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REVIEW

India's fertilizer policies: implications for food security, environmental sustainability, and climate change

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Abstract

To ensure food security, the Government of India has implemented various policies since the 1950s to provide enough and affordable fertilizer for farmers. Based on quantitative data, this paper provides a comprehensive and systematic analysis of how these policies influenced the fertilizer consumption and nutrient management and their influence on the socio-economic status of rural producers as well as environmental and climate outcomes. Increases in food grain production have paralleled the consumption of fertilizers. Even though the population of India increased more than three times from 1961 to 2022, per capita availability of rice remained almost the same, and that of wheat increased by 2.4 times. The price of urea has continuously decreased since 1977, but the price of diammonium phosphate fell only after the decontrol of phosphatic and potassium fertilizer in 1992, and the implementation of nutrient-based subsidies in 2010. Fertilizer policies have been linked to reductions in rural poverty and the contribution of agriculture to India's gross domestic product. However, the overuse of subsidized urea and underuse of phosphatic and potassium fertilizers have resulted in economic and nutrient use inefficiencies, reduced crop yields, and increased environmental risks, including nitrous oxide emissions and nitrate leaching. India's fertilizer policies must address these environmental challenges while ensuring food security for the growing population. Balanced fertilization should be incentivized through recalibrating subsidies and adopting soil nutrient-based recommendations. Gradual liberalization of urea pricing, alongside measures to ensure the affordability of phosphatic and potassium fertilizers for small and marginal farmers, will be essential to address the food-fertilizers-climatic crisis.

Keywords Fertilizer policies · Socio-economic impacts · Environmental impacts · Climate change · Balanced fertilization · Fertilizer subsidy

Introduction

India, now the world's most populous country, has achieved self-sufficiency in food grains, but its production remains resource-intensive, cereal-centric, and regionally imbalanced. Declining soil fertility has led to a steady increase in the use of nitrogen (N), phosphorus (P), and potassium (K) fertilizers to sustain agricultural growth. For instance, in 1971–1972, the production of food grains in India was 105.2 million tonne (Mt) while consumption of fertilizers was 1.80 Mt N, 0.56 Mt P_2O_5, and 0.30 Mt K_2O. Fifty years later in 2021–2022, while production of food grains increased by 3 times, fertilizer consumption had increased 11.3 times for N, 14.2 times for P_2O_5, and 5.71 times for K_2O (Government of India 2023; Fertiliser Association of India 2023). By 2022–2023, India had become the second-largest consumer of fertilizers globally, accounting for 14.83% of global fertilizer nutrient consumption. It has been reported that farmers often apply greater than recommended rates of fertilizers N and P, but ignore the sufficient application of K and other secondary and micro-nutrients (Sapkota et al. 2021). Such unbalanced and inadequate use of nutrients not only decreases the nutrient use efficiency and profitability but also increases environmental risks associated with loss of unutilized nutrients through emission and/or leaching (Foley et al. 2011; McLellan et al. 2018; Ladha et al. 2020; Bijay-Singh and Sapkota, 2023b).

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Although factors such as crop type, varietal responsiveness, and irrigation access influence the fertilizer use, fertilizer-related policies in India have played an important role both in the increase in fertilizer use and their potential mismanagement. The policies were introduced to boost agricultural productivity by keeping prices of fertilizers affordable for farmers. But India is now facing a sustainability challenge due to its heavy reliance on fertilizers. Paul et al. (2023) highlight that for every USD 1000 invested in sustainable agriculture, the Indian government allocates USD 100,000 as fertilizer subsidy. Because fertilizer policies have been driven by food security and dynamic macro- and micro-economic considerations, these were not uniform for different nutrients. Therefore, in some regions in India, farmers apply fertilizer N but without adequate amounts of P and K or regularly overfertilize with N leading to N-related environmental externalities while in other regions application of inadequate amounts of one or more fertilizer nutrients leads to low yields of crops, and deterioration of soil quality (Kishore et al. 2021; Bijay-Singh and Craswell, 2021; Bijay-Singh and Kumar, 2023a). It is high time that India should focus on balanced nutrient management to increase crop production and farmers' income while reducing environmental impact including emissions of greenhouse gases like nitrous oxide (N_2O) (Maaz et al. 2021; Sapkota et al. 2021).

To our knowledge, the role of India's fertilizer-related policies in shaping both fertilizer consumption and agricultural productivity across the country and their socio-economic and environmental implications has not yet been studied systematically. This paper evaluates the socio-economic and environmental impacts of fertilizer use and management in India, shaped by government policies over time and proposes policy recommendations aimed at achieving a harmonious balance between food security, socio-economic development, and environmental sustainability. We strongly believe that this offers critical insights for future policy development, balancing the need for food security with the environmental and climate-related challenges posed by fertilizer use.

Methodology

Data sources

The primary data for this study was obtained from multiple sources. Major fertilizer-related policies of the government of India since 1950s (Table S1) were obtained from multiple sources including Fertilizer Association of India (2023), Sharma (2014), and Katyal (2023). The information on annual fertilizer consumption across India, with a breakdown by district and nutrient type together with gross cropped area, was obtained from the annual *Fertilizer Statistics* (Fertilizer Association of India, 2023). These are the most relevant and comprehensive sources of information related to fertilizers in India. The data on agricultural production, including total food grain production, irrigated area statistics, and socio-economic indicators such as rural poverty rates, were obtained from the *Agricultural Statistics at a Glance* (Government of India 2023). This information allows for linking fertilizer use to agricultural productivity and socio-economic impacts. The data on soil N flow and associated greenhouse gas emissions were obtained from the *Soil Nutrient Budget* (https://www.fao.org/faostat/en/#data/ESB) and *Emissions Totals* (https://www.fao.org/faostat/en/#data/GT) of FAOSTAT. The authors acknowledge that reliance on secondary datasets and the study's nationwide scope may have overlooked the nuanced regional variations in socio-economic and agro-climatic conditions and their consequences on the impact of fertilizer use on food security, environmental sustainability, and climate change.

