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Mapping fertiliser consumption dynamics in India: A spatial and temporal assessment

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ABSTRACT

Fertiliser use is central to India's agricultural productivity, yet it's spatial distribution remains highly uneven. Understanding these disparities is crucial for promoting balanced nutrient management. While earlier researches have focused mainly on national or state aggregates, district-level spatial patterns have received limited attention. This study fills that gap by examining long-term trends and spatial clustering in nitrogen, phosphorus, and potassium consumption across India. National and state-level trajectories are analysed through compound annual growth rates. District-level spatial analysis was conducted using Global Moran's I and Getis-Ord Gi* hotspot analysis for the benchmark years 2013 and 2023. Results showed that although national growth rates have slowed, absolute fertiliser use continues to rise. State-level patterns reveal widening divergence with rapid expansion in central and eastern states and slower or negative growth in parts of the south and north-east states. Moran's I values indicates significant and strengthening spatial autocorrelation for all nutrients. Hotspot maps highlight distinct nutrient geographies with nitrogen intensifying across the Indo-gangetic plain and southern high-input belts; phosphorus consolidating across central and southern states and potassium remaining concentrated in the southern peninsula. These spatially differentiated patterns call for fertiliser policy frameworks that move beyond uniform directives toward region and nutrient-specific strategies. Such policies should align soil health goals with crop nutrient requirements, while improving input efficiency, reducing imbalances, and sustaining farm productivity across India's diverse agro-ecologies.

Keywords: Fertiliser consumption, Hotspot analysis, Spatial autocorrelation

Fertilisers have been central to India's gains in crop productivity, particularly under high-yielding varieties and intensive cropping systems. National statistics show a steady rise in the use of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) with per-hectare application almost doubling since the early 1990s (Borkar 2023). India is now among the largest consumers of plant nutrients globally. Yet, nutrient use remains uneven and often unbalanced, with persistent nitrogen overuse and relatively slower growth in P and K in several regions (Govindaswamy *et al.* 2025). These spatial and nutrient imbalances have important implications for soil health, fertiliser efficiency and the sustainability of cereal-based systems.

Empirical work on fertiliser consumption in India has largely focused on national and state aggregates, documenting long-term trends and growth performance (Praveen *et al.* 2020, Tiwari 2024). While this literature provides a useful macro-level picture, it relies on highly aggregated data and mostly descriptive methods, which limit insights into how fertiliser use is organized at smaller spatial units. District-level evidence remains sparse and is typically confined to selected states or agroclimatic zones. Formal spatial statistics, such as Moran's I and hotspot analysis, have only recently been applied to nutrient budgets and related indicators (Elsayed *et al.* 2025), and there is still no nationwide spatial assessment of fertiliser consumption at the district scale.

This study addresses these gaps through a multiscale analysis of fertiliser use in India. It examines long-term national trends in nutrient consumption, quantifies recent state-level growth using compound annual rates, and evaluates district-level spatial clustering of nutrients, phosphorus, and potassium using Global Moran's I and Getis-Ord Gi* statistics for 2013 and 2023. The objective is to characterize where fertiliser use is intensifying or weakening, and how spatial clustering has evolved over the last decade.

MATERIALS AND METHODS

The study analysed fertiliser consumption in India at three scales. National and state data are used to examine

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long-term trends and growth behaviour, while districts serve as the basic spatial units for assessing the spatial distribution of nutrient use. District-level patterns were evaluated for 2013 and 2023 to capture decadal changes. The analysis covered nitrogen, phosphorus, and potassium, the three major plant nutrients.

Data sources: Secondary data were compiled from Fertiliser Statistics, covering the period up to 2023 (FAI 2024). District-wise consumption data for nitrogen, phosphorus, and potassium (tonnes) were extracted for 2013 and 2023. The year 2013 represents the post-stabilization phase of the Nutrient-Based Subsidy (NBS) regime, when fertiliser pricing and distribution mechanisms across the country had largely adjusted to this specific policy reform. The year 2023 corresponds to the most recent period for which complete and consistent district-level fertiliser consumption data were available across all states. Hence, the period between these two reference years allow assessment of medium-term spatial and temporal changes in fertiliser use under a relatively stable policy framework. While national and state-level aggregates were used to examine temporal trends from 1950 to 2023 and from 2013 to 2023, respectively.

