POLICY PAPER 150

Roadmap for *Atmanirbharta* in Fertilizers

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
September 2026

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Preface

Fertilizers have been central to India's transformation from a food-deficit to food-surplus country. Together with improved varieties, irrigation and mechanization, nutrient inputs supported the rise in food-grain production from about 82 million tonnes (Mt) in the early 1960s to more than 376 Mt in 2025-26. Fertilizer security, therefore, remains inseparable from national food security.

The achievements, however, rest on persistent vulnerabilities: high dependence on imported phosphorus and potash resources and imported natural gas, exposure to global price and supply shocks, a large subsidy burden, and nutrient-use patterns skewed toward nitrogen. Low nutrient-use efficiency, soil-health concerns and environmental losses suggest that self-reliance cannot be pursued through domestic fertilizer production alone.

In above backdrop, the Academy organized a brainstorming session on "Roadmap for *Atmanirbharta* in Fertilizers" involving representatives of concerned Government departments, academia, fertilizer industry, farmers and social organizations. This Policy Paper frames *Atmanirbharta* as nutrient sovereignty through secured and diversified access to nutrients, stronger domestic manufacturing and feedstock security, technological innovation and a circular nutrient economy, and higher nutrient-use efficiency through integrated and precision nutrient management. The proposed roadmap links these priorities with farmer protection, fiscal sustainability, environmental stewardship and the vision of *Viksit Bharat* 2047.

I understand this document will be immensely useful to the stakeholders. I appreciate the efforts of the Convener, Co-Convener, Reviewer and Editors for bringing out the document in the present form.

September 2026 **(M.L. Jat)**
New Delhi *President, NAAS*

Roadmap for *Atmanirbharta* in Fertilizers

1. INTRODUCTION

Fertilizers remain indispensable for food security and productivity, but the present production and consumption models face environmental concerns, energy costs, import dependence, and fiscal pressures. These challenges highlight the need for a technological transition improving nutrient-use efficiency, reducing environmental footprints, and strengthening domestic resilience. Hence, future strategies must focus on optimizing nutrient use rather than simply increasing consumption. Strengthening nutrient security through balanced and integrated use of fertilizers, indigenous resource utilization, technological innovation, and circular nutrient economy approaches will be critical for achieving the objectives of *Atmanirbhar Bharat* and ensuring the long-term resilience of Indian agriculture.

Achieving *Atmanirbharta* (self-reliance) in fertilizers demands a multi-dimensional strategy encompassing both supply- and demand-side interventions. On the supply side, it involves strengthening domestic manufacturing, securing raw material supplies, promoting indigenous mineral resources, developing green ammonia production systems, and encouraging innovation in fertilizer technologies. On the demand side, it requires improving nutrient-use efficiency through precision nutrient management, soil-test-based fertilizer recommendations, digital advisory systems, and nutrient-efficient crop varieties. Thus, *Atmanirbharta* in fertilizers necessitates a paradigm shift from linear fertilizers economy to circular nutrient economy. India generates crop residues, livestock waste, agro-industrial by-products, municipal organic waste, sewage sludge, and other underutilized recyclable nutrient resources. Recovering nutrients from these streams can substitute imported fertilizers substantially while addressing waste-disposal challenges. Biofertilizers, bio-stimulants, and nitrification inhibition technologies can reduce dependence on fertilizers and improve nutrient-use efficiency and soil health.

The *Atmanirbhar Bharat* framework also aligns closely with India's commitments toward sustainable development, climate change mitigation, and environmental stewardship. Therefore, self-reliance must be pursued not only through increased domestic production but also through improved efficiency, sustainability, and ecological resilience. The future fertilizer sector must, therefore, integrate nutrient stewardship principles, namely the right source, right rate, right time, and right place (4R Nutrient Stewardship), alongside digital technologies, remote sensing, artificial intelligence, and decision-support systems.

In the present context, *Atmanirbharta* does not imply complete import substitution. India's limited high-grade phosphate resources and near-absence of commercially developed potash resources make absolute self-sufficiency neither technically feasible nor economically optimal. The practical objective is nutrient sovereignty: reducing strategic vulnerability while ensuring uninterrupted and affordable plant-nutrient access through a balanced portfolio of domestic manufacturing, overseas partnerships, indigenous resources, nutrient recycling, innovation and improved nutrient-use efficiency. This implies a transition from a subsidy-driven, import-dependent fertilizer economy to a knowledge-intensive, resource-efficient and environmentally sustainable nutrient ecosystem capable of supporting food security and *Viksit Bharat* 2047.

2. TRENDS IN FERTILIZER CONSUMPTION

The growth of fertilizer consumption in India closely mirrors the country's agricultural transformation over the past six decades. The expansion of fertilizer use has been one of the most important drivers of agricultural growth, enabling India's transition from a food-deficit nation in the 1960s to one of the world's largest food producers. The adoption of high-yielding varieties, expansion of irrigation infrastructure, improved agronomic practices, and supportive fertilizer policies during and after the Green Revolution substantially increased the demand for plant nutrients. Consequently, the fertilizer ($N+P_2O_5+K_2O$) consumption increased from approximately 3.38 million tonnes (Mt) in the early 1960s to about 32.93 Mt in 2024–25, while food grain production increased from about 82 Mt to nearly 354 Mt during the same period (Figure 1).

The relationship between fertilizer use and agricultural production is evident from the long-term trends in food grain productivity and fertilizer consumption. Between 1960 and 2020, fertilizer consumption increased at a compound annual growth rate of about 7.2%, significantly higher than the growth rate of food grain production (2.1%) (Sapkota and Bijay-Singh, 2025). During the same period, irrigation coverage expanded substantially, supporting greater adoption of modern crop varieties and intensive fertilizer use. These trends collectively demonstrate the central role of fertilizers in enhancing crop productivity and achieving national food security. A closer examination of nutrient-specific consumption patterns reveals a progressively increasing dominance of N fertilizers. The N consumption increased from approximately 0.2 Mt in 1960 to more than 20.0 Mt by 2024–25, while P_2O_5 consumption rose to nearly 8.0 Mt. Potassium (K_2O), however, increased much more slowly and currently accounts for less than 3.0 Mt of annual nutrient consumption (Figure 1). During the initial decades of the Green Revolution, growth in N, P_2O_5, and K_2O consumption was relatively balanced. However, from the early 1990s, N consumption accelerated much faster than P_2O_5 and K_2O, resulting in a widening nutrient imbalance.