Analytical approaches

As the study is based on more than 50 years data collected from different sources, we employed a blend of descriptive and inferential methods to evaluate the impact of fertilizer policies to fertilizer use and its consequences of agricultural production, socio-economic development, and environmental impacts. By integrating both descriptive and inferential methods, the study unravels complex relationships between policy interventions and their outcomes. We calculated the compound annual growth rates of fertilizer application and crop production to evaluate how fertilizer policies have influenced the use of fertilizers N, P, and K in different regions of the country, based on gross cropped area, size of the farms, and extent of irrigation. Relationships were established between (i) gross cropped area under irrigation and fertilizer application per unit area, (ii) per ha food grain production and fertilizer consumption, (iii) rural population below poverty line and fertilizer application in different states, and (iv) gross value added by crop production and fertilizer consumption. Such relationships allow for nuanced insights into the socio-economic and environmental dimensions of fertilizer policies. In top 12 fertilizer-consuming states, we analyzed food grain production in relation to per hectare application of fertilizers N and P from 2004 to 2021. Such state-level analyses enhance the granularity of the study, capturing regional variations and policy effects more accurately. We also examined the linkage between per capita net availability of food grains in India from 1950 to 2021 and fertilizer use influenced by various fertilizer policies. Trend analysis was conducted to evaluate the economics of applying nitrogen as urea and phosphorus as DAP on paddy and wheat, with a focus on the influence of fertilizer policies in India from 1971 to 2021. The relationship between fertilizer N and surplus N per ha and N_2O emission was established using the data from *Soil Nutrient Budget*, and *Emissions Totals* of the FAOSTAT. This information helps in analyzing the complex interplay between fertilizer policies, agricultural productivity, socio-economic outcomes, and environmental impacts over time.

Results

An overview of fertilizer policies since the 1950 s

Government of India implemented various fertilizer policies since the 1950 s (Table S1). The Fertilizer Control Order and the maximum retail price of urea were introduced as early as 1957, well before Green Revolution. In 1966, the marketing of fertilizers was liberalized. The introduction of the Fertilizer Movement Control Order in 1973 placed fertilizer distribution and interstate movement under government control. To partially offset the rising costs of producing or importing P fertilizers, a fixed subsidy of USD 15 per tonne of P_2O_5 was introduced in March 1976 (Fertiliser Association of India 2023).

Implementation of the Retention Price Scheme (RPS) for N fertilizers (except ammonium chloride) in November 1977 marked the first-time introduction of fertilizer subsidies. In 1979, the RPS was introduced for complex fertilizers, and the fixed subsidy on P fertilizers was also replaced by the RPS. Fixed subsidy on single superphosphate (SSP) was replaced by RPS in May 1982. In August 1992, the prices, movement, and distribution of all P and K fertilizers were decontrolled, which led to a significant increase in their retail price. To partially compensate for the increased cost and promote the balanced use of fertilizers N, P, and K (Sharma 2014), an ad hoc concession in the price of DAP, mono-ammonium phosphate, and NP/NPK complex fertilizers was implemented in October 1992.

In April 2003, the RPS for urea was replaced by the New Pricing Scheme (NPS), which linked urea prices to the type of feedstock used in its production. The NPS incentivized urea production from the indigenous units beyond 100% of their capacity. Nutrient-based pricing for subsidized complex-grade fertilizers was introduced in 2008. As prices of N, P, and K in urea, DAP, and muriate of potash (MOP) were used as the benchmark, the maximum retail price of complex fertilizers was significantly reduced.

The Nutrient Based Subsidy (NBS) policy for P and K fertilizers was introduced in April 2010. It replaced the product pricing regime with market price determined by demand/supply balance. The focus of the NBS was primarily on DAP and MOP. Every year, the subsidy per kg of N, P, and K changed by a small amount. Up to 2020–2021, the price of P_2O_5 in DAP and SSP increased from 0.24 to 0.48–0.54 USD/kg and that of K_2O from 0.06 to 0.24–0.36 USD/kg. However, during 2021–2022, the NBS rates on N, P, and K in DAP and MOP were increased five, five, and 2.5 times, respectively. It amounted to nearly the same subsidy per kg N in urea or DAP, which incentivized balanced use of nutrients.

Under NBS, urea prices were left untouched. A new urea policy was introduced in May 2015 to encourage urea production through efficient use of energy and to rationalize the subsidy burden on the government. This policy will continue until March 2025, with the maximum retail price statutorily fixed at USD 2.90 for a 45 kg bag of urea. In May 2015, it was made mandatory to coat all subsidized urea with neem (*Azadirachta indica* A. Juss) seed oil to enhance its efficiency. The Soil Health Card scheme was launched in February 2015 to apply fertilizers based on soil tests and crop-specific nutrient recommendations.

Three straight fertilizers—urea, MOP, and SSP—and one compound fertilizer DAP are the dominant fertilizers in India. Whereas urea comprised 81.3% of all fertilizer N used in 2022–2023, shares of DAP and MOP in fertilizers P_2O_5 and K_2O consumption were 60.5% and 56.9%, respectively (Fertiliser Association of India 2023). Between 2010 and 2022, the Government of India provided an average subsidy of USD 228.5, 110.4, and 70.5 per tonne for urea, DAP, and MOP, respectively. As a result, farmers paid only 22% of the international market price for urea, and 71% and 73% for DAP and MOP, respectively (Katyal 2023).

Government policies shaping fertilizer consumption

Fertilizer consumption

The trends of N, P_2O_5, and K_2O consumption in India as shaped by various Government policies on fertilizers introduced from 1961 to 2022 are shown in Fig. 1. While consumption of N increased almost continuously over time, P and K use was adversely affected by policies like decontrol of P and K fertilizers and NBS. Interrupted time series analysis of fertilizer consumption trends in India with interruptions as the major policy interventions (Table 1; Praveen et al. 2020) revealed that, on a long-term basis, while RPS positively affected the consumption of fertilizer N, the NBS influenced negatively. After controlling for other factors, the consumption of fertilizer N increased by 0.137 Mt/year when RPS was introduced. However, a reduction in the consumption of fertilizer N (0.798 Mt/year) was recorded when the NBS was implemented.

