

**Beyond universal access: mapping regional inequalities and spatial coldspots in India's
WaSH sector toward SDG 6**

Peer review status: This is a non-peer-reviewed preprint submitted to EarthArXiv. It has been submitted to the 'Environment, Development and Sustainability' (Springer) journal for peer-review.

Beyond universal access: mapping regional inequalities and spatial coldspots in India's WaSH sector toward SDG 6

Ajishnu Roy*

Integrative Biology Research Unit (IBRU), Department of Life Sciences, Presidency University, 86/1, College Street, Kolkata, West Bengal, 700073, India

Email: ajishnuroy1990@gmail.com

ORCID: 0000-0001-9494-3963

*Corresponding author

Disclosure statement: The author declares no conflicts of interest.

Data availability statement: All the data used here are available in a public database (NITI Aayog NDAP database, <https://ndap.niti.gov.in/>).

CRedit roles:

Conceptualization: Ajishnu Roy; Methodology: Ajishnu Roy; Formal analysis and investigation: Ajishnu Roy; Writing: original draft preparation: Ajishnu Roy, Writing, review, and editing: Ajishnu Roy, Resources: Ajishnu Roy; Supervision: Ajishnu Roy;

Abstract: National averages can conceal significant sectoral disparities and long-standing subnational injustices, despite the fact that India's flagship programs had significantly improved access to water and sanitation. This report provided a thorough, data-driven evaluation of the water, sanitation, and hygiene (WaSH) in all 37 Indian states and union territories (UTs) using 25 indicators. Pearson's correlation, network analysis, hierarchical clustering, principal component analysis, data envelopment analysis, Theil inequality, and spatial additive decomposition were all included in this multi-methodological framework. Results showed that, in contrast to the varied topographical constraints of larger states, lower administrative scales enable more consistent service delivery. A crucial 'construction-outcome paradox' was found, showing improvements in physical infrastructure do not always transfer into improvements in public health, especially when it comes to childhood stunting and nutritional outcomes. Functional school restrooms for girls were identified by network analysis as a key 'bridge node' and strategic force multiplier for integrated sub-national development. High-GDP states frequently showed a significant 'hygiene-economy gap' in behavioral indicators and waste processing, while spatial breakdown reveals spatially infectious 'coldspots' in the Northeast. Based on our empirical findings, we provide context-specific policy recommendations related to water, sanitation, and hygiene, to ensure functional sustainability and accomplish Sustainable Development Goal 6 by 2030.

Keywords: water, sanitation & hygiene (WaSH); SDG 6; sub-national sustainability; regional inequalities; India;

1. Introduction:

Water, sanitation & hygiene (WaSH) represents a multi-sectoral framework, Water, Sanitation, and Hygiene, recognized as the cornerstone of public health, essential for reducing the global burden of waterborne and neglected tropical diseases. The three pillars were functionally inseparable; for instance, the benefits of improved water quality were often negated if sanitation was poor or if handwashing practices (hygiene) were absent. The WaSH nexus acted as a primary barrier against the fecal-oral transmission route, where integrated interventions were significantly more effective than ‘siloe’d’ approaches in reducing stunted growth and enteric infections. India’s subnational environment exposed pervasive ‘WaSH poverty’, which was fueled by regional differences in topography, climate, and socioeconomic development, even when national averages may indicate growth. The WaSH nexus was intrinsically tied to gender; in rural India, women and girls’ safety, dignity, and educational outcomes were disproportionately impacted by the difficulty of collecting water and the absence of private sanitation. The resilience of sanitation infrastructure was threatened by water scarcity and extreme weather events (droughts and floods), resulting in a feedback loop where environmental stress exacerbates local hygiene crises. The WaSH interaction takes varied forms throughout the continuum; rural areas concentrate on groundwater quality and behavioral change, while urban areas struggle with piped supply and fecal sludge management. The absence of integrated evaluations that concurrently analyze water, sanitation, and hygiene (WaSH) characteristics at granular, sub-national sizes frequently hinders Goal 6. As a signatory to the 2030 Agenda, India must address the WaSH nexus through community-led complete sanitation and localized, data-driven governance to achieve SDG 6 (Clean Water and Sanitation). Even while India’s flagship initiatives, such as the Jal Jeevan Mission (JJM) and Swachh Bharat Mission (SBM), had made great strides, national averages frequently mask notable performance gaps at the state and union territory levels. Understanding the ‘sectoral imbalance’, where high accomplishments in one WaSH pillar, like toilet construction, typically fail to translate into gains in hygiene or water quality, was a crucial study gap. Beyond physical access, localized groundwater over-exploitation was posing a growing challenge to the sustainability of water resources by creating a direct conflict between long-term supply quality and resource quantity. Although infrastructure development had historically been given top priority in national sanitation strategies, there was still a persistent ‘infrastructure-outcome gap’ between meeting physical goals and guaranteeing functional improvements in public health. Traditional WaSH structures were frequently ill-prepared to handle new hygiene emergencies brought about by emerging environmental risks, such as the concentrated generation of hazardous and plastic trash.

2. Literature review:

There were a handful of studies that had focused on water, sanitation & hygiene (WaSH) sustainability (**Table 1**). The transformative effects of current flagship programs like the Swachh Bharat Mission (SBM) and Jal Jeevan Mission (JJM) were not captured by many fundamental research (Chaudhuri & Roy, 2017; Roy & Pramanick, 2019), which rely on Census 2011 or NSSO data that was more than ten years old. A number of assessments (Ghosh et al. 2022; Vatsa et al. 2023) were conducted prior to the NFHS-5’s extensive household data, resulting in progress evaluations that do not accurately reflect the state of rural and urban infrastructure today. Severe intra-state and district-level disparities were sometimes hidden by a common reliance on national-level aggregate (Roy & Pramanick, 2019; Biswas et al. 2022a). The generalizability of results was limited by the fact that existing research frequently focuses either on urban metro areas (Saroj et

al. 2020) or certain single-state scopes (Chouhan et al. 2022; Trivedy & Khatun, 2024). Many studies (Rani, 2022; Ghosh et al. 2023) focus only on binary water and sanitation access measures, leaving out the ‘hygiene’ dimension, especially handwashing practices. Physical ‘access’ or infrastructure ownership was frequently given precedence above actual service levels, such as liters-per-day (LPD) delivery or functional facility utilization, according to research (Chaudhuri & Roy, 2017; Sarkar & Bharat, 2021). Traditional WaSH models hardly incorporate contemporary environmental hygiene issues, such as the handling of toxic and plastic trash (Biswas et al. 2022b; Tripathi et al. 2024). The usage of temporally mismatched data sources limits several indices, which lowers the consistency and dependability of composite performance scores (Ghosh et al. 2022). Current frameworks (Mondal, 2022; Roy et al. 2023d; Tirkey et al. 2025) frequently rely on self-reported usage, which may be subject to social desirability bias, rather than clinical or bacteriological verification of water quality. Multi-methodological approaches that can synthesize complicated cross-sectoral interdependencies involving infrastructure, nutrition, and environmental health were lacking (Biswas et al., 2024).