The trends in fertilizer consumption have also been closely linked to changes in fertilizer policies (Figure 1). The Retention Price Scheme (RPS), introduced in 1977, provided assured returns to fertilizer manufacturers while maintaining affordable prices for farmers, thereby facilitating rapid expansion of fertilizer use and supporting Green Revolution-led productivity growth. A major shift occurred in 1992, when P_2O_5

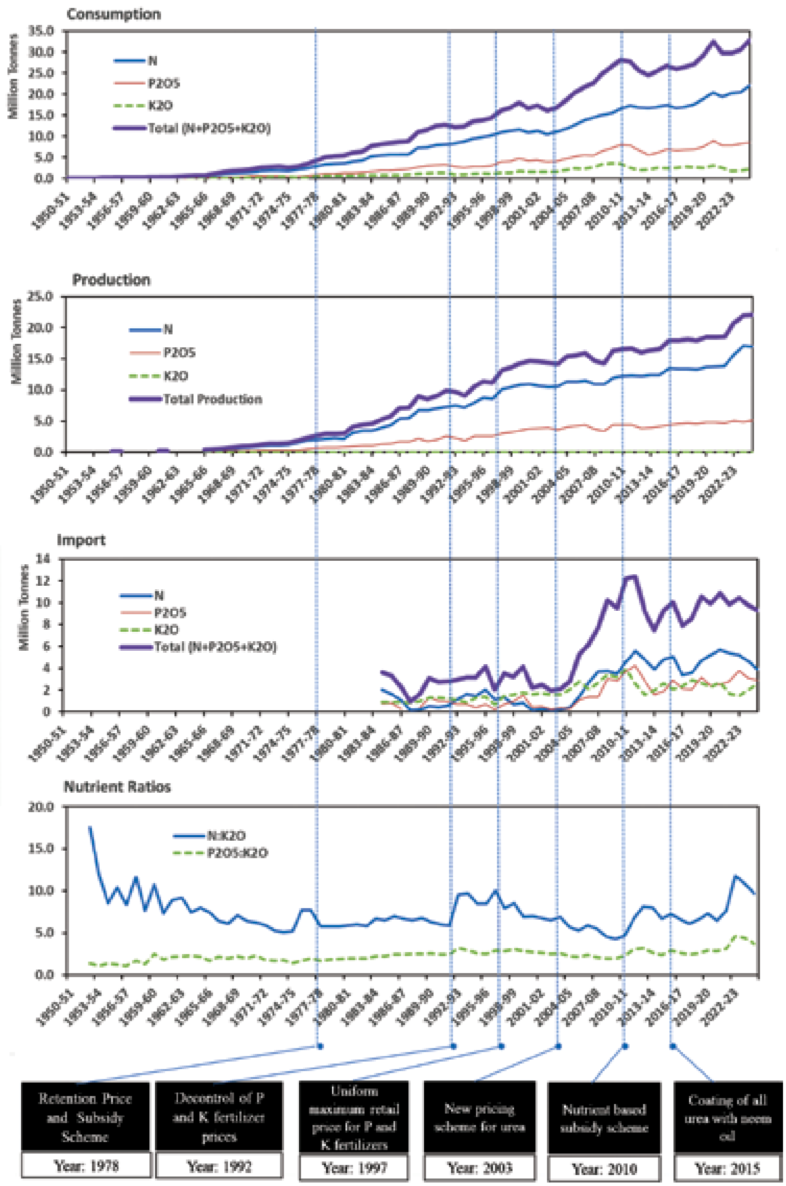

Figure 1. Long-term trends in fertilizer consumption, production, imports, consumption ratios, and major policy interventions in India (1950–51 to 2024–25)

[Sources: FAI Fertiliser Statistics (various editions); Economic Survey of India 2025–26 (Table 1.22). Production data not available for all years; gaps reflect source omissions, not zero production. Policy milestones — Decontrol of P and K fertilizer prices (1992), Uniform Maximum Retail Price for P and K fertilizers (1997) from Department of Fertilizers (n.d.-a); Retention Price and Subsidy Scheme (1977), New Pricing Scheme for urea (2003) from Department of Fertilizers (n.d.-b); coating of all urea with neem oil (2015) from Press Information Bureau (2015)] and K_2O fertilizers were decontrolled though urea remained under statutory price control. This differential pricing structure altered farmers' fertilizer-use behaviour, encouraging greater use of relatively cheaper N fertilizers. Subsequent reforms, including the Uniform Maximum Retail Price mechanism for P&K fertilizers, the New Pricing Scheme (NPS) for urea in 2003, the Nutrient-Based Subsidy (NBS) (2010), and the mandatory neem-coating of urea promulgated in 2015, sought to improve production efficiency, nutrient management, and fertilizer-use efficiency. Nevertheless, fertilizer consumption remained skewed towards N, resulting in a persistent departure from the conventionally desirable fertilizer ($N+P_2O_5+K_2O$) consumption ratio of 4:2:1. The skewed consumption ratio (nationally averaged at 10.9:4.4:1, with further wider ratios in the states of Punjab, Haryana and U.P.) is considered as one of the most significant reasons for low nutrient-use efficiency (NUE), widespread multi-nutrient deficiencies and soil health deterioration. On the other hand, research evidences, especially long-term experiments, showed balanced use of fertilizers alone or along with organic manures maintained or enhanced the soil health and productivity (Gupta *et al*., 2021).

