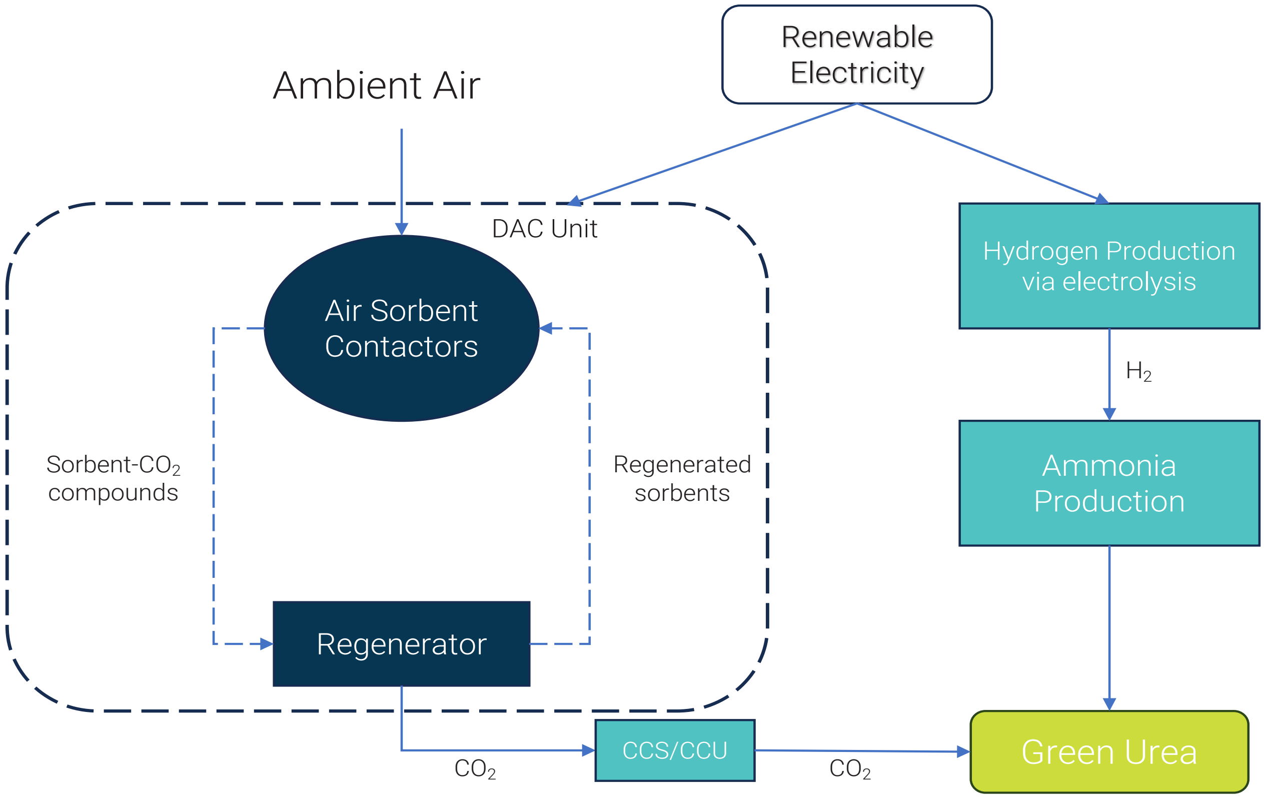


Figure 16: Green urea production via DAC[33]

DAC unit process

Liquid absorption and solid adsorption, are the primary approaches used to remove CO_2 in bulk from the atmosphere. Usually, the sorbents are placed in contact with air to react with the CO_2 present. At a later stage, the CO_2 is released in a regenerator, and the sorbents are sent back to the contactor unit. The CO_2 released from the regenerator is high in concentration, and does not require further purification before use in urea production process.

Case Study: NitroCapt's LIFE SUNIFIX Project[32]

NitroCapt is a sustainable agri-tech company headquartered in Sweden. Their flagship solution - SUNIFIX (Sustainable Nitrogen Fixation) is a revolutionary climate-neutral process to achieve nitrogen fixation. In this patented process - air, water, and electricity are the only inputs necessary for production. The innovation in infrastructure combines an energy-efficient reactor based on plasma technology, electromagnetic energy coupling, and advanced turbine technology.

This groundbreaking initiative aims to replace the traditional Haber-Bosch process for ammonia production in the European Union which forms a USD 80 billion nitrogen fertiliser market resulting in 2.5 percent of the global fossil-based GHG emissions. Further, the process enables intermittent operation, thus raising compatibility with renewable sources of electricity, including off-grid units. This can potentially result in creating a locally self-sufficient nitrogen fertiliser production ecosystem that is resilient to global energy price fluctuations.

3

Green Hydrogen Integration in Fertiliser Production

3.1 Hydrogen Ecosystem in India

India currently holds the position of the world's third-largest consumer and producer of hydrogen, following China and the USA. Projections indicate a substantial surge in hydrogen demand within India, expected to rise between 2.5 to 3.5 times by 2040[34]. Despite this growth, hydrogen's contribution to India's overall primary energy consumption is anticipated to remain below 5 percent by 2040, given the significant expansion in energy needs. The challenges associated with high hydrogen transportation costs emphasize the necessity for establishing supply centres near demand hubs, fostering the creation of hydrogen hubs and valleys. This dynamic scenario opens promising avenues for clean hydrogen suppliers, envisioning a market scale of approximately $27 billion per year by 2030 and around $40 billion per year by 2040[34].

India's electrolyser manufacturing landscape is currently in its early stages, marked by the presence of half a dozen alkaline electrolyser manufacturers, according to the Ministry of New and Renewable Energy. Independent sources claim existing electrolyser manufacturing capacity in the country stands at 300 MW[35]. Forecasts suggest that India's domestic market for electrolysers could reach $31 billion by 2050, reflecting a demand for 226 GW[36]. In the shorter term, by 2030, an estimated demand of 20 GW is anticipated, highlighting the nation's potential for substantial growth in the hydrogen ecosystem.

Regulatory Status

The Ministry of New and Renewable Energy (MNRE) defined Green Hydrogen as hydrogen produced using renewable energy where emissions arising from the production method shall not exceed 2 kilogram of carbon dioxide equivalent per kilogram of Hydrogen (kg CO_2 eq/kg of Hydrogen), taken as an average over the last 12 months[37].

In January 2023, the Government of India (GoI) approved the National Green Hydrogen Mission (NGHM) with a budget of Rs 19,744 crore, aiming to position India as a global hub for green hydrogen. The mission targets the establishment of 5 MMT per annum of green hydrogen production capacity by 2030. The mission focuses on creating hydrogen hubs and pilot projects showcasing hydrogen-based technologies integrated with renewable energy sources. Two initial financial incentive mechanisms have been proposed, including incentives for manufacturing electrolysers and incentives for green hydrogen production.

Under the Electrolyser Production Linked Incentive (PLI), incentives extend for five years, starting at Rs 4,400/kW and gradually decreasing. Eligibility criteria prioritize high-performance in Specific Energy Consumption (SEC) and compliance with Local Value Addition (LVA) norms, emphasizing a strategic balance of SEC and LVA for optimal chances of selection among beneficiaries. Under the incentive scheme for green hydrogen production (Mode 1), beneficiaries will receive a direct incentive in ₹/kg for a 3-year period, capped at ₹50/kg in the first year, ₹40/kg in the second, and ₹30/kg in the third year. Selection, based on the least averaged incentives, will be conducted through competitive bidding via SECI tenders.

The electrolyser manufacturing initiative, under the PLI scheme, garnered bids for setting up 1.5 GW capacity, with 21 firms vying for incentives to establish 3.4 GW of electrolyser manufacturing capacity against the offered 1.5 GW[38]. The green hydrogen production incentive scheme, under Mode 1, attracted bids from 14 firms for setting up facilities producing 5,53,730 tonnes of green hydrogen against the offered 4,50,000 tonnes of green hydrogen under the Strategic Interventions for Green Hydrogen Transition (SIGHT) Scheme (Mode-1-Tranche-I)[39].

Apart from the central government, numerous states have also released their own policies to promote the Green Hydrogen ecosystem. A snapshot of all the state policies and incentives is provided in Table 5-

Table 5: State-level Green Hydrogen Policies

State	Provision
Rajasthan[40]	• Provision of adequate land near RE producing units at competitive rates • 100% Electricity duty payment exemption for 7 years • 100% Land tax exemption for 7 years • 100% exemption from payment of stamp duty and change of land use and conversion of land • Exemption from payment of open charges, wheeling charges, transfer charges, electricity duty and banking charges for use of RE for 14 years • One-time reimbursement of 50% of the cost of acquiring advanced technology from premiere national institutes capped at INR 2 crores • First 5 manufacturing units investing more than 50 crores shall receive the following subsidies on plant and machinery: (a) 5% interest subsidy on term loan for 5 years, up to 10 crores per year (b) 20% capital subsidy up to INR 50 crores
Uttar Pradesh (Draft)[41]	• Gvernment has set a target for having 20 percent green hydrogen blending in the state by 2028 and reaching 100 percent by 2035 • Promote production & consumption of 100 percent green hydrogen/ammonia in new units from 2025 onwards • Setting up of a Green Hydrogen Ecosystem Funds

Maharashtra[42]	• Green Hydrogen/Ammonia Manufacturing Zone/cluster • State to give land to manufacture hydrogen-run vehicles • BEST (Brihanmumbai Electric Supply and Transport) has proposed to convert over 200 diesel-run buses into those running on green hydrogen • RE Policy may be Amended soon with Hydrogen context • Government in talks with Avaada Group for setting up a green hydrogen project worth Rs 45,000 crore in the state • JSW and Maharashtra government to work for 960 MW Pumped Hydro Storage Project
Andhra Pradesh[43]	• To target Green Hydrogen production up to the capacity of 0.5 MTPA (Million Tonnes Per Annum) or Green Ammonia production up to the capacity of 2.0 MTPA in the next five years • To create 12,000 jobs per Million Tonne Per Annum (MTPA) production of Green Hydrogen in the State • Land to be allocated for development of both Green Hydrogen/Green Ammonia Plants on priority basis at lease rate of INR 31,000 per acre per year with an escalation of 5% every two years during the project period • 100% exemption of Electricity Duty for the power consumed for production of Green Hydrogen/Green Ammonia from RE plants (with or without storage) for a period of five (5) years from CoD
Gujarat[44]	• Have released policy for leasing out government fallow land for green hydrogen production using non-conventional energy sources • The annual rent of the land allotted by the government will be Rs 15,000 per hectare
Kerala[45]	• Kerala is the first state to include hydrogen-powered mobility in its zero-emissions mobility policy • KSRTC has plans to buy 10 hydrogen buses • Hydrogen refilling infrastructure in nascent stage • 3-4 parallel processes for sorting hydrogen refilling under way • Production of green hydrogen from Kochi airport's solar power facility

Demand in the Fertiliser Sector

Currently, the primary uses of pure hydrogen include the refining of crude oil, constituting 52 percent of its applications, and ammonia (NH_3) production, which accounts for over 42 percent[46]. Ammonia, the second most frequently produced chemical globally, finds predominant use in the fertiliser sector, with 85 percent of the total production directed towards this industry[47]. Consequently, the fertiliser sector has become a major hydrogen consumer in India, constituting nearly 48 percent of the country's hydrogen demand in 2020[48]. Since the green revolution in the 1960s, India has heavily depended on inorganic fertilisers to boost agricultural output, making it the second-largest global consumer of fertilisers with approximately 63.94 million metric tons consumed in 2021-2022[49]. About 75 percent of these fertilisers are nitrate-based and rely on ammonia as a key raw material. The total grey ammonia demand in FY2022 stood at 16942.31 kT[50]. Concomitantly, the total grey hydrogen demand was 3037.53 kT[50]. Figure 17 below depicts the state-wise demand for grey hydrogen and grey ammonia vis-à-vis fertiliser production.