Our study addresses these drawbacks. This study utilizes most recently available data from the NITI Aayog National Data and Analytics Platform (NDAP) to provide a nearly real-time assessment of sub-national trajectories aligned with 2030 goals. We overcome the limitations of single-sector studies by simultaneously evaluating 25 indicators across all three WaSH pillars: water (*Wat*), sanitation (*San*), and hygiene (*Hyg*). By including all 37 Indian States and UTs, the analysis provided a comprehensive national picture while maintaining the granularity necessary to understand sub-national variations. The study explicitly incorporates modern hygiene emergencies, including plastic and hazardous waste generation, to modernize the scope of sub-national WaSH assessments.

Table 1. Comparative analysis of relevant empirical studies concerning Water, Sanitation, and Hygiene (WaSH) analyses.

Study	Location	Study period	Dimensions	Drawback(s)
Chaudhuri & Roy (2017)	India (640 districts)	Census 2011, NSSO 69th (2012)	<ul style="list-style-type: none"> - water access (piped, improved source) - sanitation access (toilet types) - rural/urban inequality indices - spatial clustering 	<ul style="list-style-type: none"> - data was over a decade old (pre-SBM). - no hygiene/handwashing data in census. - failed to capture liters-per-day service levels. - Census/NSSO data now dated
Roy & Pramanick (2019)	India (national)	2000–2015	<ul style="list-style-type: none"> - composite SDG 6 index (6.1–6.6): quality, wastewater, and ecosystem health. 	<ul style="list-style-type: none"> - heterogeneous data sources (NSSO, CPCB, CGWB) limit index consistency.

			<ul style="list-style-type: none"> - composite SDG 6 index - safe and just operating space (SJOS) framework 	<ul style="list-style-type: none"> - national-level aggregation masks severe inter-state inequities. - pre-dates the flagship SBM-G Phase 2 and JJM initiatives.
Pradhan (2020)	Urban India (states)	2012 (NSSO 69 th Round)	<ul style="list-style-type: none"> - water proximity and source type - improved latrine access - garbage collection and drainage connectivity - disease prevalence (stomach, skin, malaria) 	<ul style="list-style-type: none"> - urban-only focus limits national generalizability. - data was significantly dated (2012) relative to current infrastructure. - disease outcomes were self-reported rather than clinically verified
Saroj et al. (2020)	6 Indian Metro Cities (Mumbai, Delhi, Chennai, Bangalore, Kolkata, Hyderabad)	2004–2012 (IHDS-1 & IHDS-2)	<ul style="list-style-type: none"> - availability index: source type, supply duration, toilet presence - accessibility/hygiene index: fetch time, purification, pouring methods - intra-city inequality (Gini/Theil indices) - wealth/slum/non-slum inequality 	<ul style="list-style-type: none"> - data was significantly dated (pre-SBM and JJM impacted) - metro focus ignores the growing peri-urban and rural sprawl - lacks bacteriological water quality verification
Sarkar & Bharat (2021)	India (states)	2014–2020	<ul style="list-style-type: none"> - SDG 6.1: Safe drinking water access (Har Ghar Jal) - SDG 6.2: Sanitation coverage & ODF status (SBM) - policy/ program alignment & systems-thinking approach 	<ul style="list-style-type: none"> - relying on secondary government dashboard data - progress assessment pre-dates NFHS-5 comprehensive household data - focuses on ‘access’ over service levels like liters-per-day

Biswas et al. (2022a)	India (28 states)	2011–2019	<ul style="list-style-type: none"> - water sustainability index (WSI) - biophysical: freshwater withdrawal, stress, wastewater treatment - social: open defecation, basic water, basic sanitation services - composite scoring (0-1) - SDG 6 alignment 	<ul style="list-style-type: none"> - high-level national aggregation hides local/district crises - significant data gaps for municipal wastewater treatment years - index performance criteria weighted subjectively via PCA/reliability models
Biswas et al. (2022b)	India (36 states/UTs)	2012–2020 (NSS 69/76, CGWB, SBM-G)	<ul style="list-style-type: none"> - SDG 6.1: improved water sources - SDG 6.2: toilets, ODF districts, school toilets - SDG 6.4/6.a: Liquid waste, groundwater extraction - Rural/urban/wealth quintile disaggregation 	<ul style="list-style-type: none"> - Dependent on secondary SBM/CGWB dashboard data - ‘Safely managed’ definitions constrained by survey variables - Limited to rural sector for 5 of 7 key indicators
Chouhan et al. (2022)	Odisha (58,000 schools across 30 districts)	2019-2021	<ul style="list-style-type: none"> - benchmarks: water supply, toilet facilities, and handwashing with soap - service quality: operations and maintenance (O&M), capacity building, and menstrual hygiene 	<ul style="list-style-type: none"> - focuses exclusively on school-level infrastructure, excluding household scales. - geographical scope limited to a single state (Odisha). - initial benchmarking relied on self-reported data by school stakeholders
Dadhich et al. (2022)	Phagi tehsil, Jaipur, Rajasthan (67 villages)	Dec 2019 – March 2020	<ul style="list-style-type: none"> - sub-indices: Water (source and quality metrics like TDS/F/Cl), sanitation (ownership, usage, cleanliness), and 	<ul style="list-style-type: none"> - micro-scale focus on a single tehsil limits generalizability. - small sample size (319 respondents). - significant identified gap between infrastructure

			hygiene (soap hand-wash)	ownership and actual usage
Das et al. (2022)	India (States grouped by water availability)	NFHS-4 (2015-16)	<ul style="list-style-type: none"> - water: regional availability index and household source access - sanitation: improved vs. unimproved latrine access - hygiene/disposal: safe disposal of child stool. 	<ul style="list-style-type: none"> - state-level aggregation of water availability indices masks severe intra-state district variation - hygiene metrics were narrow, relying largely on stool disposal practices - data pre-dates the Jal Jeevan Mission
Ghosh et al. (2022)	India (640 districts)	2011–2016 (Census 2011 & NFHS-4)	<ul style="list-style-type: none"> - WASH Poverty Index - water: access to untreated source and availability away from home - sanitation: presence of latrine, bathroom, and drainage. - hygiene: residence condition, separate kitchen, cooking fuel, and handwashing with soap - multidimensional poverty framework - Spatial autocorrelation (LISA) - hotspot/coldspot mapping 	<ul style="list-style-type: none"> - combines data from temporally mismatched sources (2011 Census and 2015-16 NFHS) - pre-dates major impacted of SBM Phase 2 and JJM - high sensitivity to indicator selection.

