



RESEARCH ARTICLE

Structural dominance of primary fertilisers and micronutrient imbalances in Indian agriculture: An assessment

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Abstract

This study examines the structural dominance of nitrogen (N) and phosphorus (P) fertilisers in India's fertiliser economy which results from spatially uneven use patterns and leads to persistent micronutrient imbalances. The secondary data procured from national fertiliser statistics and soil test summaries confirms the long-term trends in production, installed capacity, utilisation, consumption and imports of N, P and potassium (K). Time series evidence shows a pronounced, policy driven bias toward nitrogenous fertilisers, with high-capacity utilisation and subsidised availability reinforcing an heavy, nitrogen fertiliser consumption relative to agronomic recommendations. Spatial autocorrelation (Global Moran's I) and Getis Ord Gi* hotspot analysis of district level primary fertiliser use for 2023 reveal significant clusters of intensive N-P application in irrigated, procurement linked grain belts particularly Andhra Pradesh, Gujarat, Bihar and the traditional northwestern region contrasting with extensive cold spots in rainfed and less commercialised areas. Overlaying state level maps of soil micronutrient deficiencies (Zn, B, Fe, Cu, Mn) with micronutrient fertiliser consumption uncovers systematic mismatches, the most deficient states are rarely the largest users of corresponding micronutrient inputs, indicating a decoupling between depletion and replenishment. These patterns suggest a dual imbalance: excessive and spatially concentrated N-P use and a crop and region-specific misalignment between micronutrient needs and markets, shaped by subsidy design, market infrastructure and cropping commercialisation. The findings underline the need to reorient fertiliser policy and investment from bulk primary nutrient supply toward spatially differentiated, system level strategies for balanced macro and micronutrient management.

Keywords: India; micronutrient deficiency; nitrogen and phosphorus; nutrient management; spatial autocorrelation; structural fertiliser dominance

Introduction

Synthetic fertilisers have played a crucial role in India's agricultural transformation by enabling high cropping intensity and sustained food production despite limited arable land and rapid population growth. Fertiliser consumption in India has surged from less than 1 million tonnes of total nutrients in the mid-1960s to nearly 17 million tonnes today, with nitrogen (N) and phosphorus (P) dominating use, especially urea accounting for 82 % of nitrogen consumption and diammonium phosphate for 63 % of phosphorus consumption (1). The production of nitrogen and phosphate fertilisers increased from 1.8 million tonnes in 1975/76 to 14.2 million tonnes by 2003/04, while potash imports rose from 0.4 to 2.6 million tonnes over the same period (1). Persistent policy support, domestic manufacturing expansion and irrigation-driven intensification have locked India into a regime favouring N-P fertilisers, with nitrogen systematically prioritised over phosphorus, contributing to nutrient imbalances and environmental concerns (2). Over the period from 1970 to 2018, total nutrient inputs were approximately 666 million tonnes of nitrogen, 189 million tonnes of phosphorus and 245 million tonnes of potassium, with chemical fertilisers contributing over two-thirds of nitrogen and over 90 % of phosphorus inputs; however, potassium

shows a negative balance indicating depletion (3). This heavy reliance on bulk use of primary nutrients has raised issues such as declining nutrient use efficiency, soil degradation affecting more than 57 % of Indian lands and environmental sustainability challenges that call for diversified nutrient management strategies (3).

The continued predominance of primary fertilisers has coincided with rising import dependence and strong spatial concentration of fertiliser use in irrigated, procurement linked grain belts (4). Extended reliance on high amounts of N and P fertilisers, typically applied with limited nutrient diversity, has accelerated depletion of non-replenished soil nutrients in these intensively farmed systems (5). Large scale soil tests now document widespread but spatially heterogeneous deficiencies of zinc, boron, iron, copper and manganese, shaped by historical fertiliser use, cropping intensity and irrigation (6). Strikingly, districts with the highest fertiliser application intensity often continue to exhibit severe micronutrient deficiencies, underscoring a disconnect between the scale of fertiliser use and the balance of nutrient supply (7).

Existing research on fertiliser production, investment and consumption largely centres on major nutrients, while micronutrient studies typically focus on soil or crop response in specific locations.

Few assessments explicitly link the structural dominance of primary fertilisers to spatial patterns of micronutrient consumption and deficiency across regions and crops. Addressing this gap, the present study analyses India's fertiliser system covering production structure, capacity utilisation, investment, import dependence and the spatial intensity of primary fertiliser use and examines how these factors shape state level micronutrient consumption and deficiency. Using nationally compiled statistics and district level spatial analysis, it develops a system level perspective on how primary fertiliser dominance, coupled with uneven micronutrient markets and cropping systems, perpetuates micronutrient imbalances in Indian agriculture.

Materials and Methods

Data sources and time coverage

This study is based entirely on secondary data compiled from nationally reported statistical sources. Annual data on fertiliser production, installed capacity, imports and nutrient-wise consumption (N, P and potassium (K)) were obtained from Fertilizer Statistics published by the Fertilizer Association of India (8). Long-term time series were constructed for the period 1951–2023 for production and consumption, 1982–2023 for capacity and capacity utilisation and 1980–2023 for imports. District-level fertiliser consumption data for 2023 were assembled from FAI records to conduct spatial analysis of fertiliser use intensity. State-level micronutrient deficiency data (zinc (Zn), copper (Cu), iron (Fe), manganese (Mn) and boron (B)) and corresponding micronutrient fertiliser consumption were compiled from Specialty Fertiliser and Micronutrient Statistics (8). Micronutrient analysis covers the most recent consolidated reporting period (2019–2024). All variables were standardised to nutrient terms where applicable.

Assessment of structural trends in primary fertilisers

To evaluate structural dominance within India's fertiliser system, nutrient-wise time series (N, P, K) were extracted and organised chronologically. Line graphs were constructed to visualise long-term trajectories and identify divergence across nutrients. Structural imbalance was assessed by comparing observed N:P:K ratios with agronomic recommendations (4:2:1). Deviations from recommended proportions were used as an indicator of nutrient distortion over time.