Fertilizer response ratio *i.e.*, kilograms of grain produced per kilogram of fertilizer nutrient applied, has steadily declined over time. During the mid-1970s, each kilogram of NPK nutrient applied generated more than 60 kg of grain. By 2021, the response ratio had declined to approximately 9 kg grain per kilogram of nutrient applied. This trend indicates that progressively larger quantities of fertilizers are required to produce an additional unit of agricultural output. The decline reflects multiple factors, including soil nutrient depletion, imbalanced fertilizer use, declining soil organic matter, emerging micronutrient deficiencies, and diminishing marginal returns from the input use.

3. CHALLENGES AFFECTING FERTILIZER SECTOR

India's fertilizer sector predominantly faces convergence of four strategic challenges: (i) high import dependence for critical nutrients and feedstocks, (ii) declining nutrient use efficiency and deteriorating soil health, (iii) increasing exposure to geopolitical and supply chain disruptions, and (iv) an unsustainable fiscal burden arising from subsidies and foreign exchange outflows. Addressing these challenges requires a transition from fertilizer security to nutrient sovereignty through a combination of domestic resource development, circular nutrient economy approaches, precision nutrient management, enhanced nutrient-use efficiency, alternative fertilizers, and policy reforms aimed at achieving long-term *Atmanirbharta* in fertilizers.

3.1. Import Dependence

Although India is currently the world's second-largest fertilizer consumer and third-largest fertilizer producer, the country imports nearly 90% of its P_2O_5 requirement and almost its entire K_2O requirement through raw materials or finished fertilizers.

During 2024-25, 5.65 Mt urea, 4.57 Mt di-ammonium phosphate (DAP), 2.27 Mt NPK/PK mixtures, and 3.54 Mt muriate of potash (MOP) was imported despite continuous rise in domestic production of nitrogenous and phosphatic fertilizers in recent years. In addition, raw materials viz. 11.95 Mt rockphosphate, 2.20 Mt sulphur and 2.12 Mt phosphoric acid were also imported to aid to domestic production. Energy efficiency in urea production has improved, with specific energy consumption decreasing from 6.04 to 5.6 Gcal/tonne. Domestic urea production remains import-dependent due to natural gas feedstock requirements. Despite production and efficiency gains, both direct fertilizers imports and indirect energy input dependence continue to shape India's fertilizer sector, highlighting the structural imbalance. The fertilizer economy continues to remain vulnerable to international price fluctuations, exchange rate movements, supply disruptions, and geopolitical uncertainties. This dependence has become increasingly important in the context of rising global competition for fertilizer resources and growing concerns regarding food and nutrient security.

3.2. Structural Distortions and Systemic Inefficiencies

Despite substantial policy support and fiscal expenditure, India's fertilizers sector continues to face deep-rooted structural distortions that undermine efficiency, sustainability, and self-reliance. These distortions have evolved over decades and are now reflected in persistent nutrient imbalances, low nutrient-use efficiency, high import dependence, and a growing subsidy burden. Addressing these challenges is fundamental to achieving *Atmanirbharta* in fertilizers (Sapkota and Bijay-Singh, 2025).

3.2.1. Regional Disparities in Fertilizer Use

Regional disparities in fertilizer use further complicate the policy landscape. High-input regions often exhibit excessive fertilizer application rates, whereas resource-constrained areas and small and marginal farmers continue to suffer from inadequate and imbalanced nutrient use. These disparities contribute to uneven agricultural productivity, declining fertilizer response ratios, and region-specific environmental challenges.

3.2.2. Supply Chain and Distribution Constraints

The fertilizer supply chain also faces operational and institutional constraints. Seasonal demand surges, logistical bottlenecks, transportation challenges, storage limitations, and dependence on imported intermediates can periodically affect fertilizer availability. Although the Department of Fertilizers has developed digital monitoring platforms and integrated fertilizer management systems to improve distribution efficiency, further modernization and data-driven decision-making remain necessary to enhance supply chain efficiency and resilience.

3.2.3. Soil Health Diagnostics and Nutrient Management

The weak linkage between soil health diagnostics and fertilizer application decisions continues to be a major concern. The Soil Health Card scheme generated one of the world's largest repositories of soil fertility information; however, the translation of these data into field-level nutrient management decisions remains limited. Fertilizer application continues to be largely blanket-based rather than need-based, reducing the effectiveness of both fertilizer use and public expenditure.

3.2.4. Innovation and Technology Adoption

Innovation adoption remains constrained by regulatory, institutional, and market barriers. Emerging technologies such as nano-fertilizers, biofertilizers, nutrient recycling systems, controlled-release smart fertilizers, and precision nutrient management tools often face challenges related to approval processes, commercialization pathways, financing mechanisms, and farmer adoption. Without stronger incentives for research and innovation and greater private-sector participation, technological transformation will be at much slower pace than the required one.

3.2.5. Transition Towards a Resilient Fertilizer Policy Framework

Taken together, these structural distortions highlight the limitations of a policy framework focused primarily on fertilizer availability and affordability. Future fertilizer policy must evolve towards a broader paradigm that emphasizes nutrient-use efficiency, environmental sustainability, technological innovation, circular resource use, and strategic resilience. Such a transition will be critical for reducing import dependence, rationalizing subsidy expenditure, improving soil health, enhancing agricultural productivity, and advancing the broader objectives of *Atmanirbhar Bharat* and *Viksit Bharat* 2047.

3.2.6. Sustainability Imperative: Current Fertilizer Paradigm

While fertilizers have contributed significantly to agricultural productivity growth, the current pattern of fertilizer use has created serious sustainability concerns. Fertilizer consumption in India remains heavily skewed towards N, primarily due to policy-induced price distortions favouring urea. On the other hand, NUE is very low: 30-50% of N, 15-25% of P_2O_5, and 50-60% of K_2O. The rest is either lost through leaching/runoff/volatilization/denitrification or rendered unavailable to plants due to soil fixation, raising costs, increasing subsidies, and causing environmental issues. Improvement in the NUE while enhancing productivity is a key challenge for sustainable agriculture.