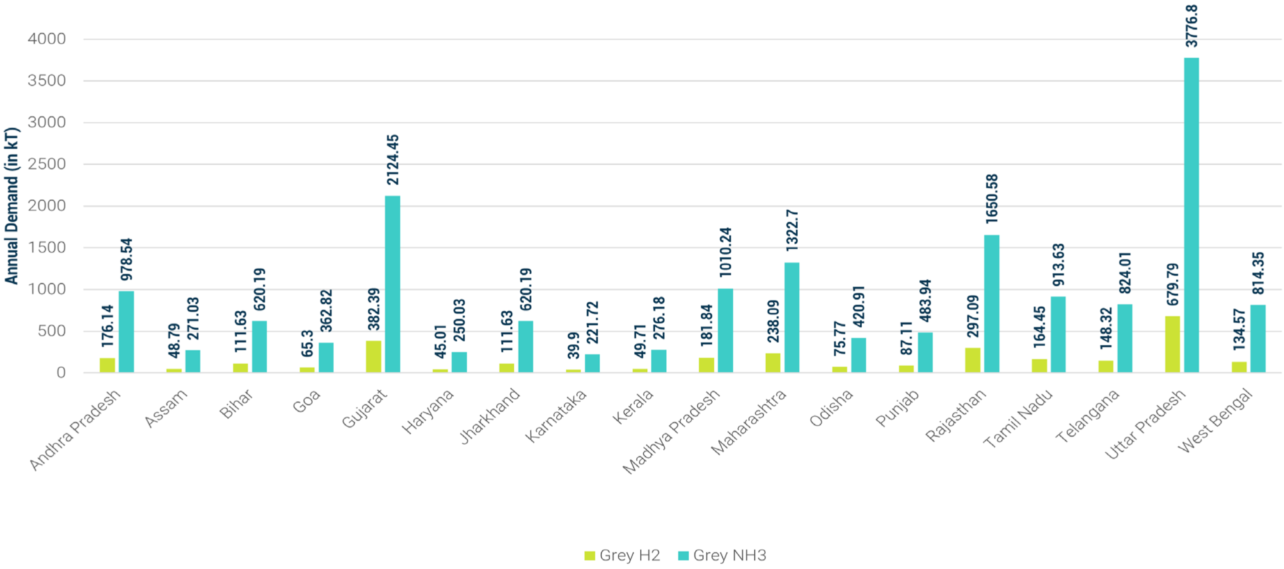


Figure 17: State-wise grey hydrogen and grey ammonia demand in India[50]

Further analysis into the hydrogen demand attributed to specific fertiliser products in India showcased that Urea constituted over 80 percent of the demand share in FY 2022.

Concomitantly, as observed in Figure 18, grey ammonia demand was highest for Urea with a share of ~82 percent.

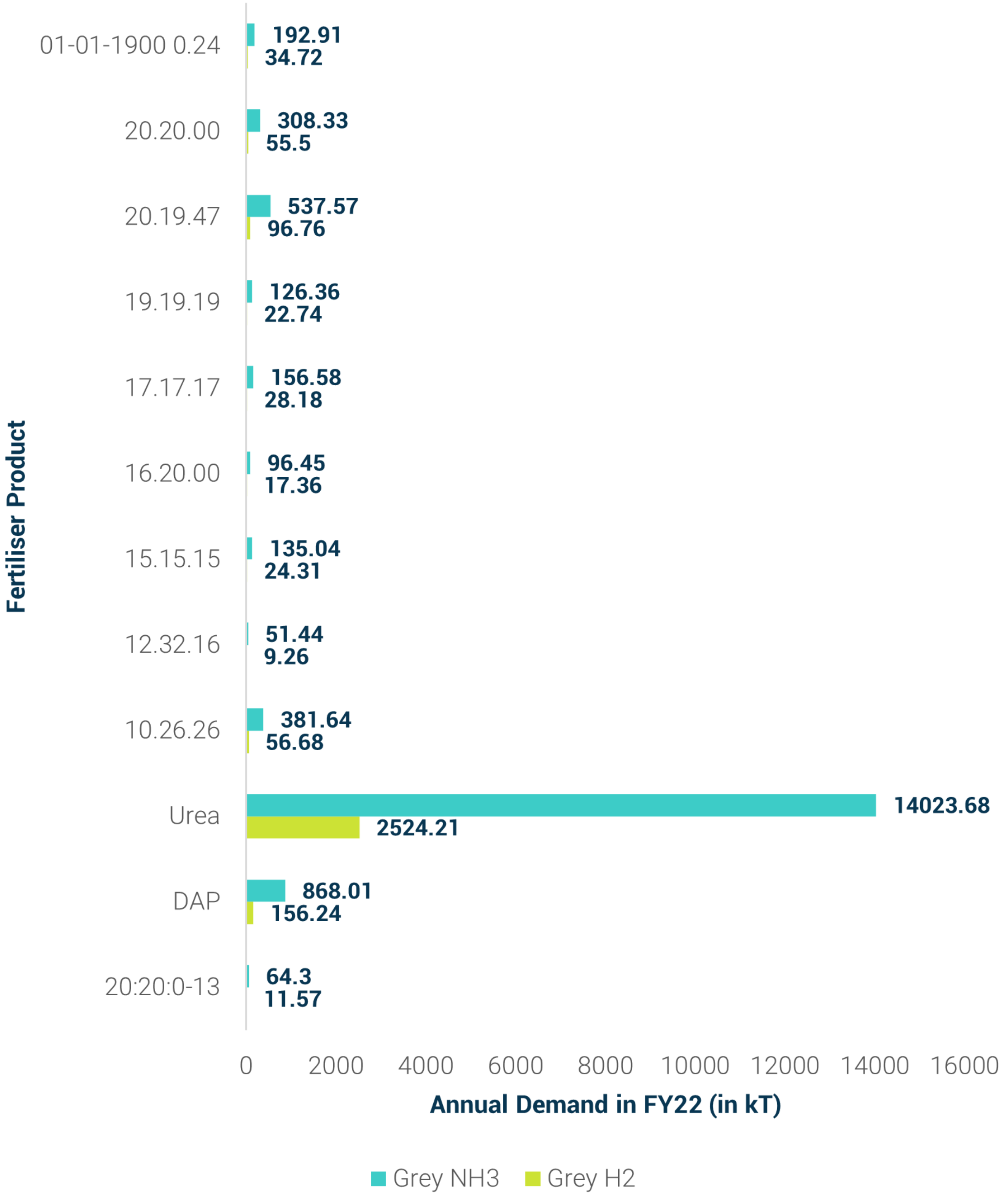


Figure 18: Fertiliser-product-wise grey hydrogen and grey ammonia demand in India[50]

3.2 Hydrogen Production Technologies in India

Hydrogen, the most abundant gas in the universe, possesses the highest energy content per weight among known fuels. Despite its abundance, free-form hydrogen is not naturally available. Molecular hydrogen can be obtained from diverse sources, including fossil fuels and renewable resources such as biomass and water splitting through solar, wind, hydroelectric, and geothermal energy. Figure 19 illustrates various pathways for hydrogen production, categorized into fossil fuels and renewable resources. Fossil fuels-derived methods involve coal gasification, hydrocarbon reforming, and pyrolysis. On the other hand, renewable resources-based production encompasses biomass processes and water splitting using renewable energy. This report will focus on renewable-energy-based methods.

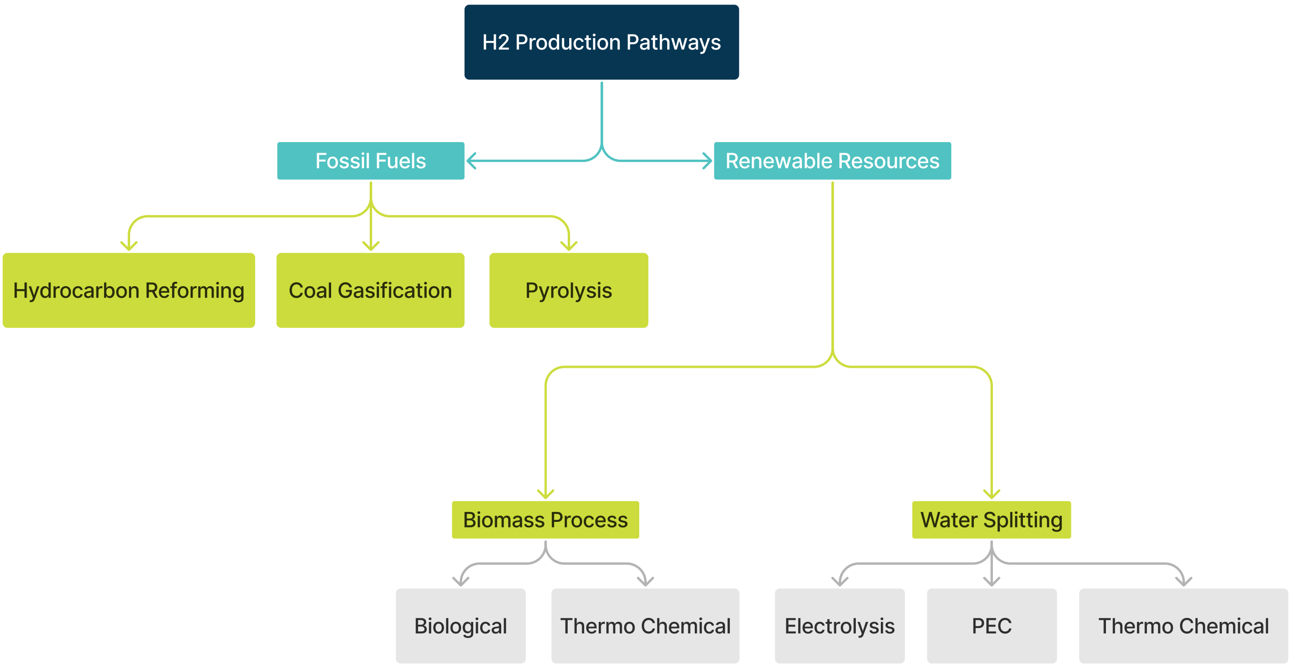


Figure 19: Different pathways for hydrogen production[51]