After implementing RPS in 1977, there was an immediate negative impact on the consumption of fertilizer P. But in the long term, the impact was positive because the removal of the fixed subsidy per tonne of fertilizer P in 1977 was restored in 1979 as a part of RPS (Table 1). Similarly, the deregulation of fertilizers P and K prices in August 1992 exhibited an immediate negative effect on their consumption (Fig. 1). In the long term, consumption of fertilizers P and K continued to increase because the deregulation of P and K was closely followed by the *concession* scheme implemented in October 1992. The concession on DAP led to an increase in consumption of fertilizer P by 1.318 Mt/year. When the NBS was implemented, consumption of fertilizer P was markedly reduced as a long-term effect to 1.253 Mt/year (Table 1). Fertilizer K consumption was not significantly influenced by RPS. But when prices of K were deregulated in 1992, only a short-term reduction in K consumption was observed. However, the NBS negatively impacted the consumption of fertilizer K both in the short and the long term (Table 1). Slightly reduced consumption of fertilizer N observed due to NBS was restored through corrections in subsidies on N, P, and K supplied through DAP and MOP introduced in May 2021.

The top 13 fertilizer-consuming states used 92.5% of the total fertilizer consumed in the country in 2022–2023 (Table S2). States like Punjab, Haryana, and western Uttar Pradesh have had high fertilizer usage due to their focus on cereal production. However, recent trends indicate significant increases in fertilizer consumption in Maharashtra, Madhya Pradesh, Karnataka, and Andhra Pradesh. Fertilizer use varied from less than 100 kg/ha in Madhya Pradesh and Rajasthan to over 200 kg/ha in Punjab, Andhra Pradesh, Haryana, Telangana, and Bihar. Fertilizer use intensity was determined by the percentage of irrigated area in the state (Fig. S1). Even in Haryana, Andhra Pradesh, and Telangana exhibiting fertilizer intensity of over 200 kg/ha, some districts exhibited fertilizer application rates less than 100 kg/ha.

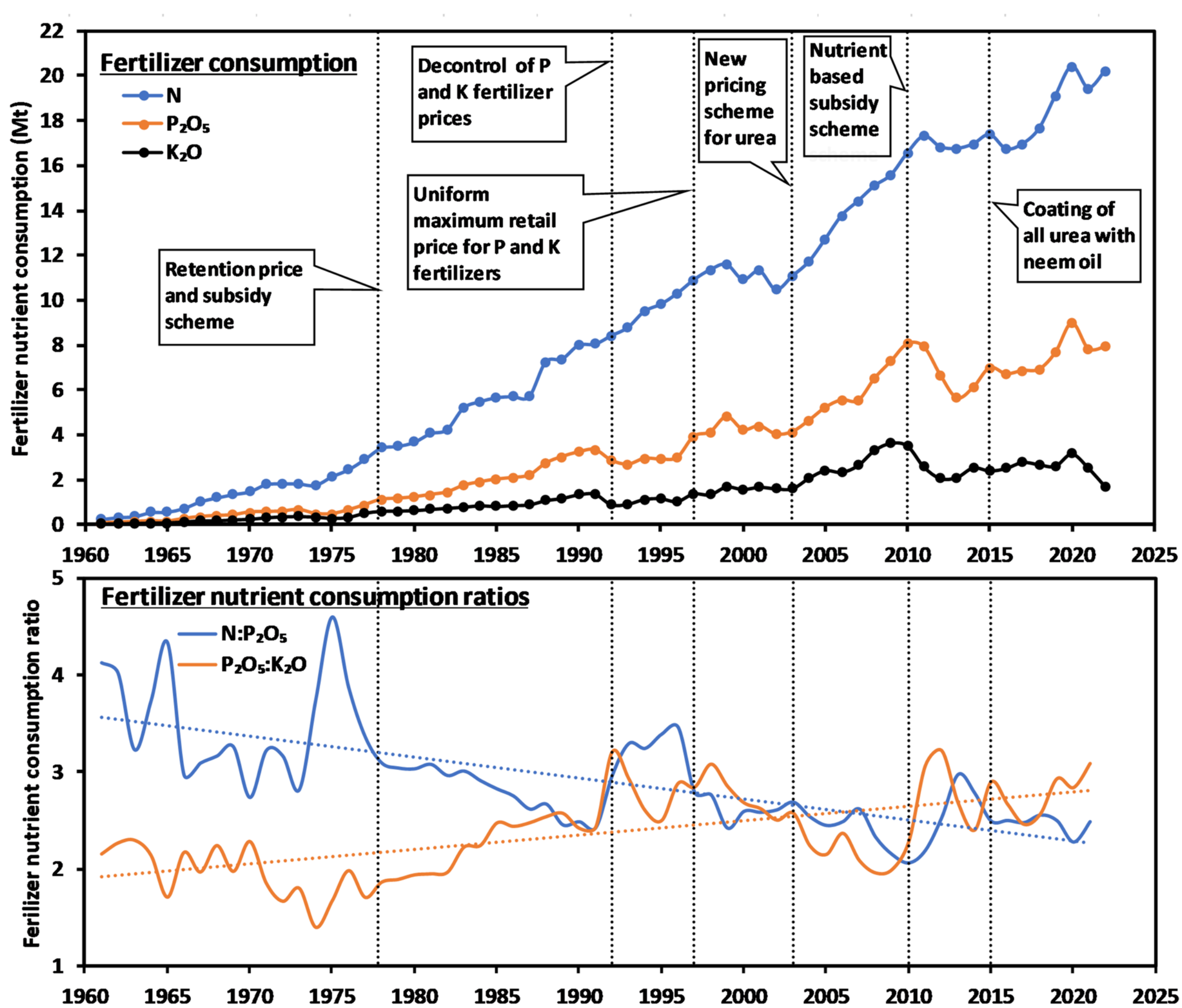

Fig. 1 Consumption of fertilizers nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), and $N:P_2O_5$ and $P_2O_5:K_2O$ ratios in India from 1961 to 2022 as shaped by various fertilizer policies implemented by the Government of India. The compound annual growth rate (CAGR) for N, P_2O_5, and K_2O was 7.5%, 8.3%, and 7.0%. Data source: Fertiliser Association of India (2023)

Table 1 Interrupted time series analysis of fertilizer consumption trends in India as affected by major government policies and important controlling factors

	Fertilizer nitrogen		Fertilizer phosphorus		Fertilizer potassium		Total fertilizer	
	Coefficient	S.E.[†]	Coefficient	S.E	Coefficient	S.E	Coefficient	S.E.[†]
RPS[‡] immediate effect	– 188.17	243.93	– 292.26**	122.58	– 49.62	84.54	– 82.56	502.73
RPS long-term effect	137.56**	64.74	86.71**	35.12	25.49	21.64	372.16**	114.72
PK decontrol§ immediate effect	174.66	235.64	– 965.38***	239.71	– 402.40***	112.44	– 890.83*	461.03
PK decontrol long-term effect	– 72.05	55.54	47.03	70.34	34.15	25.98	– 61.57	131.61
Concession¶ immediate effect			696.99	1432.99				
Concession long-term effect			1318.60**	517.52				
NBS⸸ immediate effect	565.31	452.87	98.03	504.57	– 447.44**	170.52	1287.14	1034.41
NBS long-term effect	– 798.37***	178.83	– 1253.85***	239.83	– 334.29***	64.46	– 1790.42***	429.69