3.3. Geopolitics and Supply Chain Vulnerabilities

Fertilizer supply chains are concentrated in a limited number of countries, creating significant exposure to geopolitical developments. The vulnerability of the fertilizer sector goes beyond finished products. Domestic fertilizer manufacturing sector remains heavily dependent on imported feed stocks and energy inputs. India produces approximately 85% of urea, 40% of DAP, and 90% of NPK fertilizers domestically. Natural gas accounts for up to 70% of urea production costs and nearly 85% of the natural gas consumed by urea industry is imported. Approximately 10-15% of urea, 60% of DAP and almost 100% K_2O are imported. The DAP is imported either as finished product or as key raw materials like phosphoric acid. As a result, India's fertilizer sector is not merely import-dependent; it is strategically linked to global energy and logistics networks. Consequently, geopolitical disruptions rapidly translate into higher input costs, supply chain distortions, increased subsidy burden, and inflationary pressures across the agricultural economy.

Recent global events have highlighted these vulnerabilities. The COVID-19 pandemic disrupted shipping and logistics networks, leading to shortages and increased transportation costs. Subsequently, the Russia–Ukraine conflict and recent West Asian crisis created unprecedented volatility in global fertilizer markets because Russia, Belarus and west Asian countries are major suppliers of urea, DAP, MAP, potash, ammonia, sulphur and natural gas-based fertilizer products. Besides, the export restrictions imposed by major fertilizer-producing countries further constrained global supplies.

These developments resulted in sharp increases in fertilizer prices and procurement costs for importing countries such as India. Dependence on imported rock phosphate, phosphoric acid, potash, ammonia, and natural gas has, therefore, transformed fertilizers security into a broader issue encompassing food security, energy security, trade security, and strategic autonomy.

3.4. Rising Subsidy Burden and Fiscal Implications

Fertilizer subsidies have played a critical role in maintaining affordability of fertilizers and supporting agricultural production. However, the subsidy regime has become increasingly vulnerable to fluctuations in international fertilizer and energy prices. Global disruptions during recent years demonstrated that import dependence can rapidly translate into escalating fiscal liabilities. The fertilizer subsidy bill increased sharply during periods of global commodity price volatility, highlighting the need to balance farmer welfare objectives with long-term fiscal sustainability.

When domestic production falls short of demand, additional imports are procured at international market prices to maintain affordable fertilizer prices for farmers and ensure food security. Increases in import prices are largely absorbed by the Government through higher subsidy allocations. The surge in imports during 2024–25 demonstrated that India's subsidy burden remains closely linked to global fertilizer and energy markets rather than domestic production costs alone.

Fertilizer subsidies increased persistently over the past two decades, rising from ₹16,127 crore in 2004-05 to ₹1.91 lakh crore in 2024-25 reflecting annual growth rate of 12.7 % (Press Information Bureau, 2025). Of this, urea alone accounted for 69.5%, and the remaining was for all P and K fertilizers. Urea remains heavily subsidized and subject to statutory price controls, whereas P and K fertilizers are under the NBS regime and, therefore, more exposed to international price fluctuations. This differential pricing has created strong incentives for excessive N consumption relative to P_2O_5 and K_2O, resulting in imbalanced nutrient application across the country (Katyal, 2022; Sapkota and Bijay-Singh, 2025). Fertilizer use decisions are often influenced more by relative prices than by agronomic requirements, contributing to a decline in nutrient-use efficiency and soil health.

In addition to direct fiscal costs, fertilizers imports generated foreign exchange outflows of approximately US$8.29 billion (about ₹72,000 crore) in 2024–25. Such expenditures not only constrain public finances but also reduce fiscal space available for investments in agricultural research, irrigation, climate adaptation, and rural infrastructure. Studies have also argued that large subsidy commitments can discourage efficiency improvements, and crowd out private-sector investment in fertilizer innovation and manufacturing (Katyal, 2022).

4. FRAMEWORK FOR *ATMANIRBHARTA* IN FERTILIZERS

The proposed framework is organized explicitly around four strategic pillars: (I) Strategic Resource Security; (II) Domestic Manufacturing Expansion and Feedstock Security; (III) Technological Innovation and Circular Nutrient Economy; and (IV) Nutrient-Use Efficiency and Demand Rationalization (Figure 2). Together, the four pillars treat *Atmanirbharta* as nutrient security and resilience rather than as domestic production alone.

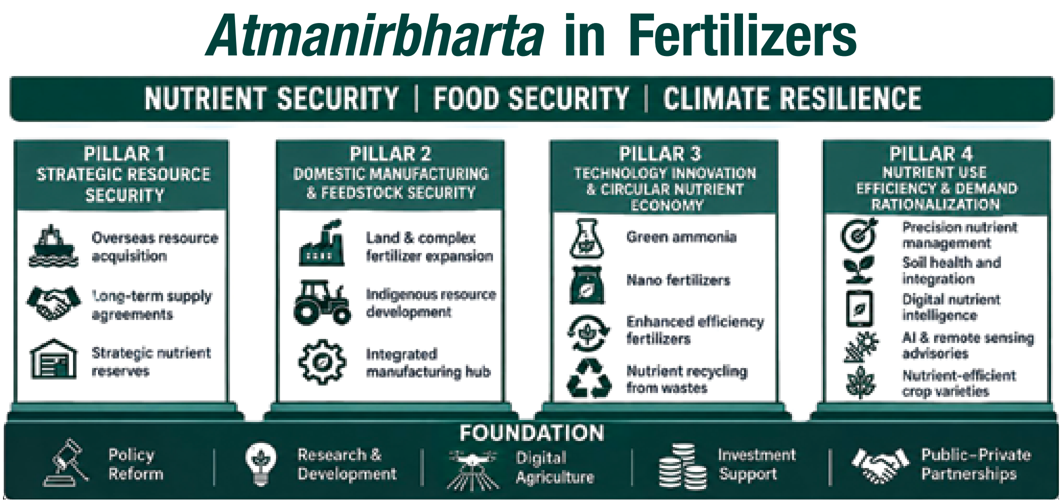

Figure 2. Strategic Framework for *Atmanirbharta* in Fertilizers in India (Source: Convener's creation)