Mondal (2022)	India (36 states/UTs)	2012–2018 (NSSO 69th & 76th)	<ul style="list-style-type: none"> - latrine access (improved/unimproved) - spatial clustering of deprivation - socio-economic determinants (education, wealth) - rural/urban differentials 	<ul style="list-style-type: none"> - single-sector focus on sanitation; omits water and hygiene. - temporal gap excludes the 2019 ODF-declaration impact. - relied on self-reported usage which may suffer from social desirability bias.
Rani (2022)	India (States/UTs)	1981–2011 (Censuses)	<ul style="list-style-type: none"> - SDWSAAI Index: availability and accessibility - source types (tap, handpump, well) - rural-urban differential gap 	<ul style="list-style-type: none"> - heavily dated (last data point was 2011 census). - did not address sanitation or hygiene dimensions. - did not account for chemical water quality (arsenic/fluoride) or seasonal supply fluctuations.
Ghosh et al. (2023)	India (640 districts)	NFHS-4 (2015-16)	<ul style="list-style-type: none"> - improved drinking water sources (IDWS) - improved sanitation facilities (ISF) - social group disparities (SC/ST/OBC/General) - spatial inequality decomposition 	<ul style="list-style-type: none"> - pre-dates major SBM Phase 2 and JJM impacted. - completely excludes the ‘hygiene’ (handwashing) dimension. - relied on binary access metrics without water quality testing
Roy et al. (2023a)	India (56 cities)	NDAP NITI Aayog	<ul style="list-style-type: none"> - SDG 6 	<ul style="list-style-type: none"> - SDG focused analysis - Only included major Indian cities - Data only 2020-2021
Roy et al. (2023c)	India (707 districts)	NFHS-5 (2019-21)	<ul style="list-style-type: none"> - open defecation (OD) prevalence - socio-economic/demographic predictors (wealth, education) - spatial hotspot/coldspot (LISA) 	<ul style="list-style-type: none"> - focuses on a single outcome (OD) rather than a composite WaSH index - relied on self-reported behavior without observation - excludes physical water quality parameters

Roy et al. (2023d)	West Bengal (23 districts)	NFHS-5 (2019-21)	<ul style="list-style-type: none"> - improved water source & collection time - improved sanitation type (private/shared) - hygiene: handwashing (soap/water availability) - district ranking/comparison 	<ul style="list-style-type: none"> - single-state scope limits generalizability - did not include clinical testing for groundwater contaminants like arsenic - hygiene metrics limited to observation-at-site proxies
Vatsa et al. (2023)	India (640 districts)	NFHS-5 (2019-21) NFHS-4 (2015-16)	<ul style="list-style-type: none"> - water source type - sanitation facility type - handwashing practices - spatial effects modeling (BYM) on child health. 	<ul style="list-style-type: none"> - spatial lag not fully adjusted for micro-climates - Pre-SBM Phase 2 sanitation improvements - self-reported WASH practices - no water quality/continuity
Biswas et al. (2024)	India (640+ districts, 36 states/UTs)	NFHS-5 (2019-21)	<ul style="list-style-type: none"> - water: improved source and proximity - sanitation: latrine and drainage access - hygiene: handwash, kitchen, fuel, house type, electricity - SDG-6 progress tracking 	<ul style="list-style-type: none"> - district aggregation masks intra-district (caste/wealth) inequities - no clinical water quality parameters (e.g., arsenic) - hygiene index uses broad proxies like electricity/cooking fuel
Roy (2024)	Northeastern India (103 districts from 8 NER states)	NDAP NITI Aayog	- SDG 6	<ul style="list-style-type: none"> - SDG focused analysis - Data only 2021-2022

Tripathi et al. (2024)	90 tribal-dominated districts in India (ST population >50%)	2015-2020	<ul style="list-style-type: none"> - improved drinking water source - improved toilet facility access - handwashing facility with soap and water - open defecation (OD) prevalence - tribal/ non-tribal disparities 	<ul style="list-style-type: none"> - aggregated tribal districts mask intra-tribal heterogeneity - no water quality/source sustainability metrics - hygiene proxy (handwashing) only
Trivedy & Khatun (2024)	West Bengal (23 districts)	NFHS-5 (2019-21)	<ul style="list-style-type: none"> - Composite WASH Index (CWI): improved water, water on premises, improved sanitation, non-shared toilets, and handwash station with soap. - spatial clustering (Moran's I) 	<ul style="list-style-type: none"> - relied on household-level self-reported data without physical verification of water quality (e.g., arsenic/fluoride common in WB). - single-state focus limits generalizability to broader Indian socio-climatic zones. - cross-sectional design cannot capture seasonal variations in water availability.
Ashrit & Joshi (2025)	India (36 states/UTs); Rural-Urban focus	July–Dec 2018 (NSSO 76th Round)	<ul style="list-style-type: none"> - water: access, distance, sufficiency, scheme benefits - housing: structure, drainage, ventilation, scheme benefits - spatial clustering of deprivation - Rural-urban decomposition 	<ul style="list-style-type: none"> - relied on self-reported data; only 3% reported water scheme benefits - composite index excludes latrine/sanitation indicators - pre-dates full Jal Jeevan Mission (JJM) implementation
Biswas et al. (2025)	India (36 states/UTs, 707 districts)	1992–2021 (NFHS-1 to NFHS-5)	<ul style="list-style-type: none"> - Water Access Index (WAI): - improved source access - on-premises availability - <5 min round-trip access 	<ul style="list-style-type: none"> - excludes bacteriological/chemical quality testing - cross-sectional nature limits causal inference - excludes sanitation and hygiene components entirely

			<ul style="list-style-type: none"> - household water treatment - socio-economic determinants - urban/ rural disparities 	
Garai et al. (2025)	India (all states & UTs)	NDAP NITI Aayog	- SDG 6	<ul style="list-style-type: none"> - SDG focused analysis - Data only 2018-2020
Tirkey et al. (2025)	NER Indian states (n=8)	NFHS- 5 (2019- 21)	<ul style="list-style-type: none"> - improved water source access - improved sanitation facility access - handwashing station availability (soap/water) 	<ul style="list-style-type: none"> - regional focus limits national-level comparisons - omits bacteriological/chemical water quality metrics - self-reported survey data prone to social desirability bias