[†]Standard error

[‡]Retention Price Scheme introduced in November 1977

[§]Decontrol of fertilizer P and K prices in August 1992

[¶]Concession on the price of some P and K fertilizers in October 1992

⸸ Nutrient-Based Subsidy policy introduced in April 2010

[*], **, and *** represent significant at 0.05, 0.01, and 0.001% probability levels, respectively

Adapted from Praveen et al. (2020)

Fertilizer management

There was a small change in N:P ratio and almost no change in P:K ratio before and after implementing RPS in 1977 (Fig. 1) because of significant long-term effect on only fertilizer N consumption. But due to deregulation of prices of P and K fertilizers in 1992, their consumption decreased immediately leading to increase in the N:P ratio from 2.42 in 1991 to 3.29 in 1993. The deregulation on P and K fertilizers and *concession* scheme also led to an increase in the P:K ratio from 2.44 in 1991 to 2.94 in 1993. While the NBS did not affect N:P ratio, the immediate negative impact on the consumption of fertilizer K (Table 1) resulted in an increased P:K ratio of 3.07 in 2011 from 2.00 in 2009. Long-term negative but differential impact on the consumption of N, P, and K—mostly negative in the case of P—is visible in the N:P ratio of 2.97 and P:K ratio of 2.68 in 2013. The N:P and P:K ratios of 2.48 and 3.09 observed in 2021 reflect the changes in prices due to NBS and consequential adjustments in P and K fertilizers consumption post- 2020. These discrepancies were largely corrected by revision in NBS rates after May 2021.

The effect of the NBS in 2010 varied widely among states. For example, N:P ratio as high as 8.73 in Bihar in 2004 was reduced to 3.41 in 2012 and 3.28 in 2021 after the NBS. On the other hand, P:K ratio increased from 1.69 to about 3.5. In states like Punjab, where consumption of N is traditionally very high, the NBS policy resulted in an increase in N:P ratio of 3.21 in 2012 to 4.42 in 2021. In contrast, due to sharp rise in the price of fertilizer K, P:K ratios as high as 19 were recorded for Punjab in 2012. In the southern India, the NBS policy led to increase in P:K ratio after 2012.

Impact of fertilizer use in food grain production

During 1961 to 2021, the area devoted to food grain farming decreased from 75.1 to 63.1% of the gross cropped area, but during the same time, irrigated area under food grains increased from 19.1 to 59.0% (Fig. 2). As increase in fertilizer use intensity in different states is directly related to extent of area under irrigation (Fig. S1), increases in food grain production as well as fertilizer use are linked to the expansion of irrigated areas in the country. The share of fertilizers applied to rainfed crops is only about 40% of irrigated crops (Katyal et al., 2023). Along with uncertain and insufficient supply of water for plant growth, low fertilizer usage causes low yields of rainfed crops, and consequently weak socio-economic status of rural communities in rainfed regions.

Food grain production in different states of the country has been influenced by both the total and relative amounts of N and P application (Fig. S2). In states like Punjab, Haryana, and Andhra Pradesh where fertilizers N and P_2O_5 have been applied at high rates (> 100 kg N/ha and ≥ 50 kg P_2O_5/ha) for more than two decades, food grain production has been the highest. In Uttar Pradesh, Bihar, and Tamil Nadu, moderate fertilizer N application rates (about 100 kg N/ha) and food grain production levels observed in 2004 are steadily increasing. Moderate

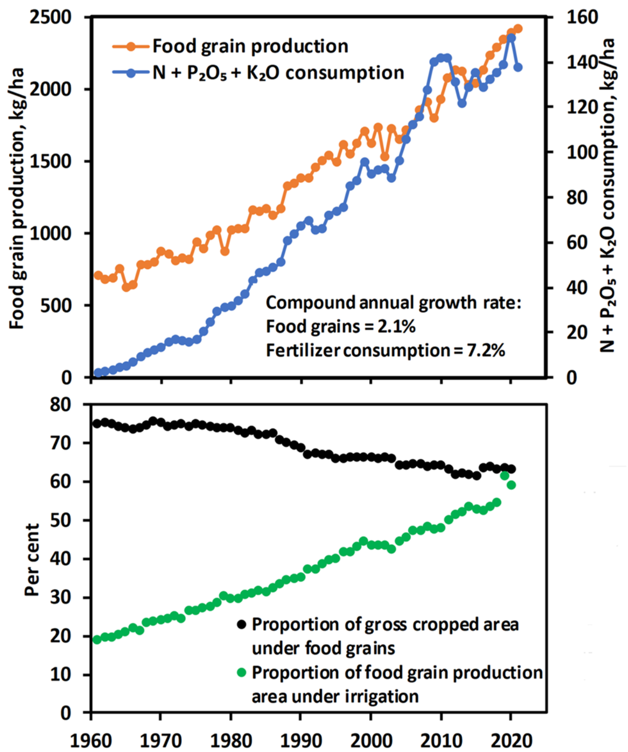

Fig. 2 Per hectare consumption of fertilizer [nitrogen (N) + phosphorus (P_2O_5) + potassium (K_2O)] and production of food grains, the proportion of gross cropped area under food grains, and the proportion of food grain production area under irrigation in India from 1961 to 2021. Data sources: Fertiliser Association of India (2023) and Government of India (2023)

food grain production has been observed in West Bengal where fertilizer N rates have been hovering around 75 kg/ha between 2004 and 2021 although adequate amount of fertilizer P has always been applied. Madhya Pradesh, Maharashtra, Karnataka, Gujarat, and Rajasthan are among the seven top fertilizer-consuming states where fertilizer N application from 2004 to 2021 is less than 100 kg N/ha and except in Karnataka, the fertilizer P application rate is also less than 50 kg P_2O_5/ha. The effect of low fertilizer application rates is clearly reflected in food production levels.