4.1. Strategic Resource Security

4.1.1. Securing Global Nutrient Resources through Strategic Partnerships

Achieving fertilizer self-reliance in India does not mean isolation from global markets. Given limited reserves of high-grade rock phosphate and near absence of potash deposits, fertilizer security must rest on resource sovereignty rather than resource independence. The Government, fertilizer cooperatives, and private companies should expand overseas investments in phosphate, potash, and ammonia fertilizer assets in resource-rich countries. Instead of relying on the spot-market imports, India should strengthen joint ventures, equity participation in mining projects, and long-term off-take agreements for assured access to critical nutrients. These arrangements can reduce supply uncertainties, stabilize costs, and improve resilience against global shocks. India should diversify sourcing to avoid dependence on limited supplier nations and establish nutrient reserves to cushion disruptions, becoming a participant in global fertilizer value chains for enhancing nutrient security and agricultural growth.

4.1.2. Beneficiation and Use of Indigenous Mineral Resources

India possesses extensive reserves of glauconite, rock phosphate, mica and silicate minerals. Glauconite, an iron-potassium silicate, contains 5–8.5% K_2O (Indian Bureau of Mines, 2018) with some deposits having up to 11% K_2O along with iron, magnesium, silica, zinc and copper. The glauconite reserves of over 2,662 Mt exist primarily in Rajasthan (Nagaur: 91%), Madhya Pradesh (Panna: 5%), and Uttar Pradesh (Sonbhadra & Chitrakoot: 4%) (Indian Bureau of Mines, 2020; NAAS, 2017). Mica waste, containing 8-10% K_2O, occurs abundantly in Jharkhand, Bihar, and Andhra Pradesh. The country has approximately 280 Mt of rock phosphate reserve in Jharkhand (34%), Rajasthan (30%), Madhya Pradesh (19%), Uttar Pradesh (8%), Uttarakhand (8%), Gujarat and Meghalaya (1%). Of these, only 15 Mt are high-grade reserves (≥30% P_2O_5), with most being low-grade. India also has polyhalite deposits of 16,000 Mt with ~12% K_2O, 6% MgO, 19% SO_3, and 12% CaO (Indian Bureau of Mines, 2020). These low-grade minerals, including indigenous rock phosphate, glauconite and polyhalite, represent potential supplementary nutrient sources where agronomic performance and beneficiation are technically and economically viable.

Rock phosphate has low solubility in neutral to alkaline soil, limiting its direct use. Their agronomic performance depends on mineral dissolution, which is often inadequate for crop needs. K release from glauconite is influenced by particle size. Their slow release makes them suitable for long-term fertility management in leaching or weathered soils. Studies have focused on developing methods to promote solubilization and improve nutrient release from these non-conventional sources as alternatives to DAP and MOP. Methods to increase rock phosphate solubility may include composting with organic wastes (P-rich organic manure; PROM), partial acidulation with acids, and PSB inoculation which promote solubilization through acidification, chelation, and enzymes. These methods make low-quality rock phosphate useful in neutral and alkaline soils, reducing dependence on imported P fertilizers.

Several beneficiation techniques have been researched to release K from silicate minerals. Surface area increase through mechanical grinding and chemical treatment with sulfuric acid and fluoric acid facilitates nutrient release. Potassium-solubilizing microorganisms (KSMs) and composting enhance K release from glauconite through organic acids. Feldspar, syenite, biotite, and vermiculite have been studied as slow-release K sources, which improve after biological weathering or treatment. Integrating these mineral sources with microbial inoculants, organic amendments, and chemical treatment offers a path to curtail conventional fertilizer use while improving soil fertility and climate-resilience.

4.2. Domestic Manufacturing Expansion and Feedstock Security

Strengthening domestic fertilizers manufacturing remains central to the *Atmanirbhar Bharat* vision. India has progressed towards urea self-sufficiency through revival of manufacturing plants and creation of new facilities. Nevertheless, production still faces structural constraints; the next phase of self-reliance must, therefore, enhance production capacity and feedstock security.

Future policies should prioritize modernization and expansion of existing plants, investments in N, phosphatic, and complex fertilizers, and faster development of mineral resources wherever feasible. Emphasis should be placed on diversified energy sources and alternative production pathways. Integrated manufacturing clusters linked with ports, energy infrastructure, and logistics networks can improve competitiveness and lower costs. Strengthening research and innovation can improve efficiency, reduce costs, and enhance sustainability.

4.3. Technological Innovation and Circular Nutrient Economy

4.3.1. Alternative and Next-Generation Fertilizer Technologies

Atmanirbharta in fertilizers requires alternate, resource-efficient, environmentally sustainable technologies. A longer-term opportunity lies in developing green ammonia and low-carbon fertilizer systems. Green ammonia, produced through renewable energy-powered electrolysis and green hydrogen, offers a pathway to decarbonize fertilizer manufacturing while reducing exposure to imported fossil fuels. As India implements its National Green Hydrogen Mission and expands renewable energy capacity, green ammonia could become a critical component of fertilizer security. In parallel, coal gasification and other feedstock technologies may provide alternate pathways to reduce dependence on imported natural gas while domestic renewable-energy infrastructure matures.

Conventional nitrogen fertilizer production relies on the Haber-Bosch process, requiring hydrogen from natural gas. Gasifying coal into synthesis gas (syngas-primarily CO and H2) allows low-cost indigenous feedstock to manufacture ammonia and urea. With the implementation of National Coal Gasification Mission, coal-to-urea could be a strategic option for strengthening fertilizer self-reliance in the foreseeable future. India possesses abundant coal reserves exceeding 360 billion tonnes, providing significant opportunities for coal gasification-based fertilizer production.