Further, Spatial relationships among districts were specified using a first-order queen contiguity spatial weights matrix, with row-standardisation applied to ensure comparability across units. The analysis was cross-validated using an alternative k-nearest neighbour weights matrix with $k = 8$ to assess the robustness of the spatial structure. Both specifications produced consistent spatial patterns, indicating that the results were not sensitive to the choice of spatial weights. Global spatial autocorrelation in fertiliser use intensity was assessed using Global Moran's I equation given below (9):

$$I = \frac{n}{W} \cdot \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad (\text{Eqn. 1})$$

Where, n denotes the number of spatial units, x_i and x_j represent observed fertiliser values at locations i and j , $\bar{x}$ respectively, is the mean of the variable across all districts, w_{ij} is the spatial weight capturing the relationship between locations i and j and W is the sum of all spatial weights. Values of Moran's I close to +1 indicate strong positive spatial clustering, values near zero suggest spatial randomness and values approaching -1 indicate spatial dispersion. Statistical significance was evaluated using Z-scores at the 5 % level. To identify localised clusters of high and low fertiliser use intensity, hotspot and cold spot analysis was conducted using the Getis-Ord G_i^* statistic (10), expressed as:

$$G_i^* = \frac{\sum_j w_{ij} x_j - \bar{x} \sum_j w_{ij}}{S \sqrt{\left[\frac{n \sum_j w_{ij}^2 - (\sum_j w_{ij})^2}{n-1} \right]}} \quad (\text{Eqn. 2})$$

Where, x_j is the observed value at location j , w_{ij} denotes the spatial weight between locations i and j , $\bar{x}$ is the mean of the variable and S is its standard deviation. Districts with significantly positive Z-scores ($p < 0.05$) were classified as hotspots, indicating concentrations of high fertiliser use intensity, while significantly negative Z-scores were identified as cold spots, representing areas with lower fertiliser use relative to the national mean.

Micronutrient deficiency-consumption alignment analysis

Finally, state-wise maps of soil micronutrient deficiencies were overlaid with corresponding state-level micronutrient fertiliser consumption to assess alignment between need and use. For each micronutrient, states were classified into deficiency and consumption classes and cross-tabulated to detect mismatches where high deficiency coincides with low use or vice versa. This integrated spatial procedure provides a system-level view of how primary fertiliser dominance translates into micronutrient imbalances across Indian agriculture.

Results and Discussion

Structural dominance in the fertiliser sector

The long-term production data reveal a clear structural asymmetry between nitrogen and phosphorus within India's fertiliser system (Fig. 1). While both nutrients expanded during the early development phase (1950s to mid-1960s), nitrogen production accelerated disproportionately after the Green Revolution. By 2024, nitrogen output is approximately 3 times that of phosphorus, indicating a persistent production bias rather than cyclical variation. Capacity and utilisation trends (Fig. 2a, b) further reinforce this divergence. Nitrogen plants have operated at consistently high utilisation rates often exceeding 90 % since the late 1990s reflecting stable demand supported by pricing and subsidy mechanisms. In contrast, phosphorus capacity utilisation has declined to nearly 70 % in recent years despite installed capacity remaining relatively constant. This widening utilisation gap signals structural prioritisation of nitrogen within industrial organisation and policy design. Together, these patterns confirm that structural dominance is embedded not only in output volumes but also in capacity utilisation and industrial performance.

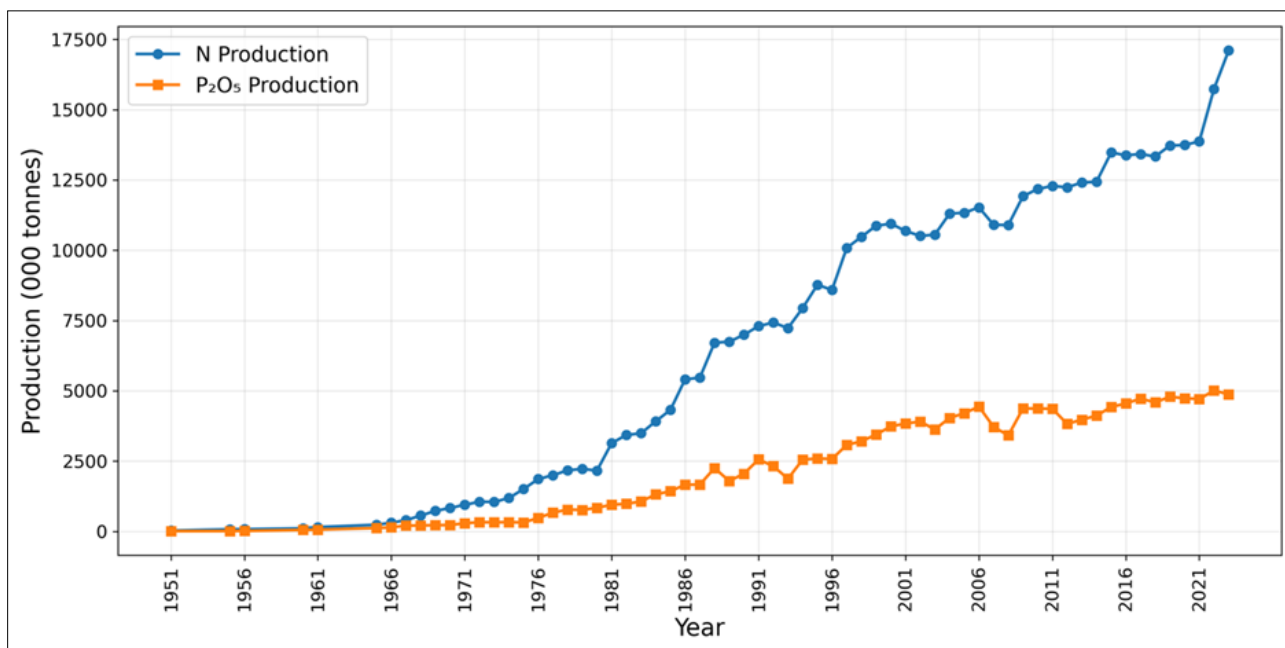


Fig. 1. All-India fertiliser production trends: Nitrogen and phosphorus, 1951–2024 (000 tonnes).