Trend and growth analysis: National and state-level temporal patterns in fertiliser consumption were analysed using time-series visualization and growth indicators. To assess changes in fertiliser use across states, the Compound Annual Growth Rate (CAGR) was employed. CAGR captures the average annual rate of increase (or decrease) between an initial and a final observation while minimizing the influence of intermediate variability.

$$\text{CAGR} = \left(\frac{X_t}{X_0}\right)^{\frac{1}{n}} - 1$$

Where X_t and X_0, Fertiliser consumption at the beginning and end of the period, respectively and n, Number of years. This indicator enables comparable assessments across states with varying consumption levels and identifies whether fertiliser use has accelerated, stagnated or declined over the last decade.

Spatial analysis framework

Spatial weights: Spatial relationships among districts were defined using a first-order queen contiguity matrix, with row-standardized weights. For validation, results were cross-checked using an 8-nearest-neighbour (k = 8) weighting matrix, which produced consistent patterns.

Global Moran's I: Spatial autocorrelation was measured using Global Moran's I (Moran 1950), expressed as:

$$I = \frac{n}{W} \cdot \frac{\sum i \sum j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum i (x_i - \bar{x})^2}$$

Where n, Number of spatial units; X_i and X_j, Observed values of fertiliser at locations i and k. $\bar{x}$, Mean value across all units, W_{ij} is the element of the spatial weight matrix defining the relationship between i and j, and W, Sum of all w_{ij}. Moran's I values close to +1 indicated strong clustering, values near 0 suggested a random pattern, and values approaching -1 reflected dispersion. The significance of Moran's I was assessed using Z-scores at a 5% probability level.

Hotspot analysis: Hotspot and coldspot clusters were identified using the Getis-Ord Gi* statistic (Getis and Ord 1992):

$$Gi^* = \frac{\sum j w_{ij} x_j - \bar{X} \sum j\, w_{ij}}{S\left(\frac{\left[n \sum j\, w_{ij}^2 - \left(\sum jwij\right)^2\right]}{n-1}\right)^{\frac{1}{2}}}$$

Where x_j, Observed value at location j; w_{ij}, Spatial weight between locations i and j; $\bar{X}$, Mean of all observations and S, Standard deviation. Districts with significantly j positive Z-scores (p<0.05) were designated as hotspots indicating higher fertiliser consumption relative to the mean whereas significantly negative Z-scores were classified as cold spots.

Interpretation, software and reproducibility: The computed Moran's I and Gi* statistics were mapped to visualize spatial clusters and identify persistent and emerging patterns of fertiliser use across Indian districts. ArcGIS Pro 2.0.3 was used for all spatial analyses. Graphs and statistical summaries were produced using Python.

RESULTS AND DISCUSSION

This section reports national, state, and district-level results, tracing changes in fertiliser use over time and across

Table 1 Trends in nutrient consumption in India

	CAGR in nutrient consumption (%)				Nutrient consumption (000' tonnes)				
Year	N	P_2O_5	K_2O	Total	Year	N	P_2O_5	K_2O	Total
1950–59	17.2	22.3	15.1	17.8	1959	229.3	53.9	21.3	304.6
1960–69	22.9	25.7	24.6	23.6	1969	1356	416	210	1982
1970–79	10	8.7	11	9.8	1979	3498.1	1150.9	606.4	5255.4
1980–89	8.1	10.6	7.2	8.6	1989	7385.9	3014.2	1168	11568.2
1990–99	4.2	4.5	2.6	4.1	1999	11592.5	4797.9	1678.4	18068.9
2000–09	4	6.3	9.8	5.3	2009	15580	7274	3632.4	26486.4
2010–19	1.6	-0.5	-3.3	0.5	2019	19101.3	7662	2607	29370.3
2020–23	0.1	-1.9	-12.1	-1.5	2023	20456.4	8306.6	1878.6	30641.6

space. The findings are organized from national trends to state growth patterns and district-level spatial structures.