Plasma discharge technology for N fertilizer production, that offers non-fossil fuel-based pathway to fix atmospheric N bypassing Haber-Bosch processes, is gaining importance. While the concept holds promise, it requires substantial strengthening in scientific validation, methodological rigor, and techno-economic feasibility. The direct soil application of plasma-induced N fixation is innovative, as it bypasses intermediate fertilizer synthesis steps and explores the possibility of *in situ* N enrichment. If optimized, this method could potentially reduce dependence on conventional fertilizers. The prospects of piloting small modular plasma reactors for N fertilizer production in India are highly promising. Powered by renewable energy or small modular reactors (SMRs), this system has potential to replace the massive traditional ammonia plants with decentralized on-site N production. This technology upon its successful piloting will directly align with India's goals of reducing agricultural emissions, lowering urea imports and strengthening supply-chain resilience.

The nano-fertilizer formulations can deliver nutrients more efficiently while reducing application rates. Continued investment in nano-fertilizer research, validation, and scaling can reduce nutrient demand without compromising productivity. Enhanced-efficiency fertilizers, including neem-coated urea, slow-release, controlled-release, and polymer-coated formulations, can improve NUE and reduce losses.

4.3.2. Biofertilizers

Biofertilizers can supplement up to 25% of the crop nutrient needs. However, efficacy varies with microbe strains, edaphic conditions, soil organic carbon, and host plants. Biofertilizers has limited efficacy when applied standalone inputs in the stressed soil with low organic matter, with practices of stubble burning and depleted biodiversity. Such constraints reduce microbial establishment and performance. Therefore, increasing soil organic carbon and restoring microbial diversity through integrated soil health management is essential to enhance biofertlizers' effectiveness. Further biofertilizers efficacy can be improved by using location-specific efficient strains, selecting right carrier and packaging material, minimising contamination, increasing shelf-life and strengthening supply chain.

Scaling biofertilizer production and their large-scale adoption requires innovative PPP models. There is a need to encourage startups and MSMEs through financial incentives, and reducing entry barriers in manufacturing and marketing. Providing policy support and market incentives by introducing subsidies like the one extended to chemical fertilizers, mandating partial substitution of chemical fertilizers in Government schemes and creating assured markets through integration with the ongoing schemes on organic and natural farming, and awareness campaign among farmers and extension functionaries will improve trust and large-scale adoption. Research should focus on identification of efficient microbes with strong rhizosphere competence with effective N-fixing endophytes for cereals and rhizospheric modification to enhance beneficial microbe colonization. Focus should be on biopolymer-based inoculants, nano-enabled biofertilizers, and stress-mitigating inoculants to withstand climate change impacts.

4.3.3. Circular Nutrient Economy Using On-farm and Off-farm Wastes

A circular nutrient economy reuses industrial and agricultural waste and wastewater to recover and reuse plant nutrients that remain underutilized in crop residues, livestock manure, municipal waste streams, sewage sludge, basic slag, ash, industrial gypsum and food processing residues. Recovering and recycling these nutrients can create domestic sources while reducing environmental pollution and dependence on imported fertilizers. Organo-mineral fertilizers, enriched composts, crop residue-based products, and nutrient recovery from wastewater and organic wastes can support a circular nutrient economy, and enhance sustainability and resilience.

***4.3.3.1. Nutrient Recovery from Agricultural Biomass and Organic Wastes* :** India generates 762.8 Mt of crop residue, primarily from rice, wheat, and sugarcane, containing 4.55 Mt of N, 0.53 Mt of P, and 6.61 Mt of K. Additionally, 667.7 Mt of animal waste comprises 4.49 Mt of N, 1.77 Mt of P, and 3.31 Mt of K. Cattle and buffalo account for over 90% of this waste generation. Agro-industrial by-products include press mud (11-14 Mt) from sugar mills containing NPK (1-2.5% each), distillery spent wash (~40 billion litres ≈0.05 Mt solids) rich in soluble K, and oil cakes like neem, mustard and groundnut, with N content up to 9%. Oil meal (23.3 Mt) contains 1.51 Mt of N, 0.25 Mt of P, and 0.24 Mt of K approximately. Organic waste generates 10.6 Mt of N, 2.6 Mt of P, and 10.2 Mt of K yearly. Crop processing residues provide recyclable nutrients, such as rice husk (20 Mt) with high silica (15-20%) and K. Uttar Pradesh leads in organic nutrient generation, contributing 14.6% of N, 12.3% of P, and 18% of K, followed by Madhya Pradesh. On average, 10.1 tonnes of organic waste is available per-hectare in India, providing 75.6 kg of N, 18.0 kg of P, and 71.7 kg of K annually (Shanmugam *et al*., 2025).

***4.3.3.2. Urban Wastewater and Sewage Sludge* :** Rapid economic development and expanding urbanization is leading to production of huge quantities of effluents and urban wastes. Raw sludge typically contains 2–3% solids, with the remainder being water. In India, approximately 72 million m^3/day of sewage is generated of which 32 million m^3/day is being treated. Treating all generated sewage would produce approximately 4,000 tonnes of dry sewage sludge annually. Dewatered sludge typically comprises organic matter (50–70%) and mineral components (30–50%), including 1–4% of inorganic carbon. It also contains N (3.4–4.0%), P (0.5–2.5%), and significant quantities of other nutrients.

Total nutrient potential from the sludge of the existing sewage treatment facility is 97.5×10^3 t/year, which is equivalent to 0.92% urea or 0.19% NPK used presently as conventional fertilizers in India. Research suggests that safe application rates, such as 10 t/ha can improve crop growth without causing heavy metal accumulation. At present, sewage sludge is primarily utilized through landfilling, incineration, energy recovery, and seldom as a nutrient source or soil conditioner. However, the absence of formal standards remains a key constraint, raising the concerns of contamination. Also, about 80-90% of Sewage Treatment Plants (STPs) in India do not fully treat sludge, focusing mostly on thickening and dewatering rather than advanced stabilization. In reality, these nutrients originate in rural soils, move to cities through food, and are then lost instead of being returned. For closing the nutrient loop, there is a need to move from a linear system, where nutrients flow from farms to cities and end-up as waste, to a circular system where nutrients are recovered and returned to the soil.