Hydrogen production from biomass

Biomass, derived from renewable organic matter, serves as a valuable source for hydrogen production through either biological or thermochemical processes. In biological processes, dark fermentation utilises anaerobic bacteria to produce hydrogen, organic acids, and CO_2 from carbohydrate-rich substrates, while photofermentation employs photosynthetic bacteria under anaerobic conditions, utilising sunlight to generate hydrogen and CO_2 from biomass. Thermochemical processes, including pyrolysis, gasification, and hydrothermal liquefaction, represent effective methods for producing hydrogen-rich gas from biomass. Pyrolysis involves the thermal decomposition of biomass at high temperatures, yielding biochar, bio-oil, and hydrogen-rich gases. Biomass gasification converts dry biomass into a combustible gas mixture, primarily composed of CO and H_2. Both biological and thermochemical processes offer promising routes for sustainable hydrogen production from biomass, with ongoing research focused on optimizing efficiency, enhancing yields, and contributing to a future where biomass-derived hydrogen plays a significant role in meeting global energy demands.

The processes have been summarized In Table 6 below.

Table 6: Summary of hydrogen production technologies from biomass

Hydrogen Production Techniques from Biomass [52]	Dark Fermentative Hydrogen Production	Photofermentative Processes	Pyrolysis	Gasification	Hydrothermal Liquefaction[53]
Feedstock	Carbohydrate-rich substrates	Organic molecules	Biomass (forest residues, crops, municipal waste, microalgae, animal byproducts)	Biomass (forest residues, crops, municipal waste, microalgae, animal byproducts)	Biomass (forest residues, crops, municipal waste, microalgae, animal byproducts)
Key Products	Hydrogen, organic acids, CO_2	Hydrogen, CO_2	Biochar, bio-oil, non-condensable gases, including hydrogen	Combustible gas mixture primarily composed of CO and H_2	Liquid biofuels, hydrogen, and other gaseous products
Process Characteristics	Anaerobic bacteria, operates at any time	Photosynthetic bacteria, sunlight-dependent	Thermal decomposition at high temperatures	Conversion of dry biomass into a combustible gas mixture	Biomass conversion into bio-oil, gases, and solid residues

Hydrogen Production Techniques from Biomass [52]	Dark Fermentative Hydrogen Production	Photofermentative Processes	Pyrolysis	Gasification	Hydrothermal Liquefaction[53]
Efficiency and Yield	Limited by metabolic constraints, suboptimal hydrogen yields	High theoretical hydrogen yields, strict environmental control	Fast pyrolysis preferred for high hydrogen yield	Catalytic gasification enhances syngas production	Efficient and versatile, cleaner and concentrated hydrogen yields
Versatility and Waste Minimisation	Limited range of substrates, emphasis on waste minimistion	Limited range of substrates, emphasis on waste minimisation	Versatile, wide range of biomass sources, waste minimisation	Versatile, wide range of biomass sources, waste minimisation	Versatile, wide range of biomass sources, waste minimisation
Environmental Impact	Emphasis on sustainability	Emphasis on sustainability	Efficient and versatile, cleaner and concentrated hydrogen yields	Efficient and versatile, cleaner and concentrated hydrogen yields	Efficient and versatile, cleaner and concentrated hydrogen yields
Energy Efficiency[54]	60–80	0.1–12	35–50	30–60	85–90
H_2 yield (g/kg of feedstock)[55]	4–44	9–49	25–65	40–190	0.3–2
Cost (USD/kg of feedstock)[56]	1.68–2.57	2.57–2.83	1.59–2.20	1.77–2.05	0.54–1.26
Ongoing Research Focus	Optimisation for higher yields, environmental control	Optimisation for higher yields, environmental control	Catalytic enhancements, optimization for efficiency	Catalytic enhancements, optimization for efficiency	Catalytic enhancements, optimization for efficiency
Future Role in Global Energy	Potential contribution to sustainable energy demands	Potential contribution to sustainable energy demands	Significant role in cleaner, concentrated hydrogen production	Significant role in cleaner, concentrated hydrogen production	Significant role in cleaner, concentrated hydrogen production

Hydrogen production from water

Hydrogen production from water encompasses diverse methods, each presenting unique advantages and challenges. Electrolysis, a straightforward approach, involves passing an electric current through water to generate hydrogen and oxygen, with technologies like alkaline water and proton-exchange membrane electrolysis showing promise despite cost challenges. Thermolysis, a thermochemical process, decomposes water at high temperatures, but issues with elevated temperatures and hydrogen-oxygen separation persist. Photoelectrolysis integrates solar energy absorption with electrolysis, utilising semiconductor-based photoelectrodes to split water into hydrogen and oxygen, with material properties significantly impacting performance. Biophotolysis leverages biological processes, with direct biophotolysis using microorganisms during photosynthesis, while indirect biophotolysis accumulates carbohydrates, addressing challenges of low hydrogen yield. While each method has its merits, ongoing research focuses on improving efficiency, reducing costs, and enhancing the viability of water-based hydrogen production for a sustainable future. The processes have been summarized in Table 7 below.

Table 7: Summary of hydrogen production technologies from water

Hydrogen Production Techniques from Water	Energy Source	Key Features	Challenges	Applications	Environmental Impact	Maturity	Energy Efficiency[57]	H_2 yield (g/kg of feedstock)[58]	Cost (USD/ kg of feedstock)[59]
1. Electrolysis	Electricity	Alkaline, proton-exchange membrane, solid oxide options	Cost competitiveness with fossil fuel-based production	Industrial hydrogen production, grid balancing	Emission-free with renewable energy	Commercial	55-80	111	4.15–10.30
2. Thermolysis	Heat	Thermochemical water-splitting process	High temperatures (>2500 °C), hydrogen and oxygen separation concerns	High-temperature industrial processes, solar and non-fossil fuel applications	Energy-intensive, challenges in scale-up	Research & development	20–50	111	7.98–8.40
3. Photoelectrolysis	Solar	Integrates solar energy with electrolysis	Material properties, corrosion, reactivity impact performance	Solar-driven hydrogen production, distributed energy systems	Renewable energy utilization	Research & development	0.06–14	111	4.98–10.36
4. Biophotolysis	Microorganism metabolism	Biological processes for hydrogen production	Low hydrogen yield, sunlight collection challenges (direct biophotolysis)	Bioremediation, green microalgae-based systems	Environmentally sustainable	Research & development	10–15	111	1.42–2.13

3.3 Challenges of Green Hydrogen Adoption

Green Hydrogen adoption faces a three-pronged challenge on the technical, financial, and operational fronts. Current technology is limited in its scope for large scale deployment.

High production costs: The electrolysers are yet to attain commercial viability to produce hydrogen at competitive costs. At present the cost of green hydrogen is ~75 percent[60] higher than the cost of grey hydrogen. On the demand-side, a similar barrier persists where the cost of adopting green hydrogen comes at a premium that lowers cost competitiveness with fossil-based hydrogen.

Energy losses: At each stage of the value chain, green hydrogen incurs energy losses. At the electrolysis stage, energy losses account for about 30 percent. If the hydrogen end-use is located off-site, then energy losses to the tune of 20 percent is incurred owing to compression, liquefaction, or conversion to hydrogen carriers such as ammonia. Further, the transport of hydrogen itself requires energy which accounts for 10 percent equivalent of the hydrogen energy.

Reliable supply of renewable energy: A stable and reliable source of renewable electricity is critical for green hydrogen production. Fluctuating power supply to the electrolysers drastically affects their performance, thereby negatively impacting the cost of production and operation[61].

Lack of a dedicated value chain: There are additional infrastructure requirements to store and transport hydrogen for its use as a feedstock in various end-use industries. However, the high initial investment burden has been a barrier to scaling the required infrastructure. These costs tend to spill over to the final hydrogen product, thus prohibiting cost competitiveness over fossil-based hydrogen.

Absence of a hydrogen certification framework: There is a price differential between hydrogen produced from fossil fuels and the hydrogen produced via the electrolysis of water using electricity generated from renewable resources. There are buyers in the market who will pay a higher price to procure low-carbon hydrogen. This can happen out of compliance with laws (compliance/regulatory carbon market) or voluntarily. However, it is impossible to determine the embedded emissions by perusing the end-product. Therefore, there is a need to bridge the information asymmetry between the buyer and the seller of hydrogen to create a transparent hydrogen market. Developing a common international framework is essential, to avoid free-riding and unfair competition, while also enabling cross-border trade to harness the potential of the green hydrogen economy.

Guarantee of sustainability: Typically, renewable electricity is intermittent, and thus the grid-connected electricity is considered as a stable source, enabling longer hours of electrolyser function, and thereby reducing the cost of hydrogen. However, the mix of fossil-fuel-based electricity in the grid reduces transparency for the consumer to pay a premium for the green hydrogen. A robust certification framework will aid in bridging this concern and promote uptake of green hydrogen.

3.4 Green Hydrogen Infrastructure Requirements

Infrastructure is a key prerequisite to developing a robust hydrogen supply chain that is reliable and can support the growing demand as we progress toward sustainable production pathways. Given the nascent stage of the green hydrogen economy in the country, there is a need to focus on creating production, storage, transportation, and distribution infrastructure. While investments in R&D vis-à-vis hydrogen infrastructure are critical, they must be accompanied by the development of infrastructure that has attained high technology readiness.

Requirements at the Ecosystem Level

Hydrogen production requires access to water, renewable electricity, and connection with local transportation networks. These specifications bring emphasis on the location where the green hydrogen production units must be set up. Distribution can occur via shipping and pipelines. Hydrogen pipelines are similar to natural gas pipelines, and the prospects of repurposing some of the gas pipelines to transport hydrogen could be explored. Demonstrations on the lines of hydrogen blending in the gas pipelines are already underway. For Shipping, there is an additional process of conversion to liquid ammonia. Hydrogen is highly volatile in nature and there is a need to incorporate infrastructure that is capable of handling high pressure (~700 bar) such as specialised compressors and storage containers to transport hydrogen. Further, hydrogen-compatible ports for processes such as reconversion, and trucks fitted with ceramic trailers are necessary for delivering the hydrogen to the site of end-use.