National trends in fertiliser consumption: National fertiliser trends provide the broad context for interpreting patterns through decadal CAGR and nutrient volumes since the 1950s (Table 1). Fertiliser use expanded rapidly in the early decades with total nutrient consumption growing at 17–24% annually during the 1950s and 1960s, reflecting the spread of chemical fertilisers supported by irrigation expansion and policy thrusts around the green revolution. Such a trend has been reported previously in the literature (Praveen *et al.* 2020).

Growth moderated steadily from the 1970s onwards. CAGR declined to about 10% in the 1970s, 8% in the 1980s and 4–5% during the 1990s and 2000s indicating a transition from an expansion phase to a more stabilized use pattern as high-use states approached saturation and marginal increases became smaller (Jeyanthi and Kannan 2024). In the recent decade, a sharper divergence emerged. Total nutrient CAGR fell to 0.5% during 2010–19 and turned negative between 2020–23, yet absolute nutrient consumption reached record levels exceeding 29–30 million tonnes. Nitrogen use alone exceeded 20 million tonnes despite near-zero growth. By contrast, phosphorus (-1.9%) and potassium (-12.1%) recorded pronounced negative growth. This divergence in growth trends across the major primary nutrients reinforces long-standing concerns about nutrient imbalance highlighted in national assessments (Tiwari 2024). Overall, the national trends show persistently high fertiliser demand but diminishing growth momentum, providing a baseline for examining spatial divergence at the state and district levels.

State-level growth patterns in fertiliser consumption: State-wise growth rates showed marked heterogeneity in fertiliser consumption across India (Table 2), reflecting differences in agroclimatic conditions, cropping systems and access to inputs. Strong positive growth is observed in several eastern and central states including Jharkhand (8.60%), Madhya Pradesh (6.22%), Rajasthan (5.08%), Chhattisgarh (4.22%), Bihar (3.82%), Uttar Pradesh (3.75%), Manipur (3.27%) and Telangana (3.12%). Mizoram also records a high CAGR (5.95%), largely due to it's low baseline. Higher phosphorus and potassium growth in states such as Jharkhand (13.04%) and Rajasthan (12.49%) is encouraging in the context of balanced fertiliser application. The recent efforts of the central government and various states to improve nutrient balance could be the reason for higher use of phosphorus and potash, at least in some states (Jadhav and Ramappa 2023).

Another group of states showed moderate or mixed growth (1–3%) including Haryana, Odisha, Gujarat, Karnataka, Tamil Nadu, West Bengal, Punjab and Maharashtra. These states generally exhibit positive nitrogen growth but more variable phosphorus and potassium trajectories, reflecting continued nutrient imbalance and sensitivity to relative fertiliser prices under the Nutrient-Based Subsidy regime as reported previously in the literature (Mahopatra *et al.* 2024). In long-established intensive systems such as Punjab and Tamil Nadu, plateauing fertiliser responsiveness may also limit further expansion confirming the findings of Sharma *et al.* (2023).

Table 2 Growth in nutrient consumption by states (%)

State	N	P_2O_5	K_2O	Total
Andhra Pradesh	-1.05	1.64	-1.81	-0.37
Assam	2.45	2.8	-11.24	0.21
Bihar	3.18	7.63	-0.22	3.82
Chhattisgarh	4.16	5.68	-1.89	4.22
Gujarat	1.75	3.73	-0.88	2.06
Haryana	1.78	4.65	5.41	2.36
Himachal Pradesh	0.68	2.14	-2.26	0.48
Jammu and Kashmir	1.2	-2.38	-1.48	0.14
Jharkhand	7.8	13.04	-1.88	8.6
Karnataka	1.79	3.79	-1.74	1.91
Kerala	-6.25	-6.22	-5.72	-6.07
Madhya Pradesh	5.65	5.85	4.9	6.22
Maharashtra	-0.08	2.73	-1.94	0.52
Manipur	4.01	2.51	-2.42	3.27
Meghalaya	-100	-100	-100	-100
Mizoram	7.78	-100	-100	5.95
Nagaland	-12.03	-35.73	-36.29	-17.59
Odisha	1.97	5.25	-3.04	2.39
Punjab	1.45	1.5	4.46	1.51
Rajasthan	4.27	7.33	12.49	5.08
Tamil Nadu	2.15	4	-2.88	1.85
Telangana	2.45	5.6	1.06	3.12
Tripura	-4.29	-6.72	-11	-6.15
Uttar Pradesh	3.18	5.71	3.28	3.75
Uttarakhand	-1.67	1.69	-1.78	-1.17
West Bengal	0.76	5.56	0.12	1.82