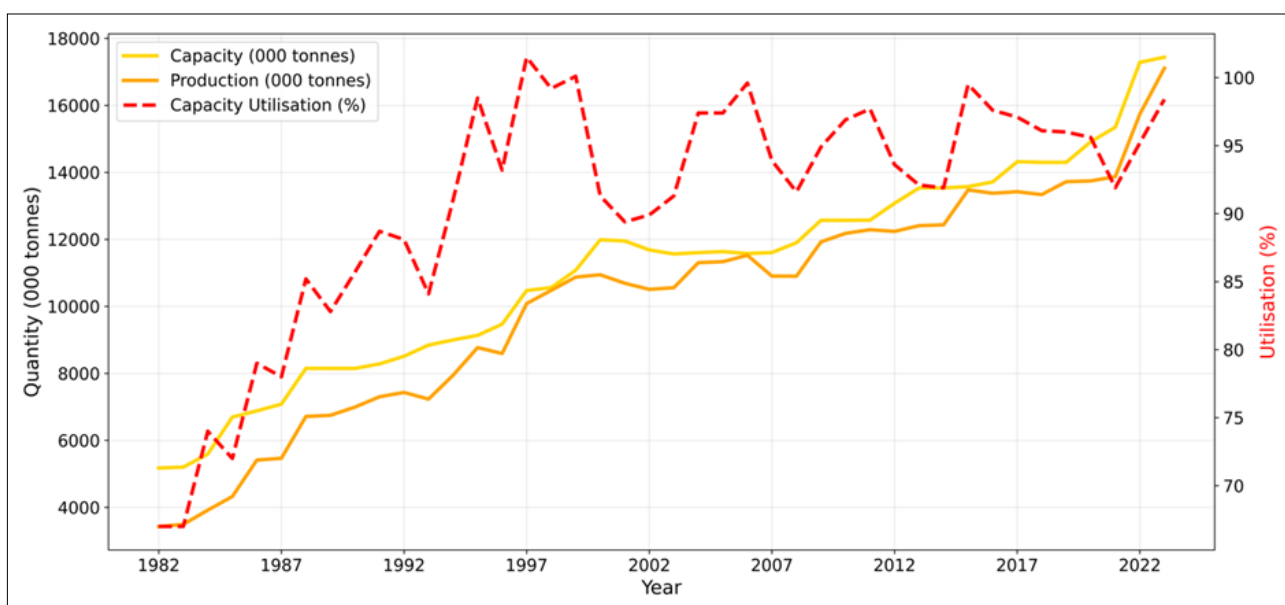


Fig. 2a. All-India capacity, production and capacity utilisation of nitrogen (1982–2023) (%).

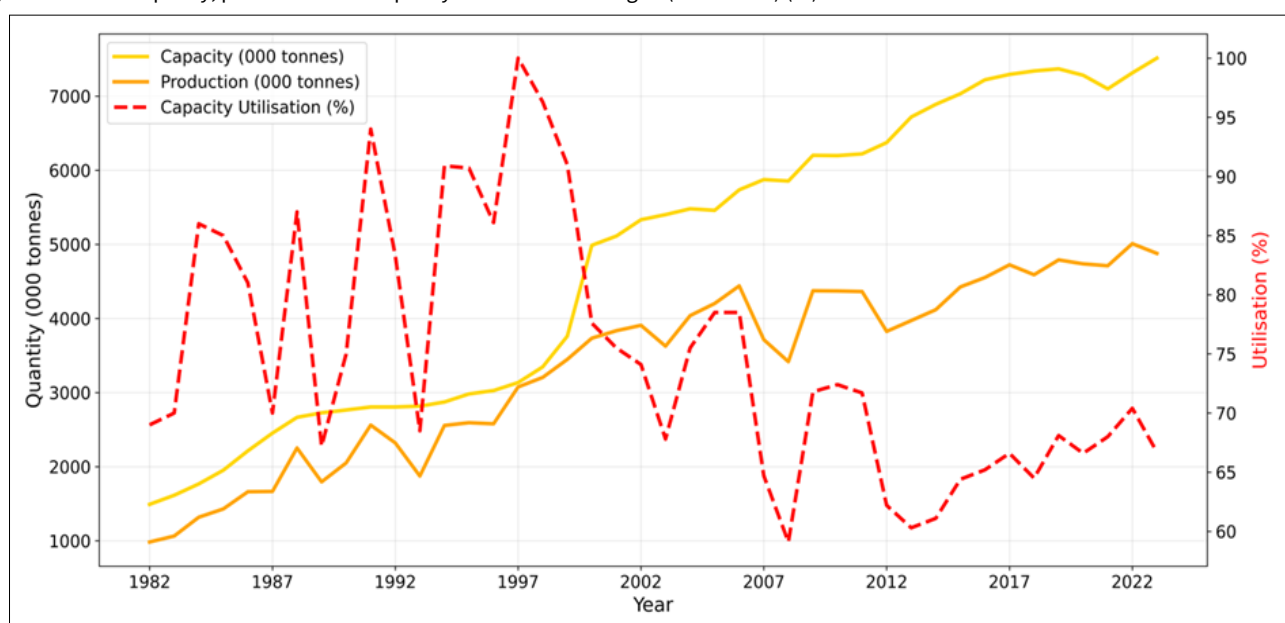


Fig. 2b. All-India capacity, production and capacity utilisation of phosphorous (1982–2023) (%).

For nitrogen, both installed capacity and actual production expanded steadily between 1982 and 2023, with capacity utilisation remaining around or above 90 % from the late 1990s onward. Sustained high utilisation indicates that nitrogen plants operate close to full capacity, reflecting stable demand reinforced by subsidy support and price incentives. By contrast, phosphorus plants exhibited near-full utilisation in the mid-1990s, followed by a gradual decline to nearly 70 % in recent years, despite relatively stable installed capacity. The widening gap between installed capacity and actual output suggests structural underutilisation, likely driven by dependence on imported raw materials and weaker demand incentives relative to nitrogen-based fertilisers. Thus, nitrogen dominance is reflected not only in aggregate production but also in differential capacity performance across nutrients.

Demand and pressure on fertilisers

The previous section showed how policy support, pricing regimes and investment decisions created an N dominant system on the supply side, visible in both production trends and capacity utilisation. The present section traces how this structural bias is transmitted into demand pressure, observable in long term consumption ratios and growing reliance on fertiliser imports.

Fertiliser consumption of N, P and K from 1951 to 2023 is presented in Fig. 3. Over time, N use increases much more sharply than phosphorus and potassium. In recent years, nitrogen consumption is roughly 3 times that of P_2O_5 . Agronomic recommendations typically suggest an approximate 4:2:1 N:P:K ratio, meaning nitrogen application should be about twice that of phosphorus and 4 times that of potassium (11). However, the national pattern shows an approximately threefold gap between N and P and an eightfold gap between N and K, deviating substantially from recommended proportional balance. This divergence suggests that high nitrogen availability and relatively lower urea prices push nitrogen use beyond agronomic norms, while phosphorus and especially potassium remain comparatively underapplied, resulting in a structurally imbalanced consumption profile.

This imbalance is closely linked to the supply-side structure documented in Fig. 1, 2a, b. Production and capacity expansion have been concentrated primarily on nitrogen and, to a lesser extent, on phosphorus, resulting in abundant and heavily subsidised stocks of nitrogen fertilisers, particularly urea. The same policy framework that prioritised bulk N and P supply also shapes farmer incentives through price differentials, subsidy design and retail availability (12). Consequently, nitrogen demand expands more rapidly than agronomic recommendations relative to P and K. The consumption trajectory in Fig. 3 therefore mirrors the earlier production divergence, reinforcing rather than correcting the structural imbalance. Fig. 4 extends the analysis to international markets by tracking imports of N, P and K from 1980 to 2023. Imports of all three nutrients increased substantially, with potassium imports rising steadily and N and P imports surging from a low base after 2004. This period coincides with the consolidation of high nitrogen consumption, when domestic production, despite high-capacity utilisation, was insufficient to meet the skewed demand pattern. For phosphorus, an increasing share of requirements is fulfilled through imports of finished fertilisers and intermediates, supplementing domestic output. For potassium, where India lacks a significant domestic resource base, nearly the entire requirement is imported; therefore, any increase in K consumption translates almost directly into higher import volumes.