Effect of fertilizer use policies on farmers' income and livelihood

The primary objective of fertilizer policies has been to ensure food security. Therefore, impact of fertilizer policies on the socio-economic status of rural communities can be best understood from the role of fertilizers in food grain production. From 1961 to 2021, per ha food grain production increased by 3.4 times when consumption of fertilizer nutrients increased by over 63 times (Figs. 1 and 2). Although improved crop varieties and the expansion of irrigated areas also contributed to increases in food grain production, there is a strong linear relationship between the per hectare use of fertilizers and food grain production in India (Fig. S3). Increased fertilizer consumption played a major role in achieving food security in India up to 1990s.

Rice is a staple food for over two-thirds of the population in India. With the population of India increasing from 364.92 million in 1951 to 1417.17 million in 2022 (Fig. 3), the demand for rice has been continuously increasing. But the per capita availability of rice has remained stable, thanks to increased rice production through increased fertilizer application (Fig. 3). Wheat constitutes about one-third of the total food grain production. As it is grown in regions with assured irrigation, increased fertilizer use has had a tremendous positive impact on its production. Thus, per capita availability of wheat in India has increased linearly from 24 kg in 1951 to 68.8 kg in 2022 (Fig. 3). This increase, achieved alongside a substantial population growth, underscores the positive impact of increased fertilizer consumption on the socio-economic status of both rural and urban populations. Greater availability of staple foods also contributes to improved health and enhanced labor productivity across various sectors.

The impact of fertilizer policies on the economics of fertilizer use depends upon fertilizer prices as well as the market value of agricultural outputs. Figure 4 plots the cost of urea and diammonium phosphate (DAP)—two commonly used fertilizers in India—relative to the market prices of rice and wheat over time. Since the introduction of fertilizer subsidies, the price of urea increased gradually from USD 0.052/kg N in 1974 to USD 0.086/kg N in 1991 to USD 0.12/kg N in 1999 and USD 0.13 to 0.14/kg N from 2001 onwards. Because the price of rice and wheat has been increasing since the 1970s, the cost of 1 kg N as

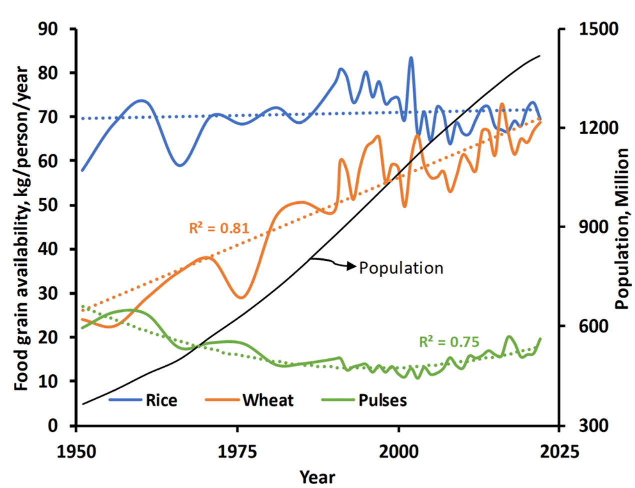

Fig. 3 Per capita per annum net availability of food grains in India from 1950 to 2021. Data source: Fertiliser Association of India (2023)

urea in terms of kg of rice or wheat has been decreasing since introducing RPS (Fig. 4). In contrast to urea, the affordability of P as DAP since the 1970s changed dramatically in response to implementing different government policies. For short periods after implementing RPS and the decontrol of P and K fertilizers, the price of P in DAP in terms of the cost of rice or wheat was the highest. Before introducing the NBS policy, the affordability of N in urea and P in DAP in terms of prevailing prices of rice and wheat was the closest. However, after implementing NBS, there was a large difference in the economic affordability of farmers to buy P as DAP and N as urea (Fig. 4). The reduced affordability of farmers to purchase fertilizer P is reflected in reduced P use from 40.6 kg P_2O_5/ha in 2010 to 28.0 kg P_2O_5/ha in 2013.

The socio-economic impacts of fertilizer policies differ with the holding size and the extent of irrigated area. While 70% of the total fertilizer consumed in the country was used in irrigated crops, over 53% of this was used by farmers with land holdings less than 2 ha and only 24% was applied to farms larger than 4 ha (Table S3). Marginal and smallholder farmers owning irrigated land size < 1 and 1–2 ha applied fertilizer nutrients at the rates of 251 and 191 kg/ha, respectively. Fertilizer application on irrigated farms > 10 ha was only 137 kg/ha (Table S3). Thus, the socio-economic effects of fertilizer policies have been experienced more by relatively small landholders and those cultivating irrigated cropland.

The relationship between per hectare fertilizer use and food grain production (Fig. S3) reveals that an increase of 0.5 t/ha in food grain production was achieved by increasing fertilizer use by 46 kg/ha. The relationship between rural population below the poverty line in major fertilizer-consuming states in India and fertilizer use per hectare (Fig. S4) revealed that with 46 kg/ha increase in fertilizer use there is a 6% reduction in the rural population below the poverty line. This is in line with McArthur and McCord (2017) who reported that socio-economic returns from fertilizer use exceed the immediate private returns, furthering the case for policy efforts. Thirtle et al. (2003) estimated that each 1% increase in crop productivity leads to a reduction in the number of poor people by 0.48% in Asia. That fertilizer use in India has positively impacted the socio-economic status of rural and urban populations is also seen from the strong relationship between per annum fertilizer consumption and gross value added to gross domestic product by crop production as economic activity associated with fertilizers (Fig. S5). Ravallion and Datt (1996) estimated that a 0.4% reduction in poverty in the short run and 1.9% reduction in the long run, can be achieved in India by a 1% increase in per hectare agricultural value addition.