Requirements at the Fertiliser Plant Level

At the plant-level, the infrastructure requirement may vary based on whether the hydrogen is produced on-site, or transported from a different location. The fertiliser plant will have to adopt additional components based on the hydrogen demand, location of hydrogen production, and usage pattern on-site.

Hydrogen production on-site: Additional to the components of a typical fertiliser plant, an electrolyser unit must be co-located to supply hydrogen. The function of the electrolyser, will further require round-the-clock renewable electricity, chilled water, and demineralised water, assuming an alkaline water electrolyser plant[62]. Based on the source of the raw materials, there may be requirement of additional units such as a demineralisation water treatment plant, and a chiller pump. Additionally, hydrogen storage requirement may be necessary. In this regard, compressors, and liquefaction plants may be set up on site, where the hydrogen can be stored in insulated tanks.

Hydrogen production off-site: In cases where the hydrogen production facility is located off-site, transporting liquid hydrogen via ceramic trailers is a common method. In this case, the fertiliser plant must be equipped with a reconversion unit, where the hydrogen is converted back to the required gaseous form. In scenarios where the distance is longer, and a business case for conversion to ammonia arises, the fertiliser plant will have to be equipped with infrastructure for ammonia cracking [63].

3.5 Cost of Green Hydrogen

As Figure 20 showcases, the cost of green hydrogen revolves around INR 263-368 per kg of hydrogen as opposed to the price of grey hydrogen which hovers around INR 160-220[64]. The cost of grey hydrogen is dependent on natural gas which is marred with price volatility. The variation in green hydrogen costs is attributed to the type of electrolyzer technology. Another vital facet to underscore here is that these price points are arrived at when exemptions on electricity duty and taxes are considered. These exemptions have reduced the cost by 35-40percent.

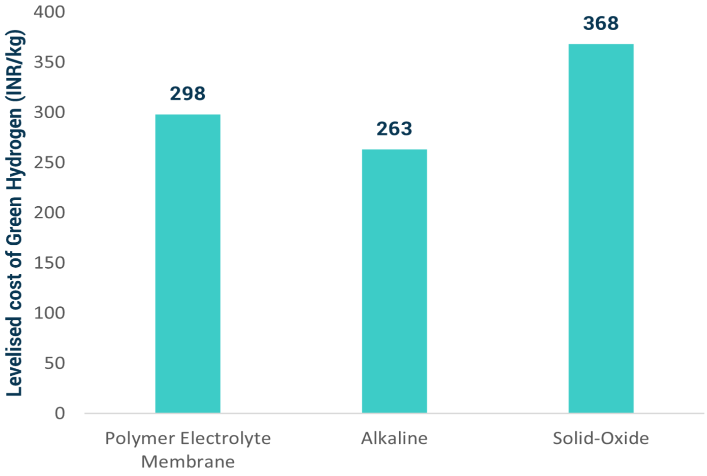


Figure 20: Levelised cost of green hydrogen by electrolyser technology[64]

Assessments by NITI Aayog[36] indicate that the price of green hydrogen could achieve cost parity by 2030, and further projections indicate that green hydrogen will significantly undercut grey hydrogen in price. As observed in Figure 21, the cost of green hydrogen is cheaper in 2030 by 48.9 percent from current levels, and is expected to further decline by ~77 percent in 2050. The price of grey hydrogen is projected to be over 2.5 times the cost of green hydrogen in 2050.

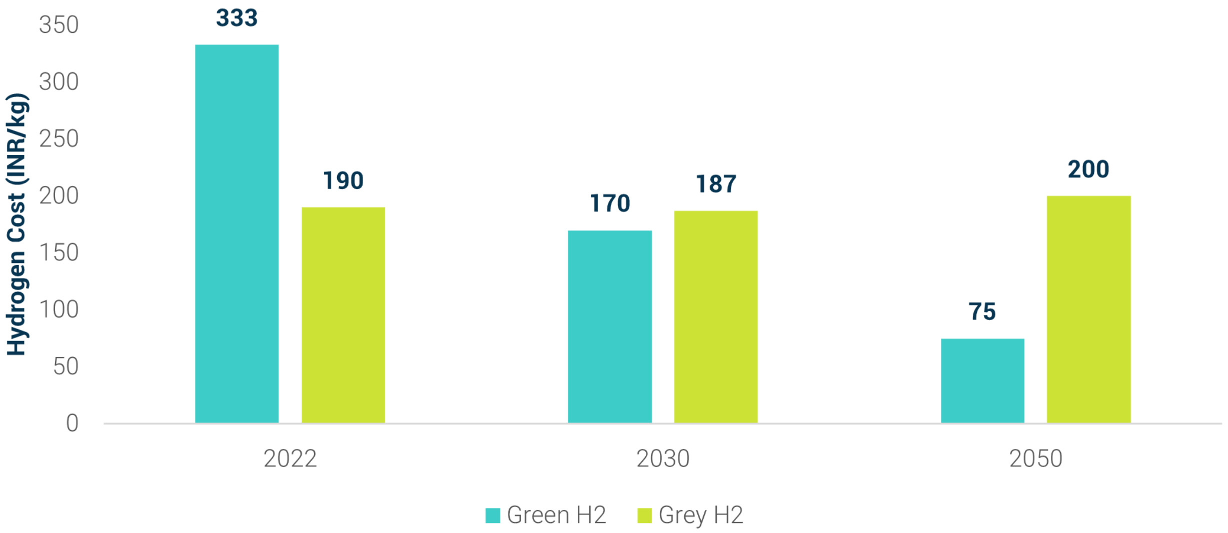


Figure 21: Cost Projection of Green Hydrogen[36]

4

Impact of Green Hydrogen-based Fertilisers on the Demand-side

4.1 Methods of Fertiliser Application

Various methods are employed to apply fertilisers based on their State - solid, liquid, and gaseous. Concerning gaseous fertiliser, anhydrous ammonia is the only type in this category. Typically, it is stored under pressure and lower temperatures. This liquified ammonia is applied by subsurface injection where it quickly vaporises whilst fixating nitrogen in the soil simultaneously. Solid and liquid fertilisers have a host of application methods as observed in Figure 22.

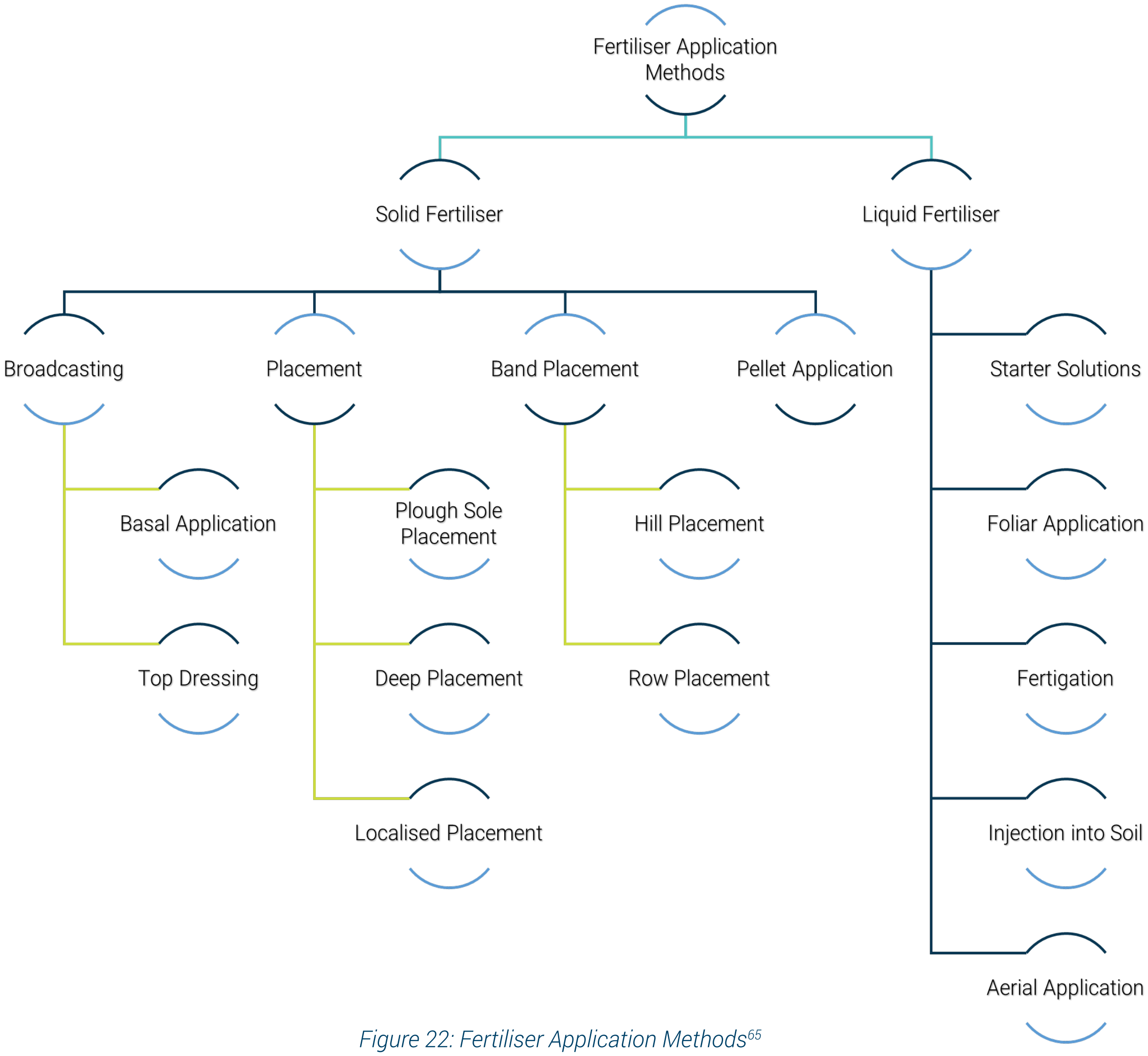


Figure 22: Fertiliser Application Methods[65]

Selection of the appropriate method of fertiliser application is contingent to the amount and timing of nutrient uptake required. Various factors such as crop variety, planting date, soil health, and weather conditions are essential to consider. Applying the fertiliser close to the time the crop requires the nutrients is critical to optimise usage efficiency, and has minimal pollution impact on the environment. In the case of Urea and DAP, both fertilisers must be incorporated immediately into the soil via placement methods if there is no irrigation or rainfall to wash into the soil. This prevents losses via emission of ammonia into the air. Similarly, the primary nutrients such as potash, and secondary nutrients such as zinc must be applied in a manner where it is immediately incorporated. This is essential to avoid losses due to run-off and erosion.