The import trajectories reveal the external manifestation of internal structural dominance. A fertiliser economy centred primarily on nitrogen and, secondarily, phosphorus generates not only an N-heavy and ratio-distorting demand pattern, but also increasing exposure to global fertiliser markets for P and especially K. Taken together, a clear causal chain emerges: supply-side dominance of N and P creates biased availability supported by heavy subsidies; farmers respond with disproportionately high nitrogen use and relatively inadequate potassium application; and the resulting demand pressure is progressively met through imports, embedding vulnerability to international price and supply shocks within an already imbalanced nutrient regime.

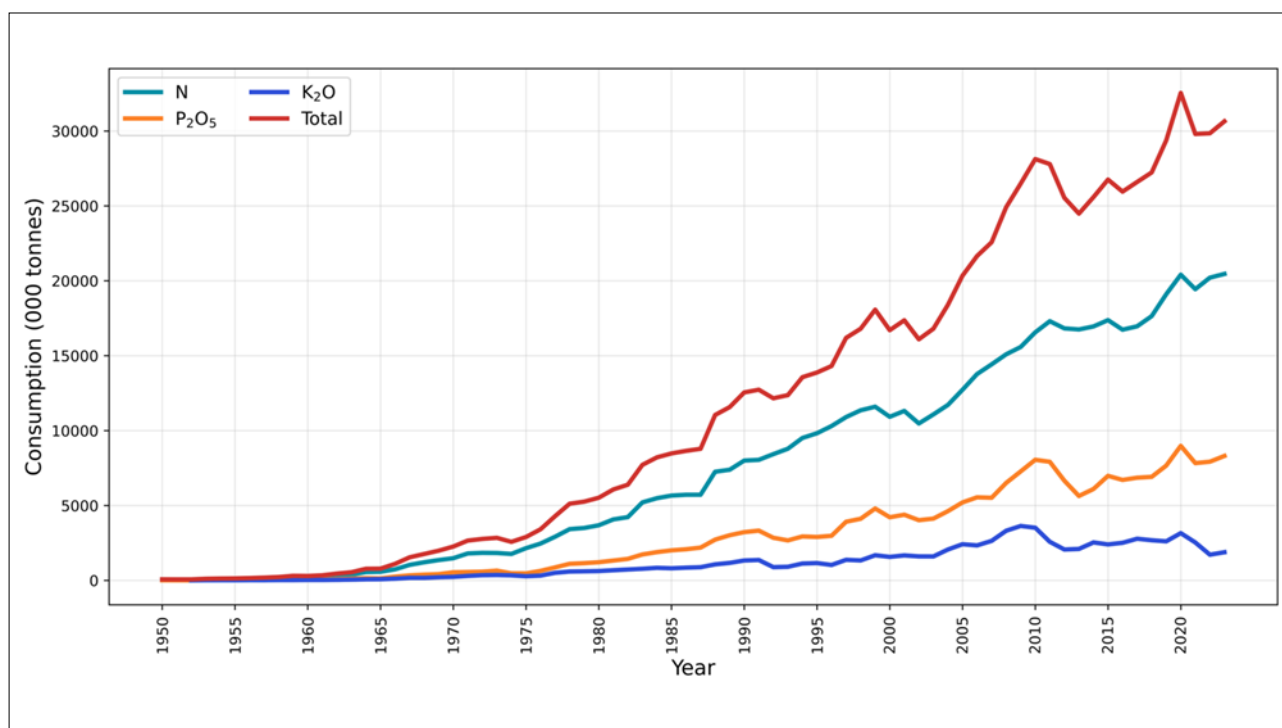


Fig. 3. Long-term trends in fertiliser consumption of nitrogen, phosphorus and potassium in India (1951–2023) (000 tonnes).

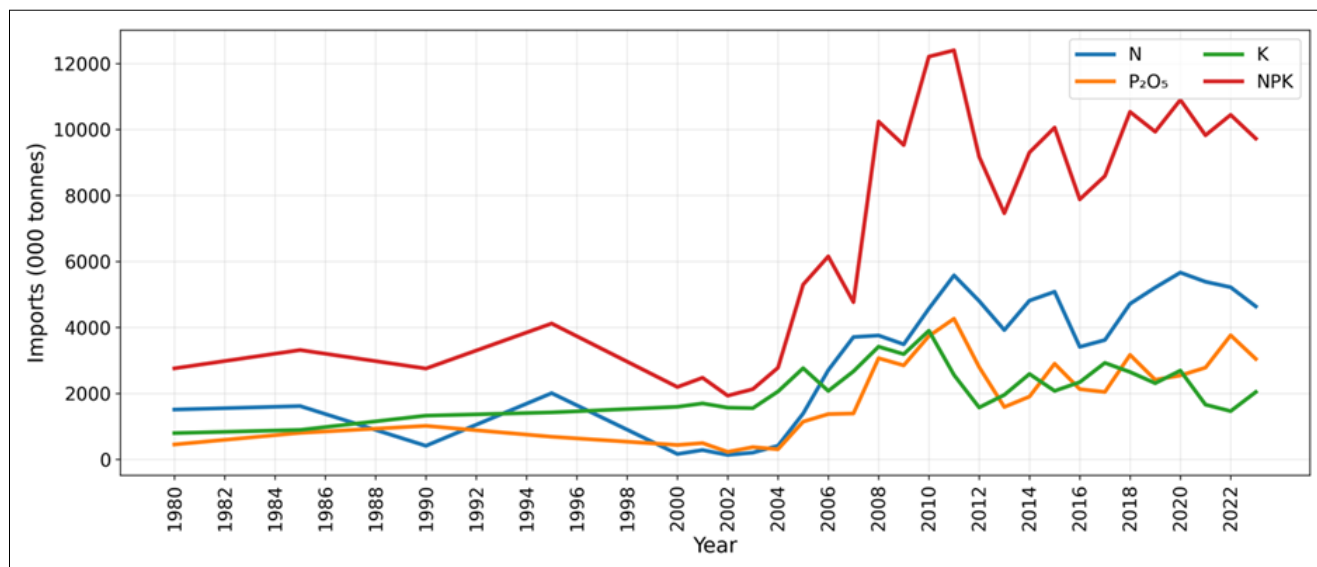


Fig. 4. Long-term trends in fertiliser imports of nitrogen, phosphorus (P_2O_5) and potassium (K_2O) in India (1980–2023) (000 tonnes).