States with marginal or near-zero growth such as Assam (0.21%), Jammu and Kashmir (0.14%) and Himachal Pradesh (0.48%) essentially represent hill regions where terrain, cropping patterns and small farm sizes naturally constrain input intensification. Declining growth is observed in Andhra Pradesh (-0.37%), Uttarakhand (-1.17%), Kerala (-6.15%), Nagaland (-17.59%), etc. consistent with it's emerging organic orientation as reported by Das *et al.* (2021) previously. Hence, interstate growth patterns revealed widening divergence in fertiliser use underscoring the need to examine how these differences translate into district-level spatial clustering.

District-level spatial structure and hotspot dynamics: Spatial patterns in fertiliser use arise from agro-ecological continuity, irrigation access, cropping systems and market linkages that often extend across district boundaries (Qu *et al.* 2025). Moran's I provides an overview of whether consumption is spatially clustered or dispersed and how this structure has changed over time (Table 3).

Table 3 Global Moran's I statistics for district-level fertiliser consumption in India

Year	Remark	N	P_2O_5	K_2O
2013	Moran's I	0.49	0.39	0.24
	Z-score	27.68	22.31	14.82
	Pattern	Clustered	Clustered	Weakly clustered
2023	Moran's I	0.55	0.43	0.30
	Z-score	31.02	23.65	16.04
	Pattern	Clustered	Clustered	Weakly clustered

The estimates indicate clear and statistically significant spatial clustering in both 2013 and 2023. Nitrogen showed the strongest spatial dependence followed by phosphorus while potassium displays comparatively weaker clustering. Importantly, Moran's I values increase for all the nutrients over the decade suggesting a strengthening spatial structure in which high and low use districts become more distinctly organized. While Moran's I confirms the presence and intensification of clustering, it does not identify the location of these clusters. The Getis-Ord Gi* therefore complements the analysis by mapping the specific hotspots and coldspots associated with each nutrient.

Spatial hot and cold spots of nitrogen application: The spatial distribution of nitrogen use showed a clear geography of intensification and persistence across Indian districts (Fig. 1). In 2013, strong hotspots were concentrated in the Punjab-Haryana belt reflecting sustained irrigation, cereal dominance and long-standing nitrogen-responsive systems (Shah *et al.* 2025). A second high-use corridor extended across Maharashtra, northern Karnataka and Andhra Pradesh, consistent with commercial crop patterns and higher cropping intensity (Bode *et al.* 2023). Smaller hotspots in central Uttar Pradesh and southern Gujarat indicated localized intensification linked to irrigated tracts in the regions (Jadhav and Ramappa 2023).

By 2023, hotspot patterns expanded and reorganized. The Indo Gangetic Plain showed marked eastward and southward intensification forming a continuous Uttar Pradesh-Madhya Pradesh nitrogen belt driven by wheat–rice systems and improved fertiliser access (Chaudhuri *et al.* 2023). The north-western cluster remains strong while parts of Maharashtra, northern Karnataka, Andhra Pradesh and Gujarat showed hotspot contraction, possibly reflecting a shift away from nitrogen-heavy crops or improved nutrient balancing (Kumar and Babu 2025). Coldspots remain spatially stable. The Assam-Arunachal-Nagaland hill zone remains a pronounced low-use region due to rainfed cultivation, limited distribution networks and low-input systems. A second enduring coldspot spans Kerala and southern Tamil Nadu shaped by perennial crop dominance and reduced nitrogen responsiveness (Jacob *et al.* 2025).