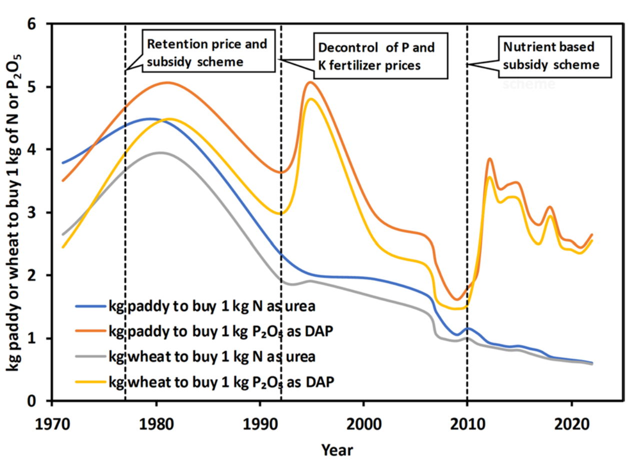

Fig. 4 Trends in the economics of application of fertilizer N as urea and fertilizer P_2O_5 as diammonium phosphate (DAP) on paddy and wheat as influenced by fertilizer policies in India from 1971 to 2021. Data sources: Government of India (2023), Fertiliser Association of India (2023)

Impact of fertilizer policies on environmental degradation and greenhouse gas emission

The imbalanced use of fertilizers N, P, and K is widespread across India. It is largely due to implementation of fertilizer policies like RPS, deregulation of P and K, and the NBS, which always kept urea highly subsidized as compared to P and K fertilizers. The high fertilizer N rates of more than 200 kg/ha or 100 to 200 kg/ha observed in different districts of several states (Table S2) can be categorized into two distinct groups of imbalanced use of fertilizer nutrients:

1. High fertilizer doses comprising more than optimum fertilizer N rates, and less than or optimum P and K rates.
2. Moderate fertilizer doses but with N dose close to optimum or slightly more, and P and K doses less than optimum.

Imbalanced use of fertilizer nutrients under both these categories leads to low fertilizer N use efficiency resulting in environmental hazards and economic loss (Ladha et al. 2020; Sapkota et al., 2023). The imbalanced fertilization can pose a potential threat to the environment as surplus N may escape to the atmosphere as a potent greenhouse gas N_2O or may pollute surface and groundwater bodies via runoff and leaching as nitrate.

Data available at the *Soil Nutrient Budget* (https://www.fao.org/faostat/en/#data/ESB, accessed 19 February 2024) domain of the FAOSTAT allows estimation of surplus N per annum in India as the difference between total N input and crop removal. As surplus N acts as an important driver of losses of N via emission of N_2O gas from cultivated soil (McLellan et al. 2018), it was plotted in Fig. 5 vis-à-vis annual N_2O emission (following IPCC Tier 1) as available at the *Emissions Totals* domain of the FAOSTAT (https://www.

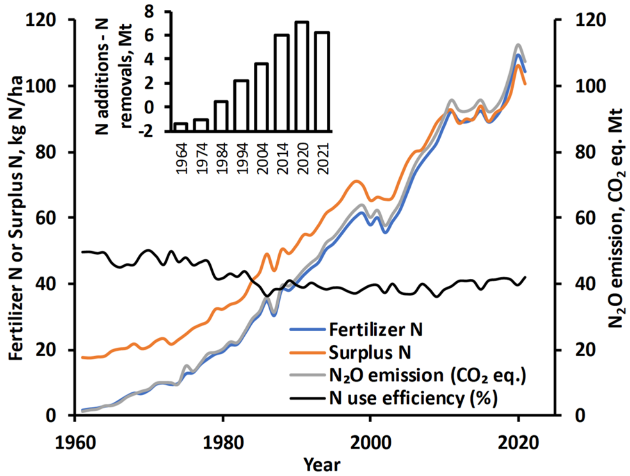

Fig. 5 Fertilizer nitrogen (N) and surplus N per ha and emission of nitrous oxide [N_2O as carbon dioxide (CO_2) equivalent] in India from 1961 to 2021 based on data on N flows being disseminated through the *Soil Nutrient Budget* (https://www.fao.org/faostat/en/#data/ESB, accessed 19 February 2024) and *Emissions Totals* (https://www.fao.org/faostat/en/#data/GT, accessed 19 February 2024) domains of the FAOSTAT. The inset Figure shows data on N additions minus N removals in different years. Data source: Katyal (2023)

fao.org/faostat/en/#data/GT, accessed 19 February 2024). The fertilizer N application rates and N use efficiency (crop removal as percentage of total N application) are also plotted in Fig. 5. Loss of N via N_2O emissions from cultivated soils in India is driven by surplus N and even more closely by the fertilizer N rate.

In the state of Punjab in north-western India, fertilizer consumption has increased from 37.5 kg/ha in 1970–1971 to 241.1 kg/ha in 2022–2023; corresponding values for India are 13.2 and 138.1 kg/ha, respectively. Nitrate–N content in groundwater in Punjab is increasing since 1975 (Bijay-Singh et al., 1995; Bhardwaj et al. 2012). Chhabra et al. (2010) estimated that 29% of the applied fertilizer N in Punjab is lost via leaching from the soil to groundwater bodies. The role of imbalanced application of fertilizers N, P, and K in accelerating nitrate leaching beyond the rooting zone of crops in Punjab has also been demonstrated by Bijay-Singh and Sekhon (1976). Although government policy introduced in 2015 to coat urea with neem oil possessing nitrification inhibition properties aimed at increasing N use efficiency in crop production, Bijay-Singh (2016) did not find it effective enough to significantly increase crop yields or reduce urea application rate. Therefore, no conspicuous effect of coating urea with neem oil on nitrate leaching or N_2O emission has been reported from India.

Considering all N inputs and N removal through crop production, N surplus in soils in India has increased from 17.5 kg N/ha in 1961 to 100.8 kg N/ha in 2021 (Fig. 5). When N input from only mineral fertilizers was considered, N became surplus only after 1984 (Katyal 2023). Excessive residual inorganic N in the soil resulting from application of high fertilizer N doses stimulates the mineralization of soil organic matter resulting in its net loss (Bijay-Singh and Sapkota, 2023b). Therefore, in regions (such as in Punjab, Haryana, Andhra Pradesh, and western Uttar Pradesh) where fertilizer N is being applied in higher than the recommended doses on a long-term basis, soil health may deteriorate (Bijay-Singh 2024) and in the quest to maintain high crop yield levels, farmers may set in motion a spiral of decline in soil functions and crop productivity. This phenomenon may then necessitate the application of even more fertilizer N to achieve same yield level and affect the socio-economic status of the rural communities.