Spatial concentration of the primary fertilisers

The spatial analysis of fertiliser use shows that structurally biased growth in primary nutrients is not only a national-level phenomenon but is also distinctly patterned across regions. Spatial autocorrelation results indicate that fertiliser consumption intensity is clustered rather than randomly distributed, with statistically significant hotspots emerging in specific parts of the country. The 2023 hotspot analysis identifies high-intensity clusters in Andhra Pradesh, Gujarat, Bihar and the traditional north-western grain belt, while other regions appear as cold spots or remain at intermediate levels of use (Fig. 5).

These spatial patterns align with the historical co-evolution of irrigation expansion, high-yielding varieties and input support policies (1). Regions such as Punjab, Haryana and western Uttar Pradesh and more recently parts of Gujarat and Andhra Pradesh, were early adopters of irrigated, input-intensive cropping systems and consequently became focal areas for large-scale deployment of urea and other primary fertilisers (13). Bihar's emergence as a

contemporary hotspot reflects the eastward spread of agricultural intensification under public distribution and food procurement regimes, combined with increased access to subsidised fertilisers and groundwater (1). Over time, input supply chains, extension services and credit systems in these regions have been structured to favour bulk N and P products, particularly urea, DAP and complex NPKs, creating dense fertiliser distribution networks that sustain high application intensities (14).

The spatial clustering of high consumption represents the territorial expression of the same structural forces that shape national production and demand (13). In regions with high irrigation density and procurement-linked cereal dominance, incentives to apply large quantities of N and P are strongest and these areas emerge as statistically significant hotspots in the spatial autocorrelation analysis (14). In contrast, many rainfed or less commercialised regions remain cold spots, characterised by lower input use and weaker integration into national fertiliser and grain markets. Importantly, hotspot regions also face heightened risks of

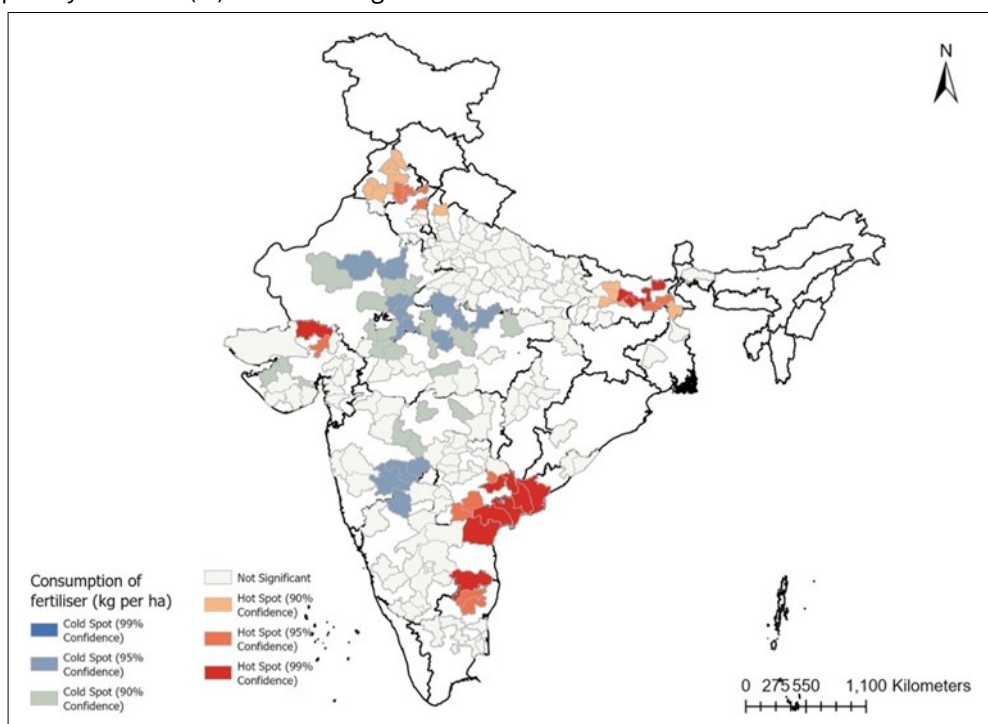


Fig. 5. Hot spots and cold spots by intensity of fertiliser consumption in 2023.

nutrient imbalance. Soil assessment studies show that districts with the highest fertiliser application intensity often exhibit persistent micronutrient deficiencies, particularly of zinc, boron, iron, copper and manganese. This indicates that higher levels of primary nutrient application do not ensure balanced soil or crop nutrition. The concentration of N- and P-intensive fertiliser use in Andhra Pradesh, Gujarat, Bihar and the north-western region therefore signals not only zones of intensified production support but also potential epicentres of long-term soil nutrient depletion and sustainability risks.

Overall, the spatial autocorrelation and hotspot results demonstrate that the national bias toward primary fertilisers is produced and reinforced through specific regional clusters of intensive use. These clusters connect the industrial structure of fertiliser supply and aggregate demand patterns to concrete agricultural landscapes where structural dominance is most deeply embedded and where the consequences for nutrient imbalance, soil health and long-term productivity are likely to be most severe.

Micronutrients and their consumption mismatches

State-level micronutrient patterns indicate a fertiliser system centred on bulk N-P supply rather than balanced micronutrient management. Large-scale soil analyses reveal widespread but spatially heterogeneous deficiencies of zinc, boron, iron, copper and manganese across India. However, comparison of deficiency maps with state-wise consumption of micronutrient fertilisers (Fig. 6, 7) shows that the most deficient states and the highest-consuming states rarely coincide, revealing a pronounced mismatch between agronomic need and actual use. For zinc, the highest soil deficiencies occur in Tamil Nadu, Madhya Pradesh and Rajasthan, whereas the largest users of zinc sulphate are Punjab, Maharashtra and Uttar Pradesh. Similar divergences appear for other micronutrients. Copper deficiencies are most severe in Tamil Nadu, Rajasthan and Odisha, yet consumption is concentrated in Madhya Pradesh. Iron deficiencies are prominent in Rajasthan, Gujarat and Maharashtra, while iron application is higher in Maharashtra, Punjab and Karnataka. Manganese deficiencies are pronounced in Rajasthan, Punjab and Uttar Pradesh, but consumption is led by Madhya Pradesh and Punjab. Boron shows acute deficiencies in Jharkhand,

Odisha and several North-Eastern states, whereas major use is observed in West Bengal, Madhya Pradesh and Maharashtra. These patterns reinforce earlier findings that even regions with high fertiliser application intensity often experience persistent micronutrient deficiencies, indicating that fertiliser scale and nutrient balance remain decoupled.