3. Methodology:

We have composed a dataset of 25 indicators (**Table 2**) related to water, sanitation, and hygiene (WaSH) for all states & UTs of India (**Table 3**). To handle incomplete entries (n=35, 3.58%) in our dataset from the NITI Aayog NDAP database, we performed data imputation using the Iterative Imputer technique, which was a variation of the Multivariate Imputation by Chained Equations (MICE) algorithm (Van Buuren & Groothuis-Oudshoorn, 2011), rather than univariate mean imputation, as the latter can reduce variance and distort correlations between developmental indicators. The algorithm follows a ‘round-robin’ strategy. For each variable containing missing data, a regression model (Bayesian Ridge Regression) was fitted using the other variables as predictors. The missing values were then predicted based on this model. This probabilistic approach was particularly suitable for datasets with multicollinearity (where indicators might be correlated) as it introduced regularization parameters during the estimation. The analysis was implemented using the ‘*Scikit-learn*’ machine learning library in Python.

The linear relationships between the 25 indicators were statistically quantified using Pearson’s correlation (**Fig 1**). It produced an organized matrix of coefficients and significance levels that showed the direction and strength of inter-indicator interdependence, emphasizing important national trends like trade-offs and synergies. The ‘*Hmisc*’ package was used in the analysis to compute correlation matrices and p-values, and ‘*ggplot2*’ and ‘*ggdendro*’ were used to show these connections.

A network analysis approach was used to investigate the structural links among indicators. Each indication was regarded as a node in this, and an edge (connection) represents the statistical relationship between 2 indicators. For graph layout, the Fruchterman-Reingold force-directed

algorithm was used. Clusters and structural patterns in the data were automatically revealed by this technique, which places nodes with stronger connections closer together. To quantify the relative importance of each indicator within the network topology, three standard centrality metrics were calculated:

- (a) Degree centrality, i.e., the count of direct connections a node had to other nodes. Indicators with a high degree centrality function as ‘hubs’, suggesting they were central to the interconnectedness of the system.
- (b) Betweenness centrality, i.e., the frequency with which a node acted as a bridge along the shortest path between two other nodes. High betweenness indicating an indicator’s potential role as a connector or ‘gatekeeper’ between different clusters of variables.
- (c) Closeness centrality, i.e., the inverse of the average shortest path distance from a node to all other nodes, indicating how ‘close’ or accessible an indicator was to the entire network. The analysis utilized ‘*igraph*’ for network calculation.

To understand the efficiency of decision making units (DMUs, here Indian states & UTs), we have performed output-oriented Slack-Based Measure (SBM) data envelopment analysis (DEA) using variable return to scale (VRS). The water (Wat) and sanitation (San) infrastructure were the ‘foundations’ that enable hygiene (Hyg) outcomes, meaning one cannot practice effective hygiene (output) without the physical means of water and sanitation (inputs). We have used water & sanitation as inputs (8 indicators, viz., San2, San4, San6-8, Wat1, Wat4, Wat7), and hygiene as output (4 indicators, viz., Hyg3-5, Hyg7), chosen via PCA analysis. We have used the ‘*deaR*’ package for this.

Hierarchical clustering analysis (HCA) was implemented to objectively group Indian States and UTs based on similarities in their multi-sectoral WaSH profiles, revealing regional performance tiers without predefining the number of categories. It provided a hierarchical taxonomy of regional performance, identifying ‘super clusters’ of high-performing entities versus isolated outliers facing unique topographical or developmental barriers. Unlike non-hierarchical methods that require a fixed k , HCA’s tree-based structure allows for the discovery of nested sub-groups, making it more suitable. The ‘*pheatmap*’ package was used in this analysis.

The high-dimensional WaSH dataset was reduced to a few key axes of variation using principal component analysis (PCA), which made it possible to identify the most significant ‘statistical anchors’ that influence national performance disparities. It efficiently distinguishes infrastructure-dominant drivers from secondary axes by calculating indicator contribution scores and state-wise principal component (PC) loadings. This approach prevents information loss when analyzing 25 different metrics since it takes into account variable interdependencies and weighting based on actual data variation, making it preferable than basic indexing. PCA dimensions were calculated using the ‘*factoextra*’ package.

The WaSH dataset had undergone a multi-level Theil index decomposition, where larger values reflect both the contribution of individual variables to the total sectoral inequality and greater regional disparity. The Theil index allows us to partition inequality into the following:

- (a) between-group inequality (differences in WaSH performance between the categories),
- (b) within-group inequality (variation within a specific category),

(c) sensitivity to extremes: Our dataset contains significant variations (e.g., Hyg1: 0.0004 → 50.11, and San8: 0.02 → 18.93). Theil was more sensitive to the ‘tails’ (extreme outliers), which was critical for WaSH indicators where the goal was often to identify states being ‘left behind’. The formula for the Theil index (T) for n states / UTs with indicator values x_i and mean μ was:

$$T = \frac{1}{n} \sum_{i=1}^n \left(\frac{x_i}{\mu} \right) \ln \left(\frac{x_i}{\mu} \right)$$

This dual-metric approach was chosen to evaluate both the average level of WaSH achievement (MIS) and the internal balance between several indicators (EIS), guaranteeing that high scores were not solely driven by a single ‘hero indicator’. It divides states into performance quadrants, differentiating between ‘skewed performers’ (achieve high averages despite major internal disparities) and ‘balanced leaders’ (uniform progress). By punishing indicator volatility, which was crucial for finding ‘success silos’ where infrastructure exists without corresponding functional services, it provided a more nuanced view than normal averaging. Custom R functions were used for the analysis, utilizing ‘*tidyverse*’ for data processing and ‘*ggrepel*’ for labeling regional performance.

To determine whether a state’s WaSH status was influenced by its own policies or by geographical spillovers from neighbors, spatial additive decomposition (SAD) was selected to separate the effects of localized administrative actions from the effects of geographic proximity. It produced particular local and spatial deviation ratings that showed performance ‘sinks’ between high-achieving states and spatially ‘contagious’ cold areas in regions. Because the standard Logarithmic Mean Divisia Index (LMDI) required positive values (because logarithms of negatives were undefined) and a time dimension, standard multiplicative LMDI, which employs logarithms, was unable to handle our information. For this, we have utilized the ‘*pacman*’ package.