***4.3.3.3. Emerging and Non-conventional Nutrient Sources* :** Tapping renewable and non-conventional nutrient sources is another promising avenue. One such resource is human urine, an untapped nutrient reservoir. Each individual produces about 500 litres annually, containing approximately 4 kg of N, 0.4 kg of P, and 1 kg of K. At the national level, this translates into nearly 3.5 Mt of N along with significant quantities of P and K. Through technologies such as struvite precipitation, these nutrients can be recovered as safe, slow-release fertilizers at costs significantly lower than imported fertilizers, while also creating opportunities for decentralized systems and local employment.

***4.3.3.4. Industrial By-products and Bio-enriched Nutrient Sources* :** Steel slag, a steel industry by-product, is a major environmental concern for steel manufacturing units worldwide. With high CaO content (>40%) and pH (>11.0), it serves as a promising alternative to lime in acid soils, which exceed 49 Mha in India. Slag contains plant nutrients and Silica that increase yields of monocotyledonous crops and protect against stresses. India, the third largest steel producer, generates over 12 Mt of slag yearly, with less than 20 % used in cement while the rest accumulates at the production sites. Through bio-enrichment, steel slag can be used as a soil amendment to improve pH, supply nutrients, and enhance crop productivity.

Enriching bio-manure with nutrients is strategically important. India's biogas sector produces significant quantity (1.1 Mt) of fermented organic manure (FOM) annually, offering potential for its enrichment and use. Microbial technologies can transform these wastes using beneficial microbes like P solubilizers, K mobilizers, S oxidizers, cellulolytic fungi, and N fixing bacteria. The bio-enriched formulations supply balanced nutrients, improve soil organic matter, and enhance biological activity in the soil. Besides, phospho-gypsum is another untapped resource, which can be effectively used as S fertilizer and as a soil amendment for alkali soils.

Large-scale adoption of recycled products remains constrained due to inconsistent quality standards, inadequate certification framework, weak markets, and abysmal policy support; a regulatory framework is required for their commercialization integration into national strategies.

4.4. Nutrient-Use Efficiency and Demand Rationalization

4.4.1. Precision Nutrient Management

The most sustainable pathway to fertilizer self-reliance is to reduce the nutrient input required per unit of output. Precision nutrient management (PNM) should combine accessible soil testing, site-specific recommendations, variable-rate application, sensor- and drone-assisted diagnostics, and the 4R principles of right source, rate, time and place. Soil Health Card recommendations, weather and crop information, remote sensing and decision support can improve nutrient recovery and reduce losses. Breeding and deployment of nutrient-efficient crop varieties can complement these measures (Li *et al*., 2022; Srikanth *et al*., 2023). Policy incentives should reward balanced nutrient use and efficient products rather than fertilizer volume alone.

4.4.2. Integrated Nutrient Management (INM)

Integrated nutrient management should be treated as a core present-day strategy for improving NUE and soil health. It combines judicious mineral fertilizer use with organic manures, green manuring, biological N fixation, biofertilizers, crop-residue recycling and other locally available nutrient sources. *Dhaincha* and *sunnhemp* can contribute substantial biologically fixed N in cropping systems, while residue recycling and organic inputs help restore soil organic carbon and enhance nutrient availability. Over 50 years of long-term studies revealed INM aka INSAM (integrated nutrient supply and management) as the best option for sustaining high productivity and building soil health across the soil types and cropping systems. Along with capacity building training and launch of action research, initial hand holding to produce good quality FYM by the community of farmers is necessary to inspire large-scale adoption (Katyal, 2019). Scaling INM requires location-specific packages, reliable input quality, on-farm resource integration, extension support and transition incentives so that proven practices move from isolated demonstrations to landscape-scale adoption.

4.4.3. Cropping System Design and Crop Diversification

Cropping system design can reduce fertilizer demand by integrating legumes as substitute crops, break crops, short-duration grain crops, forages or green manures. Inclusion of legumes in cereal-based systems improves NUE, soil organic carbon and soil physical condition (Dwivedi *et al*., 2016). Region-specific transition strategies should identify where surplus rice or other fertilizer-intensive systems could be diversified toward pulses, legumes and regenerative practices without compromising food-security objectives.

4.4.4. Digital Nutrient Intelligence and AI-Based Decision Support

Future nutrient management systems will depend on digital agriculture technologies integrating soil information, crop requirements, weather forecasts, remote sensing, nutrient inventories, and fertilizer supply chains. India should establish a National Nutrient Intelligence Platform built upon Soil Health Card databases, AgriStack, Bharat-VISTAAR, remote sensing systems, fertilizer transaction databases, and geo-referenced soil maps. Such a platform can provide nutrient advisories, nutrient budgeting, fertilizer demand forecasting, and AI-driven support at farm, district, and national scales. Longer-term, digital twin technologies may enable simulation of nutrient flows, fertilizer demand, crop responses, and environmental impacts to support evidence-based fertilizer policy and subsidy targeting. The platform should integrate National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) soil maps, digital soil mapping products, geo-spatial nutrient deficiency layers, and remote sensing observations. High-resolution digital soil mapping can enable district-level nutrient budgeting, site-specific nutrient recommendations, and AI-enabled nutrient advisory services. Integration of these datasets will support precision nutrient governance.

5. RECOMMENDATIONS AND IMPLEMENTATION ROADMAP

Achieving nutrient sovereignty requires a single policy package that links strategic supply security with demand rationalization. The recommendations below consolidate regulatory, financial, technological and implementation measures so that the four-pillar framework is translated into sequenced action through 2047, while protecting smallholders and maintaining fertilizer availability.

The implementation of roadmap is organized in three phases: 2026–2030 for foundation building, 2031–2040 for scaling and integration, and 2041–2047 for consolidation of a nutrient-sovereign economy. Each phase combines supply security, nutrient-use efficiency, circularity, digital governance and farmer-centric implementation (Figure 3).