Part of this mismatch can be explained by differences in soil types, agro-ecologies and cropping systems (6). Zinc deficiency is particularly severe in intensively cultivated rice-wheat systems on alluvial or calcareous soils, as seen in Punjab, Haryana and parts of Uttar Pradesh, where heavy N and P application accelerates zinc depletion and sustains demand for zinc sulphate. At the same time, zinc-responsive crops such as paddy and maize are widely grown in Tamil Nadu and Madhya Pradesh, yet lower levels of commercialisation, weaker extension support and less developed micronutrient markets appear to constrain uptake despite high deficiency (6, 15). Similarly, boron is critical for oilseeds, pulses, vegetables and fruit crops that are prominent in Eastern and North-Eastern India, but formulated boron consumption is concentrated in relatively diversified and market-oriented systems such as West Bengal and Maharashtra (6).

In the arid and semi-arid tracts of Rajasthan and parts of Gujarat, coarse-textured soils, low organic matter and prolonged reliance on high-analysis N-P fertilisers contribute to deficiencies of Fe, Mn and Cu, particularly under irrigated cotton, mustard and wheat systems (15). Yet micronutrient application in these areas remains modest relative to agronomic need. In contrast, better-resourced states with stronger agro-input networks, such as Maharashtra, Punjab and Karnataka, record higher use of iron and manganese even where mapped deficiencies are comparatively lower. The state-level evidence therefore reveals a dual imbalance within a fertiliser economy dominated by primary nutrients: first, excessive and spatially concentrated N-P application; second, a spatial and crop-wise disconnect between micronutrient depletion and replenishment. Market incentives, infrastructure, cropping commercialisation and subsidy structures tend to channel micronutrient fertilisers toward already well-integrated regions rather than toward soils where deficiencies are most acute.

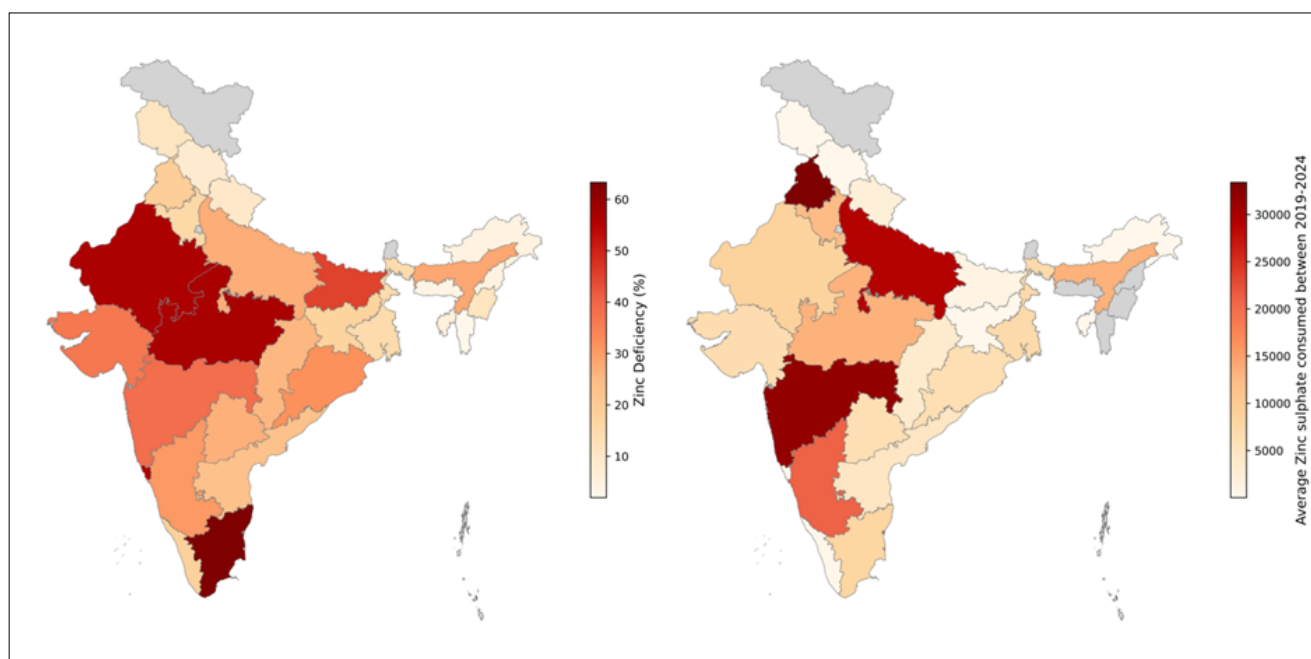


Fig. 6. Distribution of state-wise zinc deficiency (%) and corresponding average micronutrient consumption 2019–2024 (t).