A benchmarking method called relative performance analysis was chosen to measure each state’s or UT’s deviation from the national average, giving a clear picture of which areas were leading or trailing in particular WaSH categories. It identified particular sub-sector constraints, such as the pervasive rural piped water connectivity gap, by producing deviation bands that showed significant outperformers and crucial laggards. It makes it easier to identify ‘major laggards’ by focusing performance around a zero-benchmark (the national mean), providing a more user-friendly tool for policy targeting than raw percentage scores. Custom R functions were used to carry out the analysis.

Table 2. List of water, sanitation & hygiene (WaSH) indicators included in this study.

Indicator (Abbreviation)	WaSH dimension	Justification
Decadal change in extent of water bodies within forests from 2005 to 2015 (%) (<i>Wat1</i>)	Water	This acted as a proxy for environmental health and natural recharge capacity, reflecting long-term ecological sustainability.

Blocks/ mandals/ taluka over-exploited, % (<i>Wat2</i>)	Water	It provided spatial granularity of water stress, identifying localized areas where the water table is critically endangered.
Ground water withdrawal against availability, % (<i>Wat3</i>)	Water	It quantified the intensity of groundwater use relative to its natural replenishment, which is a key measure of water resource exhaustion.
Industries (17 category of highly polluting industries/ grossly polluting/ red category of industries) complying with waste water treatment as per CPCB norms, % (<i>Wat4</i>)	Water	It monitors the ‘Quality’ aspect of water by tracking the prevention of toxic runoff into communal water sources.
Population having safe and adequate drinking water in rural areas, % (<i>Wat5</i>)	Water	It measures the standard ‘access’ outcome for the most vulnerable population segment in terms of both health and availability.
Rural households getting safe and adequate drinking water within premises through Piped Water Supply (PWS), % (<i>Wat6</i>)	Water	This tracks the transition from ‘source-based’ to ‘service-based’ delivery, reflecting infrastructural modernization.
Rural population having improved source of drinking water, % (<i>Wat7</i>)	Water	It evaluates the baseline quality of water infrastructure, distinguishing between protected sources and those prone to contamination.
Schools with access to basic infrastructure (electricity, and drinking water - both), % (<i>Wat8</i>)	Water	It assesses the presence of essential utilities in institutional settings, which directly influence public health education and attendance.
Stage of groundwater extraction, % (<i>Wat9</i>)	Water	This serves as a consolidated metric for the overall hydrological sustainability of a state or UT.
Districts verified to be ODF (SBM-G), % (<i>San1</i>)	Sanitation	It validates the administrative success of the Swachh Bharat Mission (Grameen) in achieving community-wide behavior change.
Individual household toilets constructed against target (SBM-G), % (<i>San2</i>)	Sanitation	This measures the momentum and logistical efficiency of constructing physical infrastructure in rural areas.
Individual household toilets constructed against target (SBM-U), % (<i>San3</i>)	Sanitation	It tracks the progress of urban sanitation infrastructure in meeting the specific density challenges of cities.
Rural households with individual household toilets, % (<i>San4</i>)	Sanitation	It provided the ‘ground truth’ of actual toilet ownership, independent of government targets or verification statuses.

Urban households with drainage facility, % (<i>San5</i>)	Sanitation	It is essential for assessing ‘liquid waste management’, as toilet access is ineffective without functional wastewater conveyance.
Wards with 100% door to door waste collection (SBM-U), % (<i>San6</i>)	Sanitation	It monitors the efficiency of the primary link in the urban solid waste management chain.
Wards with 100% source segregation (SBM-U), % (<i>San7</i>)	Sanitation	It measures the level of community participation and technical viability of downstream waste processing.
Plastic waste generated per 1,000 population (ton/year) (<i>San8</i>)	Sanitation	This quantified the modern ‘sanitation load’, reflecting consumption patterns and potential environmental clogging risks.
Hazardous waste generated per 1,000 population (metric ton/year) (<i>Hyg1</i>)	Hygiene	This identified the chemical and industrial hygiene burden that poses a specialized threat to community health.
Installed sewage treatment capacity as a proportion of sewage created in urban areas (%) (<i>Hyg2</i>)	Hygiene	It reflected the technological ‘maturity’ of a region in mitigating the environmental impact of urban fecal matter.
Bio Medical Waste (BMW) treated to total quantity of BMW generated (<i>Hyg3</i>)	Hygiene	It is crucial for preventing the spread of infectious diseases from healthcare facilities to the public domain.
Children under 5 years who are stunted, % (<i>Hyg4</i>)	Hygiene	It acted as the ultimate ‘impact indicator’, linking long-term sanitation and hygiene failures to the physiological development of children.
Children under 5 years who are underweight, % (<i>Hyg5</i>)	Hygiene	It serves as a sensitive ‘real-time’ indicator of the intersection between poor hygiene, recurrent infections, and nutrition.
Municipal Solid Waste (MSW) processed to the total MSW generated (SBM-U), % (<i>Hyg6</i>)	Hygiene	This measures the final efficiency of the solid waste cycle, determining the amount of waste that is neutralized versus that which is landfilled.
Schools with functional girls’ toilet, % (<i>Hyg7</i>)	Hygiene	This is a specific indicator of gender-sensitive hygiene, directly impacting female education and menstrual health management.
Quantity of hazardous waste recycled/ utilized to total hazardous waste generated, % (<i>Hyg8</i>)	Hygiene	This evaluates the ‘circularity’ and sustainability of industrial waste management practices.

Table 3. List of Indian states and UTs included in this study.

Area	Identity	Area	Identity
Andhra Pradesh (AP)	State	Punjab (PB)	State
Arunachal Pradesh (AR)	State	Rajasthan (RJ)	State
Assam (AS)	State	Sikkim (SK)	State

Bihar (BR)	State	Tamil Nadu (TN)	State
Chhattisgarh (CH)	State	Telangana (TS)	State
Goa (GA)	State	Tripura (TR)	State
Gujarat (GJ)	State	Uttar Pradesh (UP)	State
Haryana (HR)	State	Uttarakhand (UK)	State
Himachal Pradesh (HP)	State	West Bengal (WB)	State
Jharkhand (JH)	State	Andaman-Nicobar (AN)	UT
Karnataka (KA)	State	Chandigarh (CH)	UT
Kerala (KL)	State	Dadra-Nagar Haveli (DH)	UT
Madhya Pradesh (MP)	State	Daman-Diu (DD)	UT
Maharashtra (MH)	State	Delhi (DL)	UT
Manipur (MN)	State	Jammu-Kashmir (JK)	UT
Meghalaya (ML)	State	Ladakh (LA)	UT
Mizoram (MZ)	State	Lakshadweep (LD)	UT
Nagaland (NL)	State	Puducherry (PY)	UT
Odisha (OR)	State		