Urea is the most widely used nitrogenous fertiliser owing to its ease of use, long-lasting impact and convenient preservation characteristics.

Fertiliser Purchase

The fertiliser market in India is expected to grow at a CAGR of 4.7 percent between 2023 and 2028[66]. Thus, fertiliser usage and purchase patterns are important parameters to consider in ramping up production facilities.

In Gujarat, more than 50 percent of its land is used for agricultural purposes[66]. The State is endowed with natural resources, in terms of soil varieties, climatic conditions, and cropping patterns. Cotton, groundnut, rice, wheat, jowar, bajra, and maize, are some of the major crops grown in the State. A study conducted in Gujarat's Kheda district sought to gather information on farmer practices concerning fertiliser usage and purchase. The findings are presented below-

Farmer Income Level: As observed in Figure 23, majority of the farmers earned between INR 20,000 to INR 30,000 per month. This is above typical farmer earnings in the country and is attributed to high awareness regarding crop cultivation. Further, most farmers also were involved in animal husbandry which provided a steady income. However, the propensity to undertake additional expenditure on fertilisers remains low.

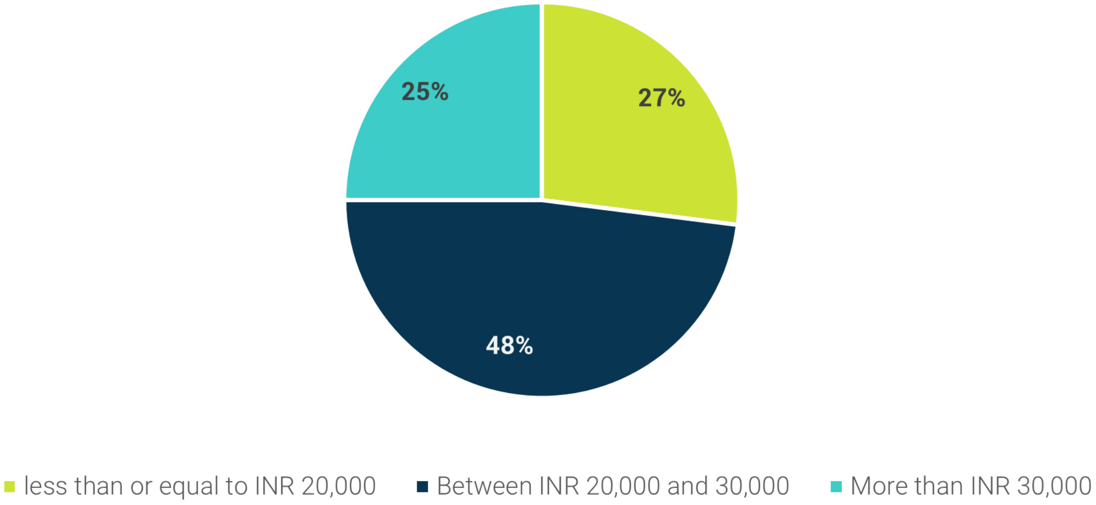


Figure 23: Farmer income levels[66]

Size of Land Holding: As observed in Figure 24, majority of the farmers were possessing land holdings between 4 to 10 acreages. A significant percentage of farmers are also small farmers with land holdings of less than 4 acreages.

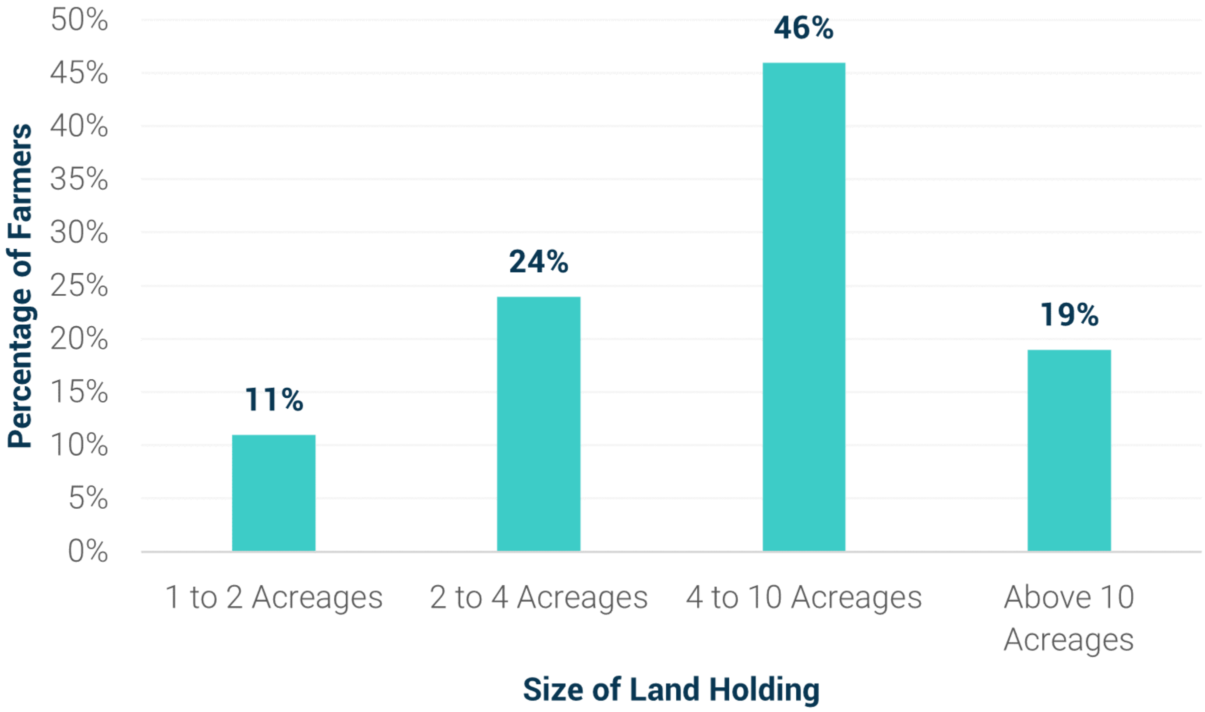


Figure 24: Size of land holdings among farmers[66]

Fertiliser Application: For crops such as paddy, a combination of complex fertilisers with urea is generally used. As observed in Figure 25, we similarly observe a majority of the farmers (54 percent) applying fertilisers in combination. This practice achieves a balanced and comprehensive nutrient supply to the soil.

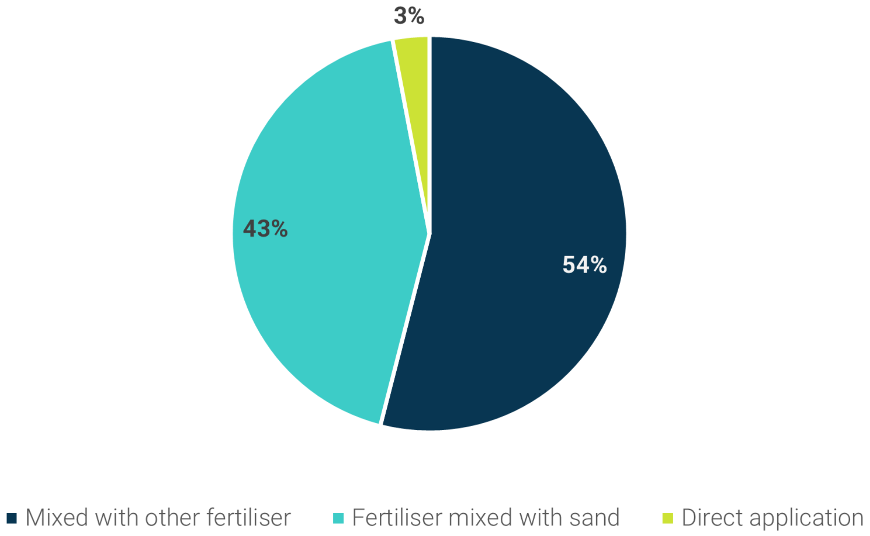


Figure 25: Fertiliser application pattern[66]

Source of Awareness on Fertiliser Usage: Farmers derive their source of information on fertilisers and other cultivation methods from various avenues. As observed in Figure 26, farmer meetings, retailer suggestions, and field demonstrations, are the primary sources of information for the farmer. They indicate a clear preference and trust for in-person sources as opposed to electronic or written communication.

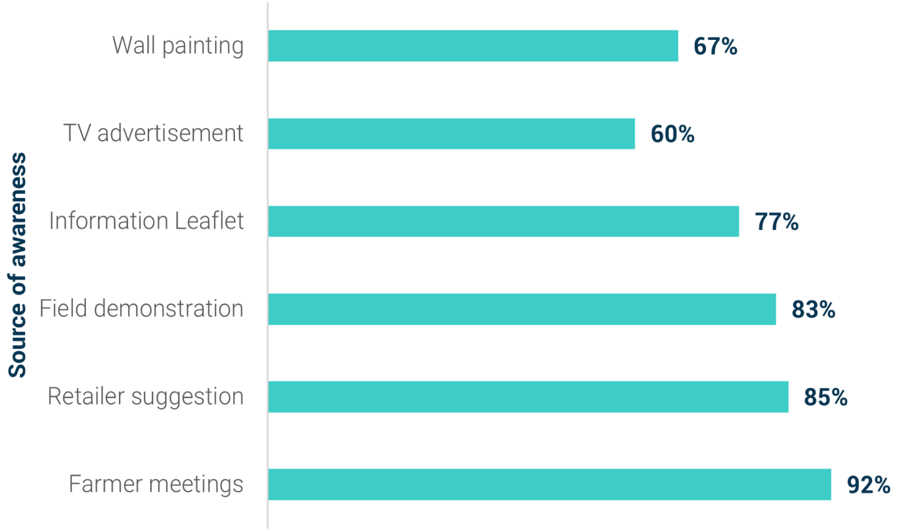


Figure 26: Farmer's sources of information on fertilisers[66]

Fertiliser Purchase Factor: Leading on the preferred source of awareness, Figure 27 describes the major factors influencing the farmer in purchasing fertilisers. We observe that the quality of product determined from previous usage experience, stands as the main factor in purchasing fertiliser. However, price of the product and nudges from the retailer also influence farmers in purchasing fertilisers.