Discussion and recommendations

Socio-economic impacts

Achieving food security for a growing population has always remained a major policy goal for the governments in post-independence India. One key strategy has been to promote fertilizer use by regulating their availability and maintaining affordability to boost crop production. Since 1961, fertilizer use per hectare in India has increased at a compound annual growth rate of 7.2%, though this growth has varied widely across states and districts due to factors such as the extent of irrigated area, cropping systems, soil and climatic conditions, and government policies. For instance, during 2022–2023, fertilizer nutrients were applied at rates exceeding 200 kg/ha in 28% of districts, between 100 and 200 kg/ha in 37% of districts, and less than 100 kg/ha in 35% of districts (Table S2). While heavy subsidization of fertilizer prices has driven increased consumption, varying policies for N and non-N fertilizers have impacted the balanced use of nutrients. India is now the second-largest fertilizer-consuming country, the third-largest producer, and the largest importer of mineral fertilizers in the world. Since 1977, different fertilizer policies to provide subsidy on fertilizers have proved rewarding. For example, in the wake of the war in Ukraine, the fixed statutorily maximum retail price of urea insulated farmers from price spikes in the international market. Without appropriate fertilizer policies, rising energy and gas prices could have added distress to the already overburdened farming community. Before 2015, China also implemented substantial fertilizer subsidies to enhance crop production (Jiao et al. 2018), but these policies led to widespread over-application of fertilizers (Cui et al. 2014).

Without applying fertilizers, India would have needed to cultivate an additional 63 million hectares to match the production achieved by using fertilizers (Katyal and Choudhari, 2021). Because there is little possibility of expanding cultivated areas, this calculation provides an indirect idea of the positive socio-economic effects of fertilizer use. In 1961, per hectare food grain production and fertilizer consumption in India were 706 and 2.17 kg, respectively. In 2021, while fertilizer use increased 63 times to 137.9 kg/ha, food production increased by over 3.4 times to 2419 kg/ha (Fig. 2). Along with the tremendous increase in fertilizer consumption achieved by subsidization of fertilizer prices, high-yielding crop varieties and increase in irrigated area led to a spectacular increase in food grain production. In 2018/2019, two-thirds of the fertilizer consumed in India was used to produce food grain crops of which 9.517 Mt or 35% was applied to rice, and 4.768 Mt or 17.55% was applied to wheat (Ludemann et al. 2022).

Increased agricultural productivity improves the socio-economic status of farmers in the form of reliable income. It also creates additional employment opportunities including for farm labor, transportation, and marketing activities. Advancement in agriculture can generally lead to labor shifting to productivity sectors which offer higher real incomes. In recent years, several researchers have put forward conceptual arguments in favor of long-term growth and poverty reduction benefits from increased agricultural productivity (Gollin et al. 2007; de Janvry and Sadoulet 2010; Christiaensen et al. 2011). McArthur and McCord (2017) developed a macro-level physical production function for yield increases and found that along with high-yielding varieties and irrigation, fertilizer constitutes a key input for food grain production and controlling factors such as human capital and land-labor ratio. They observed that increasing food grain yields by 0.5 t/ha by applying fertilizers may lead to a 14 to 19% increase in per capita income and 4.6 to 5.6% reduction in the share of labor in agriculture after 5 years. Suggestive evidence was also obtained for 9 to 12% higher non-agricultural labor productivity after a decade.

Marginal and small farms consume over 50% of all the fertilizer consumed in India (Table S3). Although there is a high level of inequality in terms of distribution of expense on fertilizers, farmers with the fewest resources spend more homogeneously on fertilizers as compared to wealthiest farmers (Paul et al. 2023). Small farmers generally apply high fertilizer doses but often generate low returns due to climatic and market conditions (Murari 2022). Future fertilizer policies to reduce subsidies may have a detrimental economic impact on small farmers because they spend a substantial amount of money on fertilizers (Paul et al. 2023; Baulanger et al., 2022).

The proportion in which fertilizers N, P, and K are applied for crop production is an important aspect of fertilizer management. While subsidized prices have increased overall fertilizer consumption, varying policies for N and non-N fertilizers have influenced the balanced use of these nutrients. A key concern in India is the decreasing response of crops to fertilizer application, particularly in regions of N overuse, an issue driven by heavy subsidy on urea. Farmers often apply fertilizers based on factors like price and availability, rather than following recommended guidelines. It results in the over-application of N and insufficient application of P and K, leading to nutrient imbalances and reduced crop yields. In states such as Punjab, Haryana, western Uttar Pradesh, and Telangana, many farmers apply fertilizer N to cereal crops 50–70% more than the recommended rates (Bijay-Singh 2017) but apply less than optimum doses of P and K. In the long term, these fertilizer management practices lead to reduced nutrient use efficiency and low economic returns. Imbalanced nutrient application, particularly of N, P, and K, has been linked to poor crop production (Lu and Tian 2017; Vitousek et al. 2009). In 144 experiments in rice-rice, 156 in rice–wheat, 48 in rice-green gram, and 60 in maize-wheat systems conducted during 2013–2014 at on-farm locations in 17 states in India, significantly higher yields in all cropping systems were obtained by applying balanced dose of N, P, and K rather than application of only N, N and P, or N and K (Singh et al. 2017). Similar results from many on-farm trials in different states of India have been reported by Panwar et al. (2019).

The Government of India should revise the policies to ensure consistent and adequate availability as well as affordability of all major nutrients that are necessary for balanced fertilization. In addition, policies should also integrate economic incentives that reward balanced fertilization practices. For instance, providing financial rewards or tax incentives for farmers who adopt soil health–based fertilization practices can further encourage balanced nutrient use. For example, introduction of NBS policy in India showed impactful results only by substantially increasing the subsidy on P and K fertilizers. The policy of coating all urea with neem oil and using soil health cards introduced in 2015 were also steps in this direction, but to achieve visible impacts, these policies need to be suitably modified (Reddy 2019). The Soil Health Card Scheme was launched in 2015 to use nutrients per fertilizer recommendations and soil tests. Although more than 200 million soil health cards have been given to farmers (https://soilhealth.dac.gov.in/legacy, accessed 04 March 2024), arbitrary criteria for collection of soil samples, inadequate capacity to handle and analyze large numbers of samples, and inability of most farmers to interpret the fertilizer recommendations limit the efficacy of these cards (Kishore et al. 2021). Therefore, a significant effect of soil health cards on the socio-economic status of farmers is yet to be observed (Fishman et al. 2019).