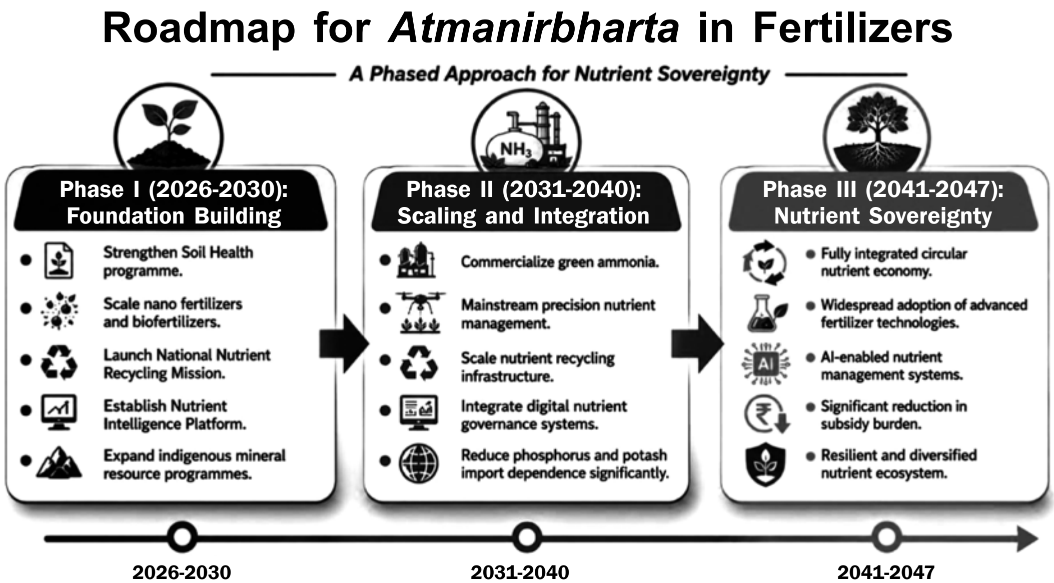

Figure 3. Roadmap for *Atmanirbharta* in Fertilizers: a phased approach (Source: Convener's creation)

Phase I: Foundation Building (2026-30)

- Strengthen Soil Health services, soil-testing capacity and site-specific recommendations, and integrate them with AgriStack, Bharat-VISTAAR, farmer ID, crop registries and land records to establish a national nutrient-intelligence foundation.
- Take-up phased reform in fertilizer subsidies by bringing urea in the ambit of NBS, incentivising INM, organic and biological resources of nutrients and other scientifically-proven good agronomic practices, and gradually moving towards supporting nutrient inputs rather than fertilizers alone.
- Strengthen supply chain security through modernization and expansion of urea and complex-fertilizer capacity, long-term gas and raw-material agreements, overseas mining/fertilizer partnerships, and enabling support for green-ammonia, coal gasification and other strategic feedstock projects.
- Develop and deploy a comprehensive framework for fertilizer distribution based on soil health and crop demand.
- Create a stronger fertilizer R&D and validation ecosystem for plasma-based N fixation, nano- and enhanced-efficiency fertilizers, biofertilizers, biostimulants,

organo-minerals and recycled nutrient products, backed by quality-testing facilities and clear commercialization standards.

- Maximize supply of quality organic manure by extending guidance on scientific composting and supporting financially to establish village cluster/community-based composting units.
- Scale the proven fertilizer-saving agronomy through INM, green manuring, legume-based systems, residue recycling, biofertilizers, precision nutrient management and location-specific extension packages.
- Launch a National Nutrient Recycling Initiative and expand the Fertilizer Control Order/related standards to enable safe, quality-assured recovery and reuse of nutrients from agricultural, livestock, agro-industrial, municipal and CBG-derived organic streams.
- Initiate a focussed research program on breeding for nutrient use efficiency, especially for P&K and also BNI (Biological Nitrification Inhibition).

Phase II: Scaling and Integration (2031-40)

- Deploy advanced soil- and plant-diagnostic systems using handheld sensors, UAVs and satellite platforms, and operationalize district-level precision nutrient-management advisories with AI, crop models and variable-rate technologies.
- Integrate nutrient governance across fertilizer distribution, subsidy administration, soil-health monitoring and nutrient-use assessment, with carefully evaluated transition toward farmer-centric direct support i.e., transition from direct benefit transfer (DBT) to direct cash transfer (DCT), where digital and institutional safeguards are adequate.
- Scaling low-carbon fertilizer production, including renewable-hydrogen-based green ammonia and improved energy/carbon management, while reducing dependence on imported natural gas feedstock.
- Expand nutrient recycling infrastructure and indigenous resource tapping programmes, including composting, bio-resource centres, organo-mineral fertilizer enterprises, and beneficiation of rock phosphate, glauconite, polyhalite and other nutrient-bearing minerals.
- Establish strategic reserves of critical fertilizer products and feedstocks and use combined efficiency, recycling, indigenous resources and diversified sourcing to achieve a substantial reduction in P and K imports.

Phase III: Nutrient Sovereignty (2041-47)

- Operate a national innovation and soil-health ecosystem supported by real-time nutrient intelligence, AI-enabled advisory systems and digital twins for policy and landscape planning.
- Establish a fully integrated circular nutrient economy wherein nutrients are routinely recovered and reused across agricultural, livestock, urban and industrial systems.
- Mainstream validated advanced technologies as priority, including nutrient-efficient varieties, enhanced-efficiency and smart fertilizers, biological nitrification inhibition, synthetic-biology products, green ammonia and scientifically validated plasma-based nutrient technologies.
- Use the combined gains in supply resilience, nutrient-use efficiency and circularity to reduce subsidy and import vulnerability while improving farm profitability, soil health, environmental performance and national food-security resilience.

Implementing Agencies

Department of Agriculture & Farmers Welfare; Department of Fertilizers, Ministry of Chemicals & Fertilizers; ICAR and State Agricultural Universities; State Departments of Agriculture and Revenue; Ministry of Housing and Urban Affairs; Ministry of Coal; Ministry of New and Renewable Energy; concerned mining, energy and environment agencies; fertilizer industries and cooperatives; and relevant start-ups and farmer organizations.

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