A broader shift occurs in central India, where fragmented, low-use districts in 2013 consolidate into a continuous tribal belt coldspot by 2023 indicating persistent structural constraints such as rainfed agriculture and weak fertiliser supply chains. Meanwhile, parts of Maharashtra and northern Karnataka transition into a stable eastern Maharashtra-western Telangana high-use zone

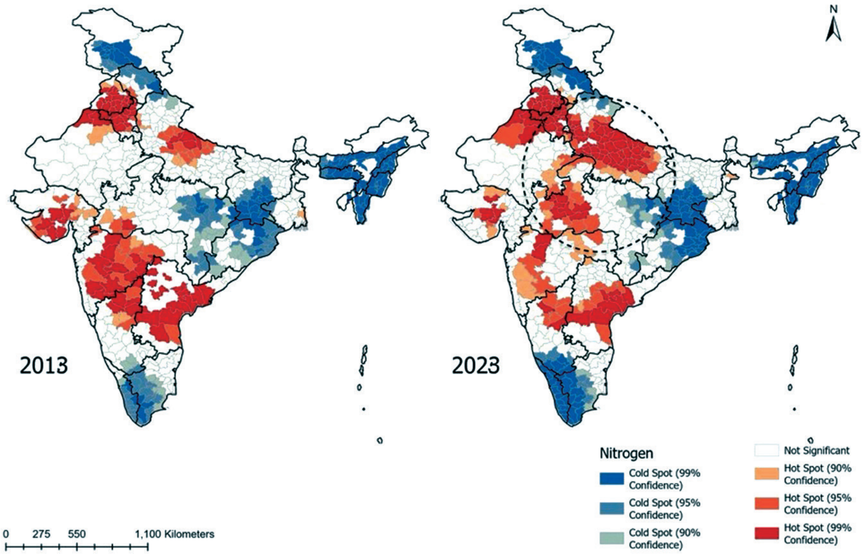

Fig. 1 Hotspots and coldspots of nitrogen consumption (2013 and 2023).

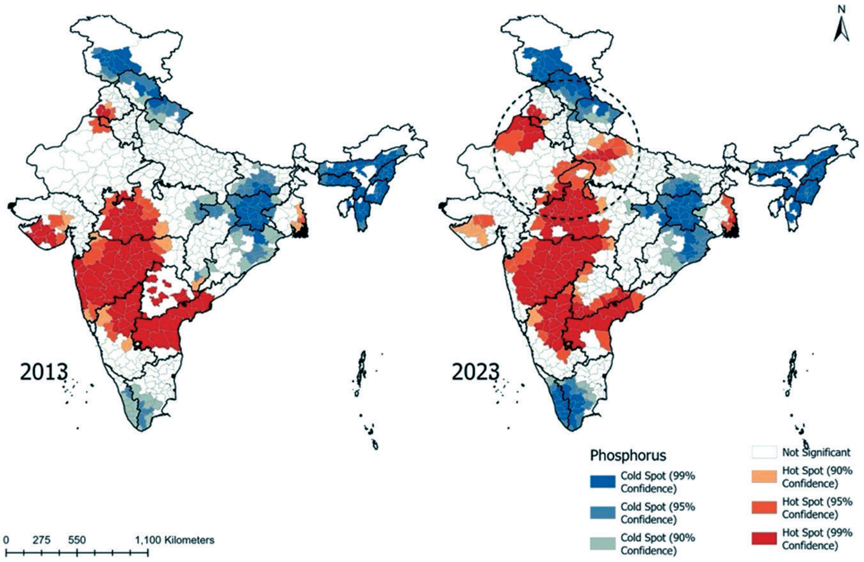

Fig. 2 Hotspots and coldspots of phosphorous consumption (2013 and 2023).

consistent with cotton, soybean and horticultural intensification (Snapp *et al.* 2023). Hence, nitrogen hotspots broaden across the Indo-Gangetic and southern commercial crop regions while coldspots deepen in the north-east, central tribal belt and peninsular south, mirroring the stronger spatial clustering observed in Moran's I.