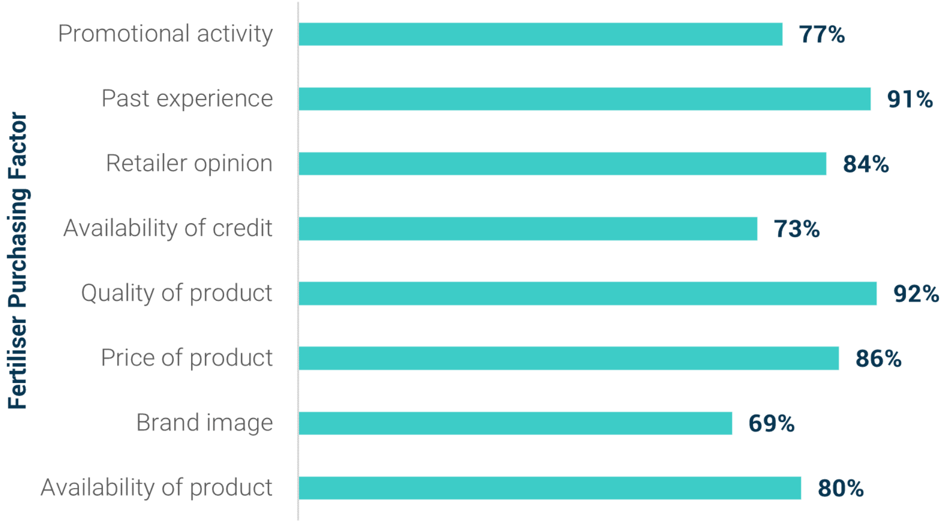


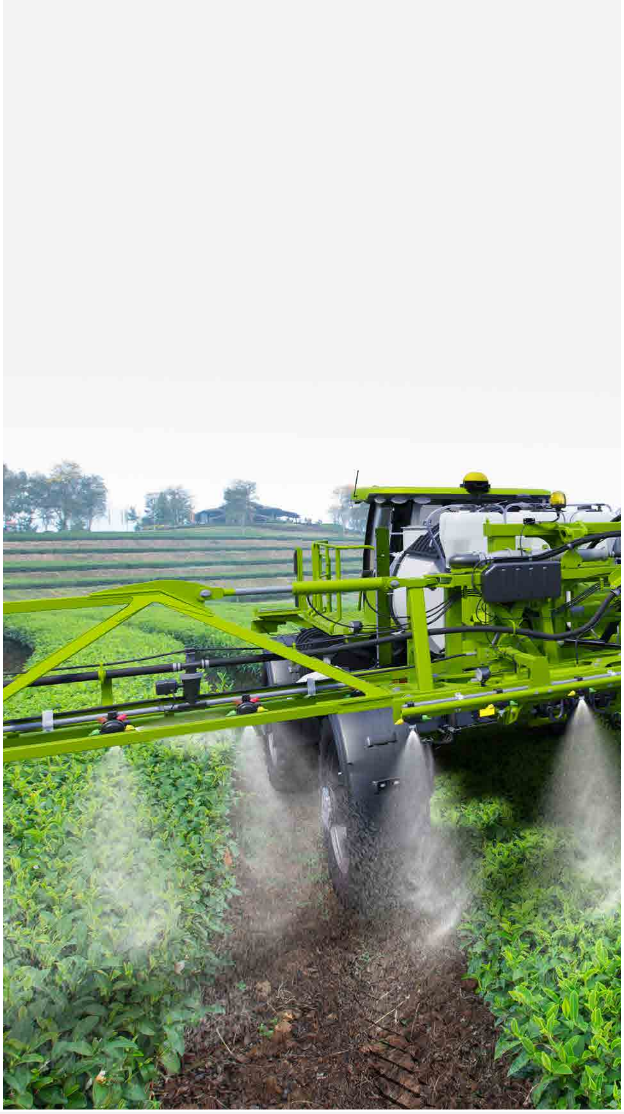
Figure 27: Factors influencing farmers for fertiliser purchase[66]

Key takeaways for sustainably-produced fertilisers-

- Promotion of sustainably produced fertilisers will have to be based on ensuring competitive price and building awareness among retailers. Ensuring regular supply to the farmers will also support the transition.
- Farmers are more receptive to in-person communication. Thus, field demonstrations, and dissemination through farmer meetings must be conducted to embed sustainably-produced fertilisers.

4.2 Technological Barriers to Green Fertiliser Adoption

- **Energy Variability and Process Stability:** The intermittency of variable energy sources, such as wind and solar, poses challenges for ammonia production. Refinements in processes are imperative to ensure stability and efficiency in the face of fluctuating energy inputs. Ensuring continuous ammonia production is crucial to prevent damage to the non-flexible Haber Bosch catalytic reactor, complicating the technological landscape.
- **Energy-Intensive Production Methods:** Traditional ammonia production, characterized by high temperatures and pressures, is inherently energy-intensive, resulting in elevated capital and operating costs. Ongoing research aims to develop methods enabling production at lower temperatures and pressures for enhanced cost-effectivenes[67].
- **Centralised Large-Scale Facilities vs. Small-Scale Production:** Current ammonia production primarily relies on large, centralised facilities with capacities of around 3,000 tons per day[58]. These facilities, strategically located near fossil fuel sources, demand extensive time and investments. Transitioning to smaller-scale, economically competitive production is essential for viability in rural, agricultural areas.
- **Infrastructure Adaptation Challenges:** The production, storage, and application of green fertilisers often necessitate additional infrastructure. Adapting existing infrastructure to meet these requirements poses practical challenges for farmers, acting as a barrier to widespread adoption.



4.3 Low-hanging Fruits to Adopt Sustainable Production Methods

Green Ammonia

India's total annual ammonia consumption is around 190 LMT (FY22)[68]. 89 percent[68] of this ammonia is domestically produced, while around 20.9 LMT[69] of ammonia is imported. The total grey ammonia demand from the fertiliser sector stands at 169.42 LMT[50]. The demand share among the major fertilisers is as shown in Figure 28. DAP and NPK constitute 17.22 percent of the demand amounting to 29.18 LMT[50].

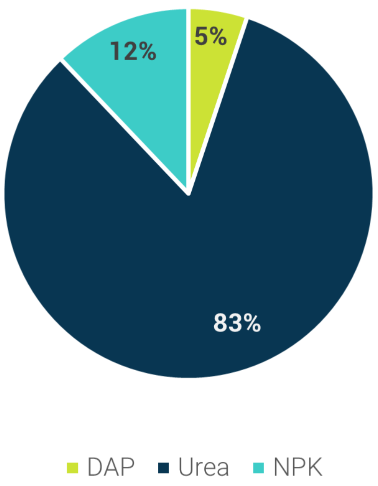


Figure 28: Annual grey ammonia demand share in the fertiliser sector (FY22)[50]

Bridging the import gap requires ramping up ammonia production facilities. Green ammonia can be produced devoid of fossil-based CO_2, and used directly in the production of DAP and complex fertilisers. By promoting green ammonia production in India, there is scope for India to attain self-sufficiency while also abating emissions in the fertiliser sector. As shown in Figure 29, the ammonia demand for producing DAP and NPK is around 8.28 LMT higher than India's ammonia import requirement. Thus, the transition to domestically produced green ammonia via renewables or biomethane for use in DAP and NPK, can subsume the import requirement of ammonia, and serve as a route to achieve self-sufficiency of ammonia in India.

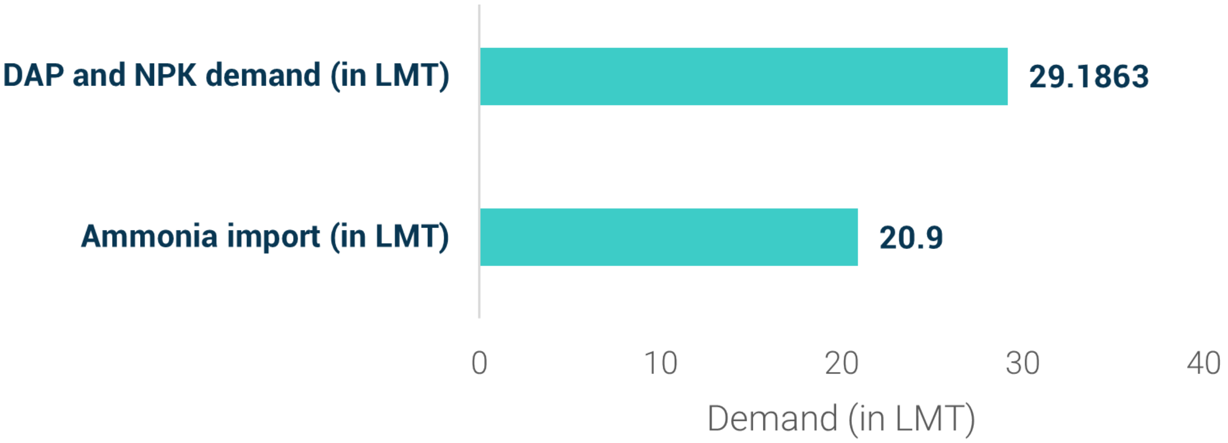


Figure 29: Ammonia Demand of DAP and NPK comparison with ammonia import requirement[13]

Cost Analysis of Grey and Green Ammonia

The cost of ammonia is dependent on key parameters such as the CAPEX, OPEX, cost of electricity, and cost of natural gas (for grey ammonia). Table 8 captures the parameters assumed to calculate the cost of grey and green ammonia. Corresponding to the data, we derive the cost of grey ammonia – INR 189.81/kg of ammonia, and the cost of green ammonia – INR 295.77/kg of ammonia.

Table 8: Key Assumptions for Ammonia Cost Analysis[70]

	Grey Ammonia	Green Ammonia
CAPEX (INR/ tonne of ammonia)	149606.10	232720.6
OPEX (INR/ tonne of ammonia)	3740.15	4654.41
Electricity requirement (MWh/ tonne of ammonia)	0.3	10
Natural gas requirement (MMBtu/ tonne of ammonia)	35	N/A
Electricity cost from Grid (INR/MWh)[71]	5190	
Renewable Electricity cost (INR/MWh)[71]	5840	
Price of Natural gas (INR/ MMBtu)	997.41	N/A

With advancements in technology, the CAPEX and OPEX is expected to decline with improving economies of scale. Further, renewable electricity is set to become cheaper, which will render green ammonia cost competitive to grey ammonia, despite the higher electricity requirement. The volatile price of natural gas also builds a case for transitioning to green ammonia which is resilient to energy shocks. As observed in Figure 30, grey ammonia prices exceeded that of green ammonia in the months of July through September, 2022. The graph captures the trend in grey ammonia prices corresponding to the monthly averages of natural gas prices[72].