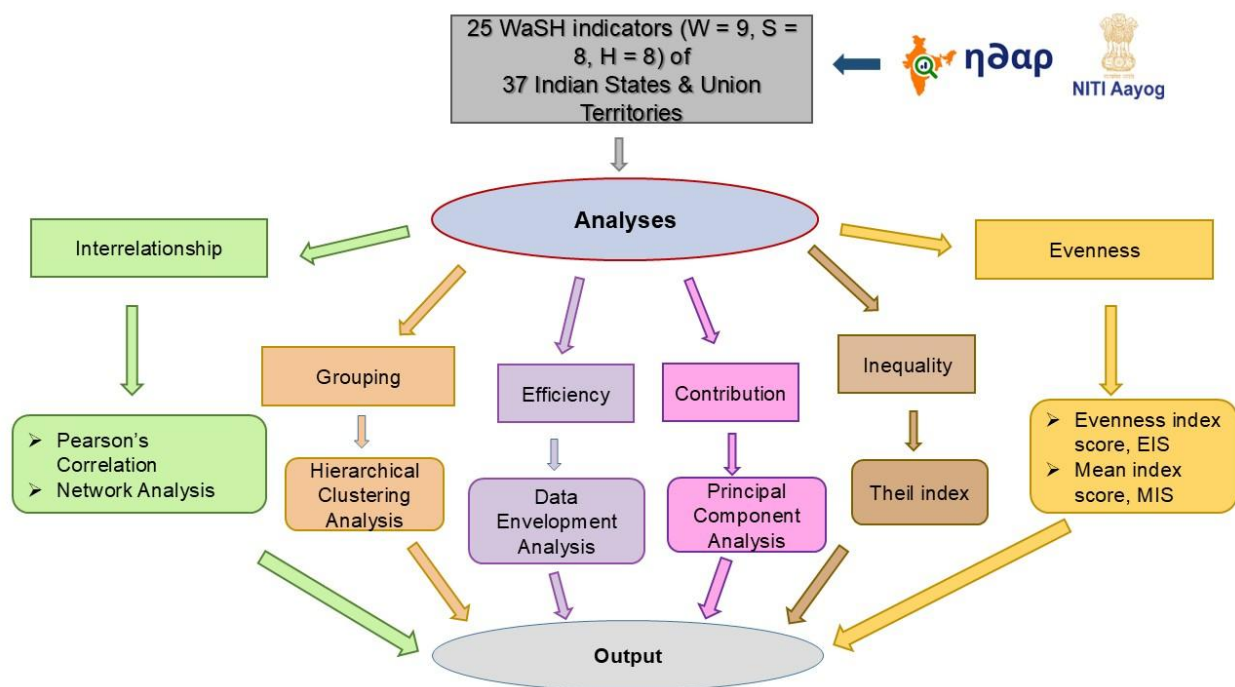


Figure 1. Integrated multi-methodological framework for sub-national WaSH assessment in India.

This schematic outlines the analytical workflow used to evaluate 25 indicators (9 Water, 8 Sanitation, and 8 Hygiene) sourced from the NITI Aayog National Data and Analytics Platform (NDAP). The framework integrates 6 advanced analytical streams, interrelationship (Pearson's Correlation, Network Analysis), grouping (Hierarchical Clustering), efficiency modeling (SBM-DEA), variance contribution (PCA), inequality decomposition (Theil index), and performance-

evenness balancing (MIS, EIS), to synthesize a comprehensive profile for 37 Indian States and UTs.

4. Results:

4.1. *Pearson's correlation:*

The availability of specialized girls' restrooms and access to basic utilities in schools (Hyg7↔Wat8) were nearly perfectly correlated ($r=0.948$, $p<0.001$) across the entire WaSH sector, indicating integrated infrastructure design (i.e., institutional synergy). Door-to-door waste collection efficiency (San6) was the primary driver ($r=0.937$, $p<0.001$) for successful source segregation at the ward level (San7) (i.e., urban waste chain coupling). The over-exploited blocks (Wat2) were a direct, strong predictor ($r=0.863$, $p=0.003$) of the stage of groundwater extraction (Wat9) in a region (water resource exploitation linkage). Stunting and underweight indicators (Hyg4↔Hyg5) moved in tandem (i.e., child health cluster) ($r=0.838$, $p=0.005$), reflecting generalized nutritional and sanitation-hygiene deficiencies. Wat3↔Wat9 had a correlation ($r=0.845$, $p<0.001$) much stronger than the national average ($r=0.44$). It means in Indian states (**Fig 2a, Supplementary File 1, Supplementary File 10 S1-S9**), groundwater withdrawal was a far more dominant factor in extraction stages compared to UTs (**Fig 2b, Supplementary File 1**).

In the water sector, consistent with total WaSH findings, the stage of extraction (Wat9) was purely driven ($r=0.863$, $p=0.003$) by over-exploited blocks (Wat2). High groundwater withdrawal volumes (Wat3) were associated ($r=-0.685$, $p=0.041$) with lower access to improved drinking water (Wat7), suggesting depletion compromises source reliability (i.e., quality vs. quantity conflict). In the sanitation sector, San6↔San7 had the most dominant trend; waste processing (San7) relied entirely ($r=0.937$, $p<0.001$) on the efficiency of this urban waste duo (i.e., collection-segregation loop).

In the hygiene sector, Hyg7↔Hyg8 had the strongest negative correlation ($r=-0.98$, $p<0.001$) in the hygiene; indicating a resource or policy trade-off between school-level hygiene (Hyg7) and industrial hazardous waste recycling (Hyg8) (i.e., hygiene paradox). BMW treatment and school girls' toilets (Hyg3↔Hyg7) were highly correlated ($r=0.911$, $p<0.001$), likely due to centralized public health infrastructure funding. Effective BMW treatment (Hyg3) negatively correlates ($r=-0.821$, $p=0.007$) with poor hazardous waste recycling (Hyg8), suggesting divergent industrial vs. medical waste priorities (i.e., specialized waste conflict).