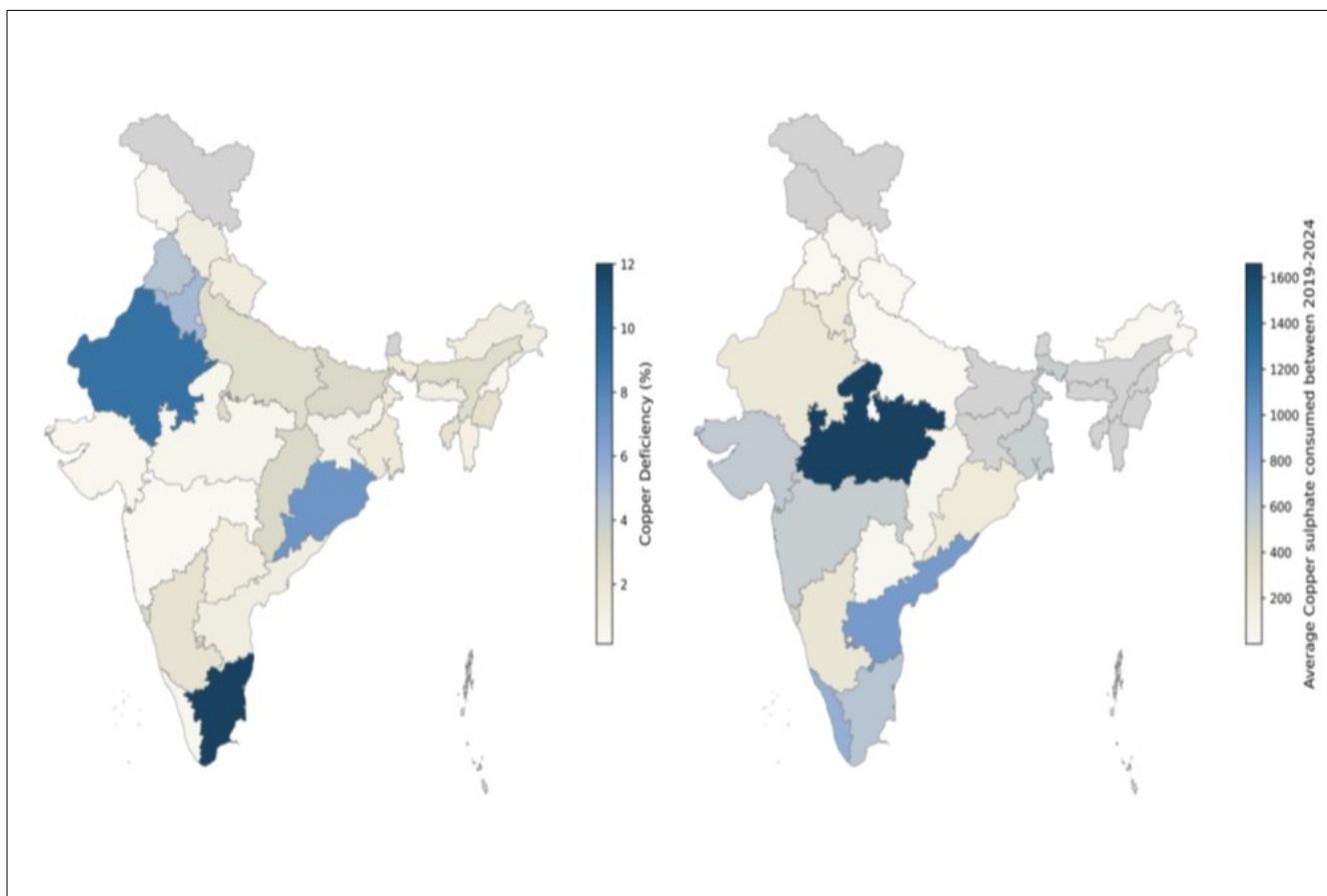


Fig. 7a. Distribution of state-wise copper deficiency (%) and corresponding average micronutrient consumption 2019–2024 (t).

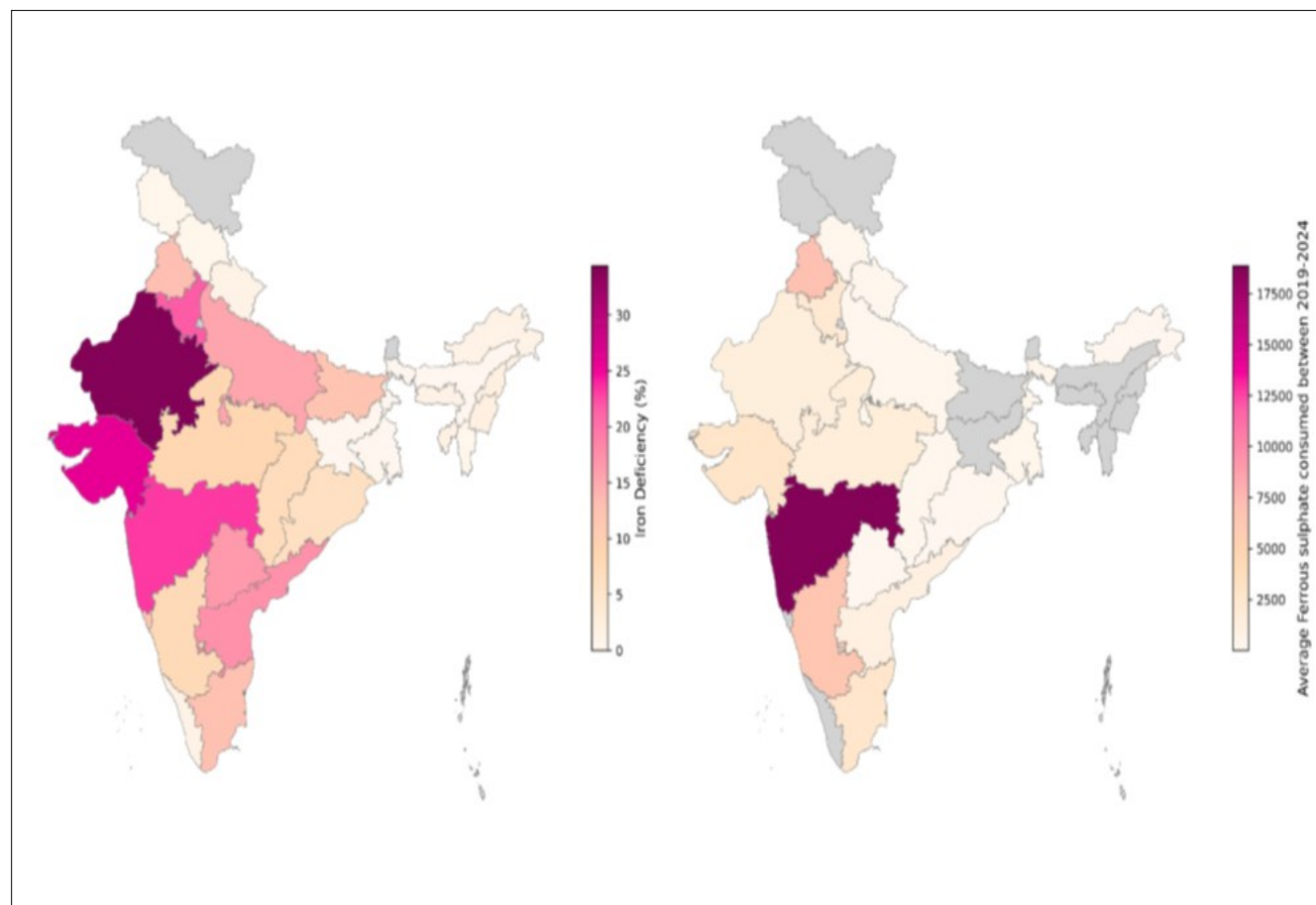


Fig. 7b. Distribution of state-wise iron deficiency (%) and corresponding average micronutrient consumption 2019–2024 (t).