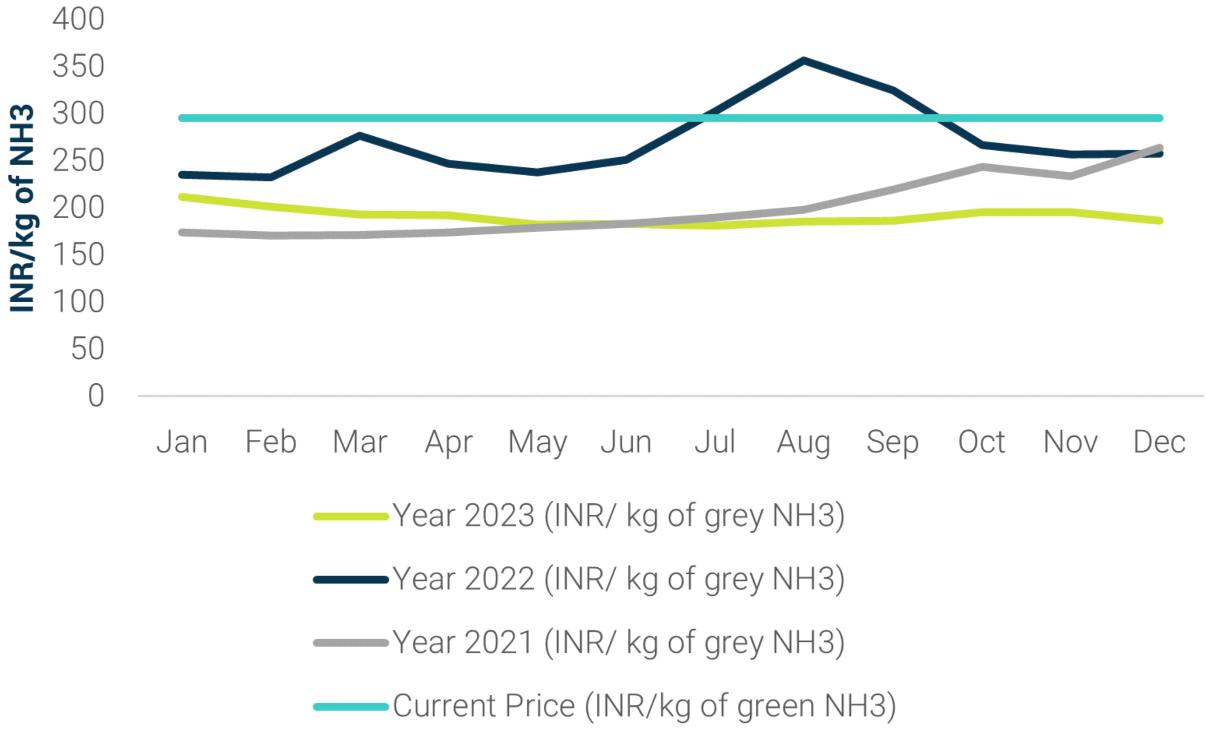


Figure 30: Price variations in grey ammonia corresponding to natural gas prices[13]

Biomethane as Feedstock

Urea is the majorly used and produced fertiliser in India. Production routes for green urea is thus key to reducing emissions and moving towards sustainable fertiliser production. Biomethane derived from biomass forms an important route in this regard. India has total surplus biomass residue of 284.45 LMT. The State-wise availability of this biomass is as shown in Figure 31.

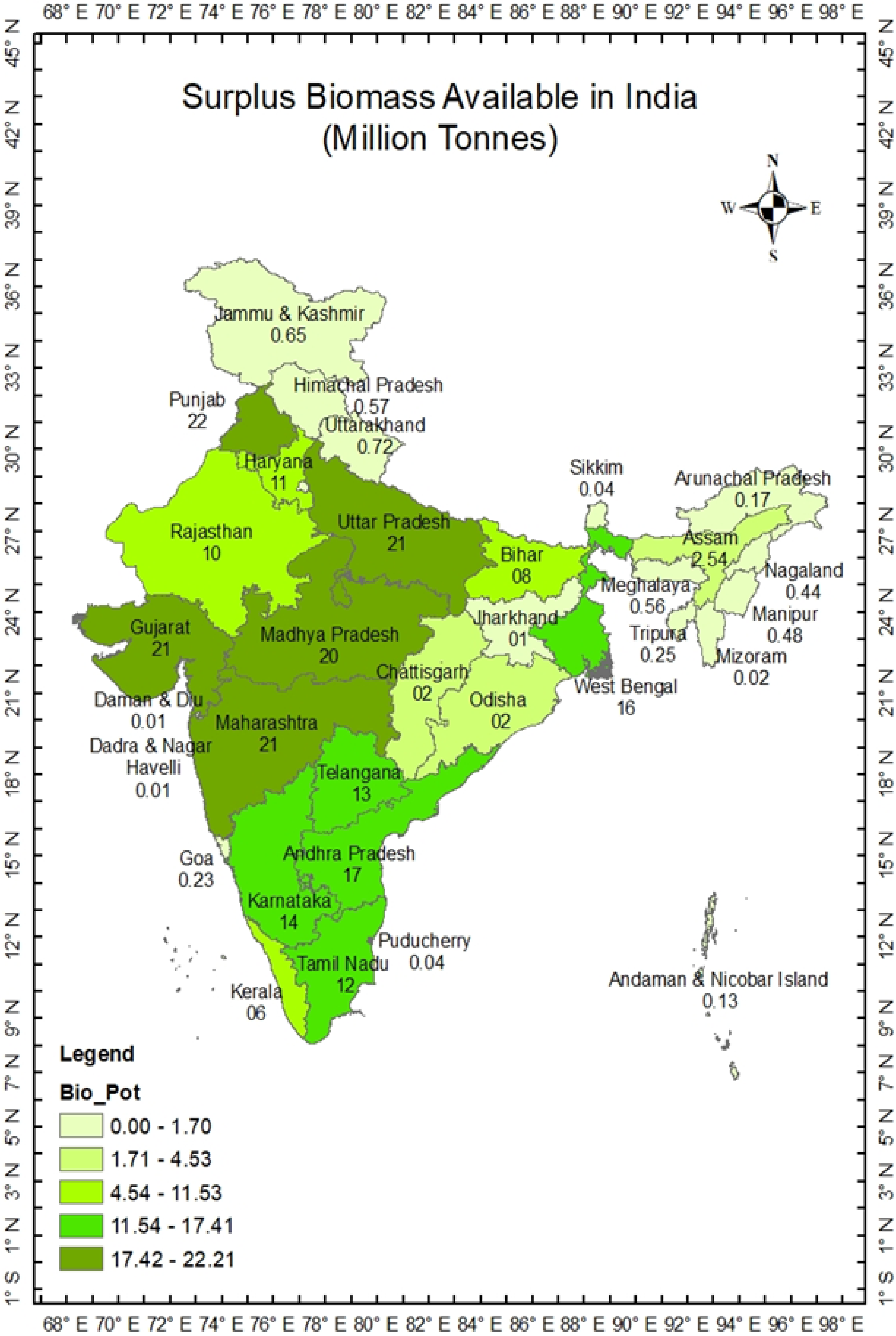


Figure 31: State-wise availability of surplus biomass[73]

Assuming that natural gas is indistinguishable to biomethane, from Table 8, we require 35 MMBtu for producing 1 tonne of ammonia. The equivalent gas requirement being 991.5 m3 of biomethane. The methane yield from various crop residues is given in Table 9.

Assuming the average biomethane yield of 279.5 m3/ tonne of feedstock, we estimate that 1 tonne of ammonia potentially requires 3.54 tonnes of feedstock. From the previously mentioned total available surplus, we estimate that there is **~80 LMT of ammonia production capacity in India to be harnessed.** Given the total ammonia imports hover around 20.1 LMT, this builds a case for developing a biomass feedstock value chain to support production of green urea via carbon-neutral biomethane.

Table 9: Methane yield from crop residue[68]

Crop residue	Methane yield (m3/tonne)
Rice	335.6
Wheat	213.43
Maize	360
Rye	179
Barley	320
Oats	240
Rape Seed	252
Sugar Beets	360
Sugar Cane	195
Sorghum	340

5

Recommendations and Conclusion

Although the fertiliser sector contributes to emissions, it plays a crucial role in ensuring food security in India. Therefore, initiatives aimed at decarbonising the fertiliser industry should carefully consider a few key factors. Firstly, it should not adversely affect farmers through higher fertiliser prices or increased application efforts. Secondly, while organizations involved in fertiliser production will eventually need to transition to sustainable products, it's essential to establish and demonstrate a compelling business case for a large-scale shift. Until then, financial support should be extended to these organizations for exploring pilot projects. Nevertheless, these organizations must invest in research and development to remain competitive against emerging startups offering fossil-free fertilisers, which are expected to gain traction in the short-to-medium term.

Historically, urea has been the primary fertiliser used for nitrogen fixation owing to its high nitrogen content and ease of handling. Over 90 percent[74] of domestically produced ammonia is utilised for the production of urea. However, the shift towards green urea necessitates the use of green ammonia and CO_2 sourced from a carbon source that does not contribute to a net increase in emissions, such as biomass or Direct Air Capture methods. Simultaneously, this change in production pathways should not result in an elevation of the Levelized Cost of Urea (LCOU). Of late, various research programs have been initiated to reduce the production costs of green urea. These programs explore flexible and time-varying chemical production methods, enabling the utilisation of low-cost renewable energy while minimizing expenses related to high-energy or chemical intermediate buffer storage. The research findings indicate that the LCOU is lower than the global spot prices for the years 2021 and 2022, suggesting the potential feasibility of integrating this concept into mainstream practices. It is crucial to investigate its direct linkages within the Indian context as the production of green urea provides consistent operating costs following the initial capital investment. This may result in the establishment of long-term, fixed-price urea sale agreements, thereby eliminating a significant source of uncertainty for farmers.

Furthermore, the report also emphasises the significance of investigating alternative nitrogenous fertilisers with comparable cost and application convenience to facilitate a smooth transition for farmers. As per the IPCC, the utilisation of urea as a fertiliser leads to around 0.735 metric tons[75] of carbon dioxide equivalent emissions per metric ton of uera after application, attributable to the fixation of nitrogen in the soil. It is evident that urea contributes additional carbon dioxide emissions beyond those generated by the production facility necessitating a shift towards other products.