Environmental impacts

Fertilizer policies implemented in India since 1977 initially aimed to achieve food security by providing subsidies on different fertilizers and then to reduce government's burden on subsidy. However, significant disparities in the subsidization of different fertilizer nutrients have not only prevented the achievement of balanced fertilization but also led to the overapplication of N fertilizers, resulting in numerous environmental externalities. This outcome is predictable, as trade-offs in agricultural systems often prioritize productivity over environmental sustainability (Breure et al. 2024). Because environmental and climate change issues are mostly linked with N fertilizers, India is yet to move from the precarious zone to the safe zone in terms of sustainable N management index (Zhang and Davidson 2016; Sachs et al. 2022). According to Paul et al. (2023), India's failure to create a sustainable link between farming and food security is exacerbated by these environmental and climate issues, with the excessive use of N fertilizers contributing to declining soil health (Bijay-Singh 2024), increasing environmental pollution and contributing to climate change.

Increased fertilizer consumption over time has linearly increased N_2O emissions (Fig. 5). In response to higher than recommended fertilizer N doses, increase in N_2O emission can be even higher because it has been reported to follow exponential, hyperbolic, or asymptotic relationships (Kim et al. 2013; Shcherbak et al. 2014) depending on the crop, soil type, and climate (Albanito et al. 2017). About 77% of N_2O emissions in India originate from fertilizer N used in crop production (Pathak et al. 2014). From 1981–1982 to 1991–1992, when fertilizers were subsidized under RPS, the average N:P ratio was 2.7. After deregulation of P and K fertilizers in August 1992, consumption of P and K fertilizers was reduced and N:P consumption ratio jumped to as high as 3.5 by 1996–1997 (Fig. 1) resulting into increased N_2O emission between 1992–1993 and 1996–1997 by 0.122 Mt N_2O/year (Fig. 5) (Some et al. 2019). Before deregulation of P and K fertilizers, N_2O emission increased only at 0.077 Mt N_2O/year. In 1997, the policy of setting a maximum retail price for NPK fertilizers was implemented. As a result, from 1997–1998 to 1999–2000, N_2O emissions increased at a slower rate of 6.4%, compared to the 18% between 1992–1993 and 1996–1997 (Some et al. 2019). In 2010, introduction of NBS led to an immediate price increase and reduced consumption of P and K fertilizers, which resulted in increased annual N_2O emissions from 112.74 Mt CO_2 eq. in 2008–2009 to 120.85 Mt CO_2 eq. in 2011–2012 (Some et al. 2019). To deal with increasing environmental impacts of overuse of N fertilizers, Chinese government stopped the fertilizer manufacturing subsidy in 2015 (Wu et al. 2018) and introduced the *Zero Growth Strategy* to curb excessive use of fertilizers and enhance N use efficiency (Wang et al. 2023). As estimated by Wu et al. (2024), this change in policy reduced annual greenhouse gas emissions by 3.88 Mt with minimal impact on food production.

Policy implications

This study underscores critical policy implications aimed at balancing food security and environmental sustainability in India. The food-fertilizer-environment challenge is to boost food production while reducing environmental impacts by curbing excess fertilizer use and increasing it where necessary. Therefore, fertilizer policies in India over the coming years must be designed to ensure that applied nutrients are utilized efficiently, enhancing productivity with minimal losses. A primary recommendation is recalibrating the subsidy structure to address the disproportionate reliance on subsidized urea, which has led to overuse of N fertilizers and underuse of P and K. To address imbalanced fertilizer use, the study advocates for gradual liberalization of urea pricing, paired with enhanced subsidies for P and K fertilizers to ensure affordability for small and marginal farmers. This balanced approach could encourage the adoption of sustainable fertilization practices without compromising agricultural productivity. By increasing subsidies for P and K, while maintaining support for N at balanced levels, policymakers can encourage farmers to apply the appropriate ratios of nutrients, leading to improved yields and soil fertility. Policy reforms are also required to regulate the production and import of fertilizers to ensure consistent and adequate supply of all major nutrients.

Additionally, the study emphasizes the need for economic incentives and education programs to promote soil nutrient–based fertilizer management. Policies like expanding and refining the Soil Health Card Scheme and introducing financial rewards for balanced fertilization can foster long-term environmental and economic benefits. Investments in low-carbon technologies and improved fertilizer management strategies are also recommended to align India's agricultural practices with global climate goals. By addressing these interconnected challenges, the proposed policy reforms aim to sustain food security, improve farmer livelihoods, and reduce the environmental footprint of fertilizer use, contributing to a more resilient agricultural system.

It is important to note that practical implementation of policy recommendations, such as recalibrating subsidy structure for balanced fertilization, could face resistance from stakeholders and require further exploration of political and economic feasibility. Lastly, the analysis focuses primarily on chemical fertilizers, with limited attention to alternative or organic inputs, which could offer complementary pathways to achieving sustainable agriculture. These limitations highlight areas for further research to build upon the findings of this work.

Conclusions

This paper systematically examines the impact of India's fertilizer policies on fertilizer consumption patterns, nutrient management, rural socio-economic conditions, and environmental outcomes, emphasizing the need for a balance between food security and sustainability. Fertilizer policies in India have been crucial in ensuring food security by promoting the use of fertilizers through a system of controls and subsidies that regulate prices, production, import, availability, and distribution. Despite a threefold increase in India's population from 1961 to 2022, the rise in food grain production—driven by increased fertilizer use and expanded irrigation—has supported socio-economic progress by maintaining stable per capita availability of food grains. However, unequal subsidization of different fertilizer nutrients has led to imbalanced fertilizer use across many regions of India, characterized by excessive use of N fertilizer and insufficient use of P and K fertilizers. This imbalanced fertilizer application has resulted in reduced fertilizer use efficiency, causing economic losses and exacerbating environmental and climate change issues such as increased N_2O emissions and groundwater pollution from nitrate leaching.

To mitigate the environmental and climate impacts of fertilizer use, India's future fertilizer policies should focus on improving nutrient efficiency. It highlights the importance of recalibrating subsidies and promoting soil nutrient–based recommendations to encourage balanced fertilization. Gradual liberalization of urea pricing, coupled with measures to make phosphatic and potassium fertilizers affordable for small and marginal farmers, is proposed as a crucial strategy to address the interconnected challenges of food production, fertilizer use, and climate change.

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Data availability This study is based on secondary data obtained from publicly accessible records and policy documents from multiple sources. No primary data were collected. The datasets supporting the findings, including those used to construct the associated figures and tables, are available from the corresponding author upon reasonable request.

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