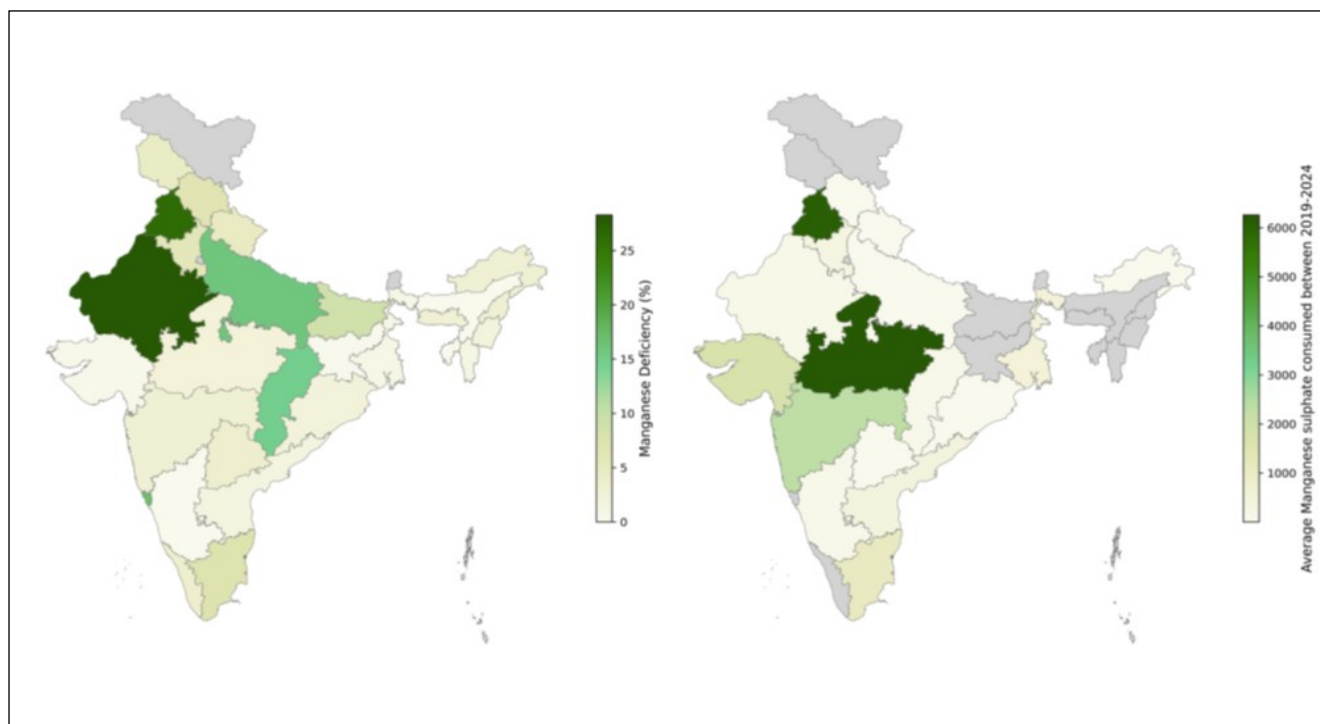


Fig. 7c. Distribution of state-wise manganese deficiency (%) and corresponding average micronutrient consumption 2019–2024 (t).

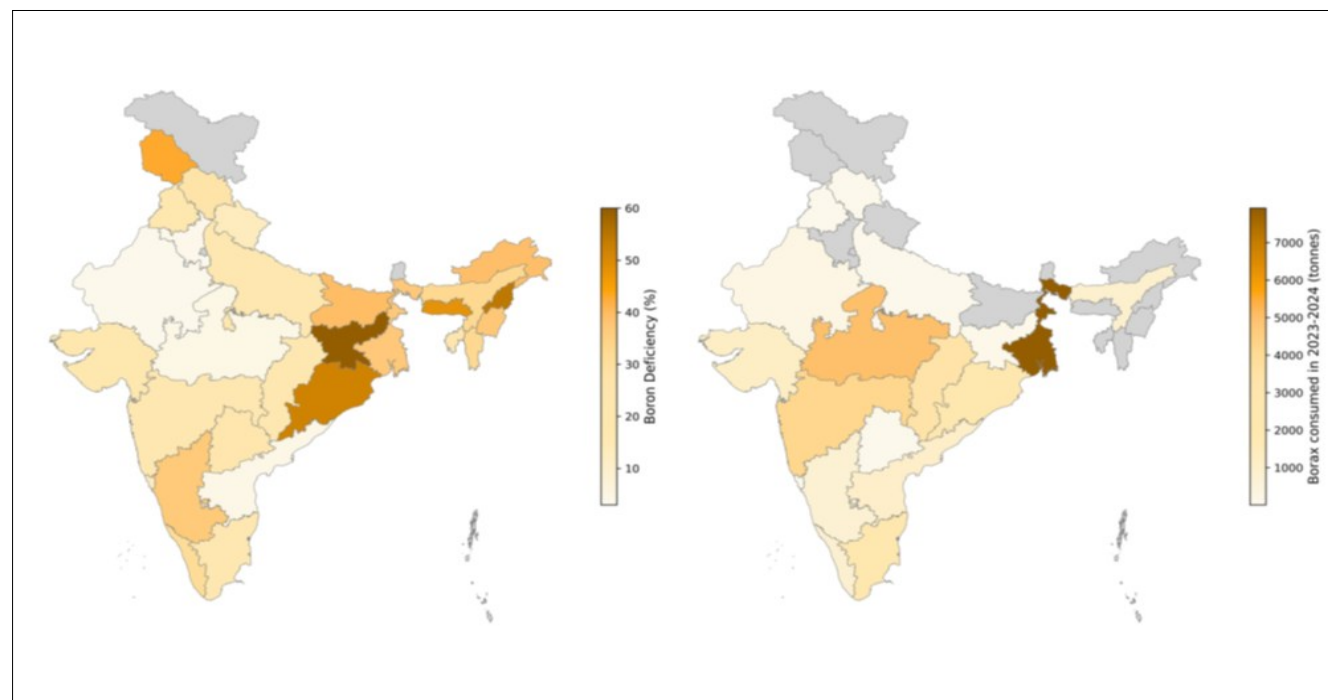


Fig. 7d. Distribution of state-wise boron deficiency (%) and corresponding average micronutrient consumption 2019–2024 (t).

Conclusion

This analysis shows that India's fertiliser economy is structurally locked into a nitrogen- and phosphorus-heavy regime, with production capacity, utilisation and policy incentives overwhelmingly favouring primary nutrients over a diversified nutrient basket. The study connects structural and spatial dynamics to state-level micronutrient outcomes, revealing two layers of imbalance: excessive and spatially concentrated N-P application and a systematic mismatch between regions with the most severe micronutrient deficiencies and those with the highest micronutrient fertiliser use. The decoupling of micronutrient depletion from replenishment, mediated by market infrastructure, crop commercialisation and subsidy design, indicates that high input intensity does not ensure balanced soil nutrition or long-term sustainability. Future research

should extend this system-level perspective in three directions. First, integrating finer-scale soil and crop response data with farm-level management information would allow clearer quantification of the yield and environmental consequences of these nutrient imbalances over time. Second, scenario analysis of alternative subsidy and pricing regimes could help identify policy levers capable of gradually reorienting the fertiliser system toward balanced macro- and micronutrient use while maintaining food security. Third, coupling spatial fertiliser data with climate and water-use indicators would clarify how structural dominance of primary nutrients interacts with emerging stresses such as groundwater depletion and climate variability, thereby informing region-specific nutrient management and investment strategies.

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Authors' contributions

HB conceptualised the study, compiled and curated the data, performed the statistical and spatial analyses and drafted the manuscript. PKV supervised the research, provided methodological guidance and critically revised the manuscript for important intellectual content. DKT contributed to data interpretation, supported the analytical framework and assisted in reviewing and refining the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

Authors hereby declare that AI technology in the form of Grammarly was used solely for language editing and stylistic improvement of the manuscript. The scientific content, data analysis, methodological design, interpretation of results and conclusions were entirely developed by the authors.

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