Finally, drawing insights from the comprehensive study, the report outlines specific recommendations for the successful integration of green hydrogen and green ammonia into the fertiliser production landscape in India, as follows-

5.1 Existing Fertiliser Plants

Develop value chain for sustainable feedstock: The road to emission abatement in the fertiliser sector is likely to see a range of technology options that are adopted before we can transition to pure renewable hydrogen. In this regard, value chains that enable access to feedstock for production routes such as those involving biomass, must be developed.

- **Innovative financing options for fertiliser manufacturers:** Implementing modifications in current fertiliser production facilities demands substantial initial investments from manufacturers. Given the price sensitivity of the final product, it becomes imperative to devise innovative financing options that prevent the transfer of these costs downstream.

- **Purchase mandates for green hydrogen:** Introducing purchase mandates for green hydrogen presents a promising proposition when encouraging current fertiliser production facilities to adopt sustainable practices. This aligns with the recommendation put forth by the Union Minister for New and Renewable Energy. More importantly, these mandates should commence with modest quantities and incrementally increase in subsequent years. The predetermined thresholds for these mandates should be established through consultations with industry experts, considering the maximum feasible transition from grey hydrogen to green hydrogen within the constraints of existing infrastructure. This phased approach ensures a gradual but impactful shift towards sustainable hydrogen sources in the fertiliser manufacturing sector.

5.2 New Fertiliser Plants

- **Ensuring strategic location of new urea plants:** Proximity to sites with a consistent supply of carbon dioxide (CO_2) is key. This continuous availability of CO_2 can be sourced either from biomass or captured from existing thermal power plants. By choosing such locations, the necessity for establishing additional infrastructure for CO_2 supply is eliminated. This approach not only optimizes the efficiency of the urea production process but also contributes to sustainability by capitalizing on existing CO_2 resources without the need for dedicated transportation or storage systems.
- **Techno-economic comparisons via comprehensive Life-Cycle Assessment (LCA):** As biomass is low in energy density, the economies of scale must account for cost of transport and storage of sustainable feedstock, and the hydrogen produced. LCA must be employed to arrive at profitable investment decisions, and support scaling of carbon-neutral production routes.
- **Provide targeted funding:** In order to reduce the cost between alternate and current sources of production, dedicated funding with a sector specific approach is required. This will help in de-risking the early investment and creating a conducive environment for growth. Two pilot projects as proposed under the National Green Hydrogen Mission on green ammonia and green urea are steps in right direction to showcase proof-of-concept.
- **Research and Development in Alternative Nutrient Sources:** Support research initiatives aimed at discovering and developing alternative nutrient sources that are environmentally friendly, cost-effective, and easily adoptable by farmers.

5.3 Raising Awareness

- **Promotion of Sustainably Produced Fertilisers:** Farmers are at the forefront of climate change impacts, as it directly affects agricultural productivity. Thus, the end-users must be educated on the requirement for sustainable fertilisers and its broader impact in combating climate change. Outreach programs must be conducted to educate farmers on sustainable fertiliser practices, emphasising the environmental benefits and long-term agricultural productivity associated with such approaches.

References

1. https://wri-india.org/blog/hydrogen-application-indian-fertilizer-industry-introduction
2. https://www.fert.nic.in/sites/default/files/2020-082022-03/Final-AR-2022-DOF-22.pdf
3. https://sansad.in/getFile/loksabhaquestions/annex/1712/AU267.pdf?source=pqals
4. https://www.researchgate.net/figure/Forecast-of-fertilizers-consumption-upto-2030_tbl4_355467969
5. https://sansad.in/getFile/loksabhaquestions/annex/176/AU2376.pdf?source=pqals
6. https://www.iea.org/reports/ammonia-technology-roadmap
7. https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf
8. https://www.ghgplatform-india.org/economy-wide/
9. https://www.g20.org/content/dam/gtwenty/gtwenty_new/document/G20-New-Delhi-Leaders-Declaration.pdf
10. https://nigen.com/how-separate-nitrogen-from-air-ways-extract-nitrogen/#:~:text=Fractional%20Distillation%20of%20Liquid%20Air%20to%20Produce%20Nitrogen&text=By%20a%20process%20called%20fractional,air%2C%20and%20then%20collect%20it.
11. https://www.sciencedirect.com/science/article/abs/pii/S0959652620330729
12. https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf
13. Vasudha Foundation
14. https://www.fert.nic.in/publication-reports/fertilizers-scenario
15. https://www.fert.nic.in/sites/default/files/2020-082024-01/Annual%20Report%20fertilizer%20new%20new17%20%20%2029-07-2023.pdf
16. https://www.pewresearch.org/short-reads/2023/02/09/key-facts-as-india-surpasses-china-as-the-worlds-most-populous-country/
17. https://www.researchgate.net/publication/355467969_Growth_Determinants_of_Fertilizer_Consumption_in_India_Application_of_Demand_and_Supply_Side_Models
18. https://www.researchgate.net/figure/Forecast-of-fertilizers-consumption-upto-2030_tbl4_355467969
19. https://www.faidelhi.org/Frank%20notes/IJF-May-22.pdf
20. https://pib.gov.in/newsite/PrintRelease.aspx?relid=200180
21. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fert.nic.in/sites/default/files/What-is-new/Neem-Coated.pdf
22. https://ourworldindata.org/fertilizers
23. https://www.fertilizer.org/resource/public-summary-medium-term-fertilizer-outlook-2022-2026/
24. https://www.iea.org/energy-system/low-emission-fuels/electrolysers
25. https://www.wto.org/english/news_e/news22_e/igo_14nov22_e.pdf
26. https://chemicalengineeringworld.com/urea-manufacturing-process/
27. https://patents.google.com/patent/US4744965A/en
28. https://www.researchgate.net/figure/Flow-diagram-of-DAP-production_fig1_272058769
29. https://www.tiancimachine.com/industry-info/process-flow-chart-of-npk-fertilizer-production-line.html
30. https://www.fertilizerseurope.com/decarbonising-fertilizers-by-2050/#:~:text=Alternative%20production%20technologies%20to%20reduce,processes%20and%20large%2Dscale%20electrolysis.
31. https://www.iea.org/reports/ammonia-technology-roadmap
32. https://nitrocapt.com/life-sunifix/
33. https://www.sciencedirect.com/science/article/pii/S2772826922000074
34. https://www.fipi.org.in/assets/pdf/downstream-report/Hydrogen%20Market%20Report.pdf
35. https://www.informistmedia.com/india-needs-60-gw-of-electrolyser-mfg-capacity-by-2030-says-minister/
36. https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf
37. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/aug/doc2023819241201.pdf

38. https://www.deccanherald.com/business/21-firms-bid-for-incentives-for-electrolyser-manufacturing-14-for-green-hydrogen-production-2814004
39. https://www.deccanherald.com/business/21-firms-bid-for-incentives-for-electrolyser-manufacturing-14-for-green-hydrogen-production-2814004
40. https://jankalyanfile.rajasthan.gov.in/Content/UploadFolder/DepartmentMaster/197/2023/Oct/30409/19754c1396c-1eb8-49f0-b1aa-11f734668671.pdf
41. https://nghm.mnre.gov.in/admin/uploads/resources/168258672948697UP%20Green%20Hydrogen%20Policy-%20Draft.pdf
42. https://jmkresearch.com/wp-content/uploads/2023/11/Maharashtra-Green-Hydrogen-Policy-2023.pdf
43. https://nredcap.in/PDFs/2023/GO_Ms_No_14_Dt_20_06_2023.pdf
44. https://www.eqmagpro.com/wp-content/uploads/2023/05/New-GR-for-Green-Hydrogen-08
45. https://www.document.kerala.gov.in/documents/governmentorders/govtorder2811202317:21:55.pdf
46. https://www.iea.org/reports/the-future-of-hydrogen
47. https://www.sciencedirect.com/science/article/abs/pii/S0360319921020826
48. https://wri-india.org/blog/hydrogenapplication-indian-fertilizer-industry-introduction
49. https://www.faidelhi. org/statistics/statistical-database
50. https://h2hubs.in/GgHydrogenDemand
51. https://mnre.gov.in/notice/rd-roadmap-released-by-mnre-on-the-eve-of-world-hydrogen-day/
52. https://www.sciencedirect.com/science/article/abs/pii/S0961953420304530?via%3Dihub
53. https://www.sciencedirect.com/science/article/pii/S1364032117308146?via%3Dihub
54. https://www.sciencedirect.com/science/article/abs/pii/S0360319914034119?via%3Dihub
55. https://www.sciencedirect.com/science/article/pii/S2589299119300035?via%3Dihub
56. https://www.sciencedirect.com/science/article/abs/pii/S1364032116305366?via%3Dihub
57. https://www.sciencedirect.com/science/article/abs/pii/S0360319914034119?via%3Dihub
58. https://www.sciencedirect.com/science/article/pii/S2589299119300035?via%3Dihub
59. https://www.sciencedirect.com/science/article/abs/pii/S1364032116305366?via%3Dihub
60. Analysis by Vasudha Foundation
61. https://iopscience.iop.org/article/10.1149/2.0421908jes
62. https://www.barc.gov.in/technologies/awep/index.html
63. Ammonia cracking is a process where the ammonia is decomposed over a catalyst surface to produce hydrogen and nitrogen.
64. https://www.vasudha-foundation.org/reducing-the-cost-barrier-between-green-and-grey-hydrogen-in-india/
65. https://agritech.tnau.ac.in/agriculture/agri_nutrientmgt_methodsoffertilizerappln.html
66. https://journalajaees.com/index.php/AJAEES/article/view/2026#:~:text=The%20study%20found%20that%2068,satisfied%20with%20quality%20of%20fertilizer.
67. https://www.cooperative.com/programs-services/bts/Documents/TechSurveillance/Surveillance-Green-Ammonia-Production-March-2022.pdf
68. https://www.e3s-conferences.org/articles/e3sconf/pdf/2023/42/e3sconf_icstce2023_04032.pdf
69. Estimated by Vasudha Foundation from the total ammonia consumption of 190 LMT
70. https://www.energyforum.in/fileadmin/user_upload/india/media_elements/publications/20230515_GNH3_Deloitte_Study/20230707_gs_GNH3_finalprint.pdf
71. https://www.iexindia.com/
72. https://www.worldbank.org/en/research/commodity-markets
73. https://www.nibe.res.in/biomass-atlas.php
74. https://view.argusmedia.com/India-Hydrogen-GreenAmmonia-Fertilizer-LP.html
75. https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php?ipcc_code=2.B.1&ipcc_level=2

VASUDHA
FOUNDATION
Green ways for a good earth!

CISRS House, 14 Jangpura B, Mathura Road, New Delhi - 110014

www.vasudha-foundation.org