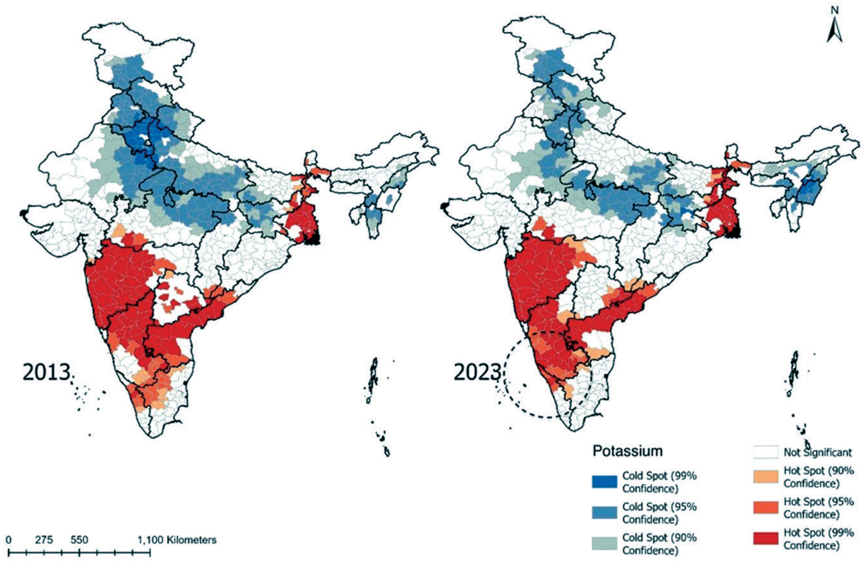

Fig. 3 Hotspots and coldspots of potassium consumption (2013 and 2023).

Spatial hot and cold spots of phosphorous application: The spatial distribution of phosphorous use showed a strong concentration of hotspots in western and peninsular India with apparent intensification over time (Fig. 2). In 2013, high-use clusters were centered in western Madhya Pradesh and most of Maharashtra extending into northern Karnataka and Andhra Pradesh. Smaller hotspots appeared in southern Gujarat, parts of Punjab, Rajasthan, and Haryana and in the southern tip of West Bengal. These regions are dominated by soybean, cotton, oilseeds and irrigated paddy, and are widely recognized as phosphorus-deficient, prompting sustained P application through fertiliser promotion, higher cropping intensity and stronger market linkages (Annappa *et al.* 2024).

By 2023, these hotspots had grown larger and become more coherent. The western central corridor covering western Madhya Pradesh, Maharashtra, northern Karnataka and Andhra Pradesh not only persists but intensifies expanding northwards into upper Madhya Pradesh and eastwards toward central Uttar Pradesh. This shift indicates increased adoption of P-responsive crops, irrigation expansion and the diffusion of high-yielding varieties. Smaller hotspots in northwestern India and southern West Bengal also expand while the southern Gujarat hotspot contracts, likely reflecting shifts in cropping patterns, water constraints or greater emphasis on balanced fertilization (Annappa *et al.* 2024).

Coldspots of phosphorus exhibit strong persistence. In 2013, low-use clusters spanned Kerala-Tamil Nadu, the Himalayan districts, most of the northeast and a broad zone across Bihar, Jharkhand, Odisha and northern Chhattisgarh. These regions remained as coldspots in 2023 as well, often with more coherent clustering. Their stability reflects enduring constraints such as rainfed and low-input production systems, limited distribution networks, low adoption of P-intensive crops and in some southern and hill districts, stronger reliance on organic nutrient sources as noted previously by Srinivasarao *et al.* (2020). Overall, phosphorus maps showed the consolidation of a major western-central high-P corridor while northeast and eastern India, the central tribal belt and the southern peninsular region remain in persistent low-use states. These patterns align with rising Moran's I, indicating increasing spatial concentration in phosphorus application.

Spatial hot and cold spots of potassium application: The spatial distribution of potassium use showed a clear southern and western concentration of hotspots, along with extensive low-use belts across northern and north-eastern India (Fig. 3). In 2013, Prominent hotspots were located across the southern peninsula spanning Maharashtra, northern and eastern Karnataka, coastal and Rayalseema districts of Andhra Pradesh and much of Telangana. Additional clusters extend to parts of Karnataka, Tamil Nadu and Kerala. A separate hotspot emerged across parts of West Bengal consistent with the long-term fertiliser responsiveness of paddy systems and reported soil potassium depletion in these regions. This confirms the finding of Das *et al.* (2021). These patterns align with areas characterized by multi-cropping, commercial crops and pronounced soil potassium deficiencies.