4.2. *Network analysis:*

In the total WaSH sector, both 'schools with electricity/water' and 'functional girls' toilets' (Wat8↔Hyg7) exhibited the highest degree (6) and betweenness (13), serving as the primary structural hubs for integrated WaSH. Urban drainage (San5) holds a high degree (6) and betweenness (1), acting as a vital link between sanitation infrastructure and broader public health outcomes. The modest degree (3) and significant betweenness (8) of door-to-door garbage collection (San6) indicate that it serves as a crucial gatekeeper for the flow of waste management (i.e., sanitation pivot). The most significant bridge for cross-sector policy was the school sanitation (Hyg7) node, which had a betweenness of 13. Improving girls' restrooms probably unlocks

improvements in several other variables. Although both were related, the withdrawal rate (Wat3) was a more important strategic control point than the extraction stage, according to groundwater's (Wat3) high betweenness (9) compared to extraction (Wat9). With a low degree (2) and high betweenness (8), rural drinking water PWS (Wat5) appears to be an 'exclusive bridge' that links particular rural clusters to the main network.

Groundwater withdrawal (Wat3), which drives all other water measures, was the most linked node in the water sector (degree=7) (**Fig 2c, Supplementary File 2**) and serves as the network's center or regulatory anchor (closeness=0.44). Changes here spread through the water sector more quickly than any other indicator, with improved rural water sources (Wat7) having the highest closeness (0.51). As a link between industrial output and environmental water health, industrial CPCB compliance (Wat4) had a high betweenness (3). Wat7's combination of degree (6), betweenness (8), and closeness (0.51) makes it the most statistically significant indicator (network leader) for the water sector.

In the sanitation sector (**Fig 2d, Supplementary File 2**), the SBM-U core, i.e., urban waste collection and segregation (San6-7) formed a perfectly balanced hub system with identical degrees (5). Rural household toilets (San4) exhibited the highest closeness (2.17) and betweenness (7), making it the 'power node' of the sanitation network. Urban drainage (San5) and plastic waste generation (San8) were tightly coupled (i.e., waste-drainage link), both showed high closeness (>1.38). San4's closeness of 2.17 was exceptional, suggesting that rural toilet coverage (San4) was the most 'reachable' and influential node for total sanitation health. Plastic waste's (San8) high closeness suggested that plastic waste generation was a highly sensitive indicator that reflected the performance of the entire sanitation chain.

In the hygiene sector (**Fig 2e, Supplementary File 2**), hygiene's 4 nodes (viz., Hyg2, Hyg5-7) share the maximum degree (7), creating a highly 'braided' network where nutrition, waste processing, and infrastructure were inseparable. Solid waste processing (Hyg6) holds the highest betweenness (3) and high closeness (0.85), acting as the central nervous system (or heart) of the hygiene network. Girls' toilets (Hyg7) remain a dominant hub (degree=7), showed consistent importance across sectors (i.e., WaSH-education-gender nexus). Underweight children (Hyg5) showed high connectivity (degree=7), functioning as a primary outcome node for hygiene interventions. Recycling efficiency (Hyg8) was identified as a strategic bridge for hazardous waste management due to its high betweenness (2) in relation to its degree.

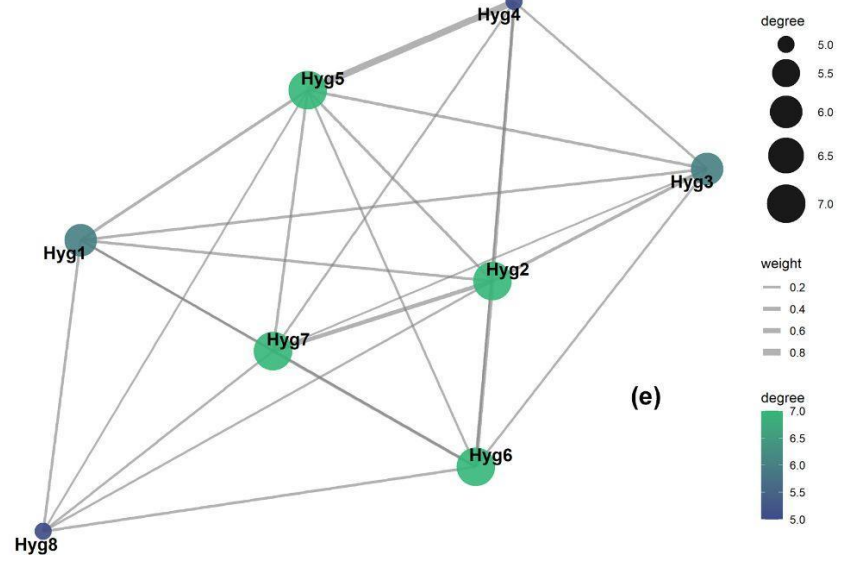
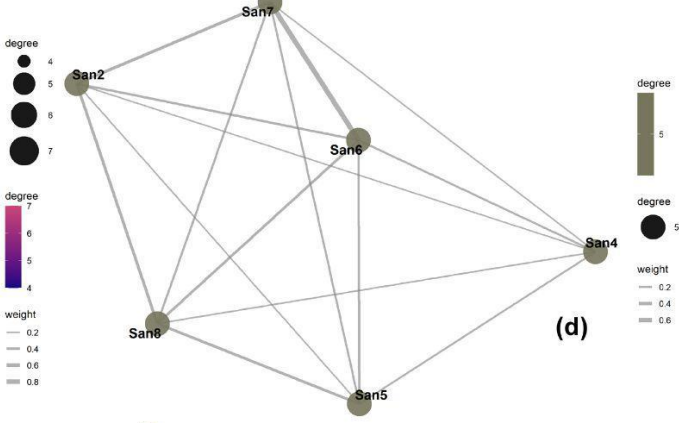
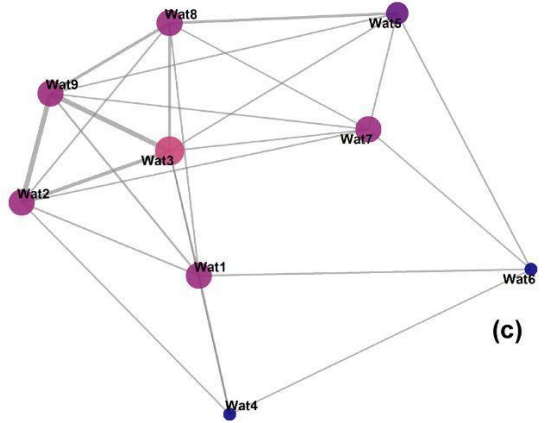
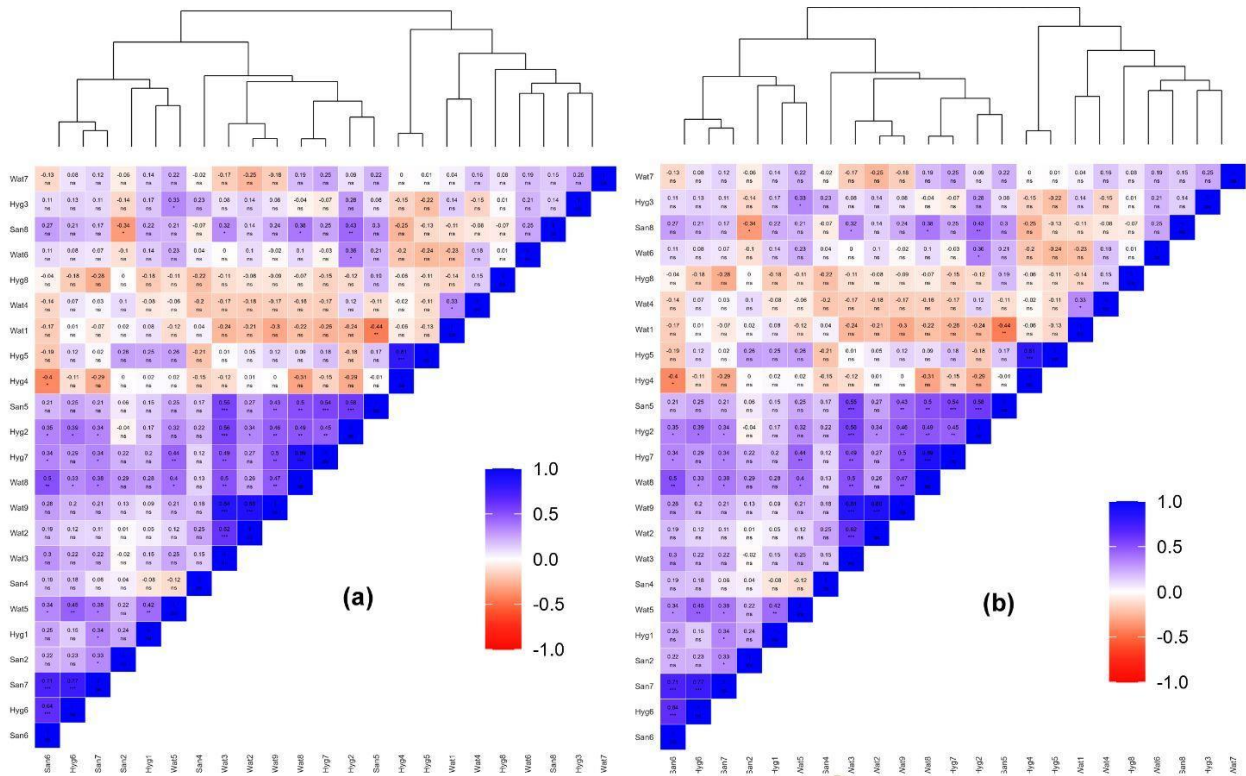