In 2023, southern hotspots remain dominant but exhibit internal shifts. The Maharashtra-Karnataka-Andhra Pradesh belt persists while intensity weakens in Telangana, where several districts transition out of hotspot status. Hotspots also contract in parts of Tamil Nadu and Kerala suggesting movement toward more balanced nutrient use or cropping changes. A new hotspot emerges in south-eastern Karnataka likely reflecting irrigation expansion and the growing adoption of fertiliser-responsive horticultural and cash crops as reported by Annappa *et al.* (2024). The West Bengal hotspot showed slight contraction, indicating improved nutrient management or shifts in crop portfolios.

Coldspots present a contrasting geography. In 2013, low-use clusters dominated northern India, the Himalayan foothills and the northeast, reflecting soil characteristics, crop mix and limited fertiliser supply networks (Rani *et al.* 2023). By 2023, coldspots are weakening across the Indo-Gangetic plain indicating gradual traction. In contrast, the north-eastern coldspot strengthens becoming more coherent due to reliance on rainfed, low-input systems and limited potash market penetration (Bhatt *et al.* 2021). Altogether, potassium exhibits persistent southern hotspot dominance, moderate re-arrangement within the peninsula and contrasting coldspot trajectories, consistent with the relatively lower Moran's I values and greater spatial fluidity in potassium use.

The spatial patterns identified in this study suggested that fertiliser policy interventions need to be differentiated across regions rather than uniformly applied. Districts that consistently emerge as nitrogen hotspots particularly in the Indo-Gangetic plains and newly intensifying regions of central India indicate price-driven over-application, pointing to the need for rebalancing nutrient subsidies to reduce the relative price advantage of nitrogen and promote more balanced fertilisation. In contrast, districts identified as phosphorus and potassium coldspots reflect chronic under-application rather than saturation; in such regions, region-specific extension programmes focusing on nutrient deficiencies, crop requirements and soil constraints would be more appropriate than broad reductions in fertiliser use. The persistence of hotspot and coldspot clusters over the decade further highlights the importance of strengthening soil testing and advisory infrastructure at the district level, enabling location-specific fertiliser recommendations based on actual soil nutrient status. Together, these findings support a shift towards spatially targeted nutrient management strategies that align subsidy design, extension efforts and soil diagnostics with district-level fertiliser use patterns.

The synthesis of results across scales indicates that India's fertiliser consumption landscape is becoming increasingly polarised. High-input districts particularly in irrigated cereal and commercial crop belts continue to intensify while large contiguous regions remain persistently low in nutrient use. This divergence reflects structural differences in cropping systems, irrigation access, market integration and price incentives, and underscores that each nutrient follows a distinct spatial trajectory. The findings therefore highlight the limitations of uniform fertiliser recommendations and reinforce the need for region-specific nutrient management strategies that account for local agronomic and institutional contexts.

While the present analysis provides a comprehensive spatial assessment of fertiliser consumption dynamics it is limited to observed nutrient use patterns and does not explicitly incorporate drivers such as soil fertility status, rainfall variability, crop composition or farm-level management practices. Since 2015, natural farming has been actively promoted in several states, which could lead to reductions in chemical inputs in areas with substantial adoption. However, spatially consistent district-level adoption data on natural farming are currently unavailable; hence, we couldn't quantify its direct contribution to the observed coldspot persistence in the present study. This is identified as a priority for future. Further, future studies could integrate spatial econometric models and ancillary datasets to identify the drivers of hotspot formation, evaluate nutrient-use efficiency and assess how policy reforms including nutrient-based subsidies, balanced fertilization incentives and emerging low-input or natural farming initiatives shape fertiliser demand across regions over time. Such extensions would further strengthen the evidence base for designing spatially targeted interventions at state and district levels.

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