Figure 2. Statistical interdependencies and structural relationships among WaSH indicators. Panels (a) and (b) present Pearson’s correlation heatmaps for 25 indicators across 28 Indian states and 9 UTs, respectively, identifying critical synergies such as the institutional link between school utilities (Wat8) and girls’ toilets (Hyg7). Panels (c), (d), and (e) utilize network maps to visualize the internal topology of the water (Wat), sanitation (San), and hygiene (Hyg) domains. Node size and proximity represent degree centrality and the strength of statistical links, identifying ‘power nodes’ like rural toilet coverage (San4) and ‘structural hubs’ such as solid waste processing (Hyg6).

4.3. Hierarchical clustering analysis (HCA):

Cluster 1, which included Andhra Pradesh, Gujarat, Tamil Nadu, and UTs like Chandigarh and Daman-Diu, accounted for 51% (n=19) of all WaSH sector entities (**Supplementary File 3, Supplementary File 10 S10-S18**), demonstrating a widespread national convergence in integrated WaSH performance (i.e., mega cluster). The NE states (e.g., Arunachal Pradesh, Assam), eastern states (e.g., Bihar, West Bengal), and mountain UTs (e.g., Jammu-Kashmir, Ladakh) that shared topographical and infrastructure issues were grouped together in cluster 2 (i.e., eastern Himalayan sub-group). A close-knit cluster 3 was created by Delhi, Haryana, Punjab, and Rajasthan, indicating a regional pattern in the North (also known as the Northern Belt), where WaSH was influenced by urban-industrial elements. With a merging height far greater than the others, Puducherry stood out in cluster 4, indicating a distinct WaSH model that was at odds with both Delhi and Chandigarh.

Manipur, Mizoram, Nagaland, and Meghalaya formed a highly tight cluster 3 in the water sector (**Fig 3a, Supplementary File 3**), which probably reflected the region’s distinct high-rainfall/hilly topography water management profile (i.e., NE water quad). Cluster 4 (e.g., Dadra-Nagar Haveli, Delhi, Haryana, Punjab, Rajasthan, Jammu-Kashmir) found a belt of states/UTs that were frequently linked to complex irrigation requirements or groundwater depletion (i.e., water stress-management belt).

The ‘sanitation leaders’ in the sanitation sector (**Fig 3b, Supplementary File 3**) were represented by cluster 1 (19 entities), which included early-adopter UTs like Chandigarh and Daman-Diu (i.e., ‘SBM core’) and states like Gujarat, Maharashtra, and Karnataka. Goa and Delhi formed a close-knit cluster 3, demonstrating a distinctive pattern in which highly urbanized locations share particular sanitation issues (such as septage management versus sewerage) (i.e., urban sanitation conundrum). The ‘Gangetic sanitation belt’, which lags behind the SBM core, was represented by Bihar, Jharkhand, and Uttar Pradesh, which were still locked in cluster 2.

In the hygiene sector (**Fig 3c, Supplementary File 3**), cluster 4 (10 entities, including Chhattisgarh, Gujarat, Maharashtra, and Uttar Pradesh) showed a massive trend, indicating that even economically strong states, such as Gujarat and Maharashtra, lag in the hygiene sector (i.e., ‘hygiene gap’ group). Mountain cultures in cluster 2 (e.g., Arunachal Pradesh, Jammu-Kashmir, Ladakh, Meghalaya, Manipur, Mizoram, Nagaland, Tripura, and Telangana) had a significant regional trend of maintaining similar cleanliness practices (i.e., Himalayan / NE hygiene group). Kerala-Assam-Bihar’s unusual grouping persists in cluster 3, suggesting a robust (if strange)

statistical relationship in their hygiene metrics. Andaman-Nicobar, Chandigarh, Daman-Diu, Dadra-Nagar Haveli, Delhi, and Lakshadweep formed a massive cluster 1 (66% of UTs), showed hygiene was more standardized among UTs than among states (i.e., ‘big 6’ hygiene core).

4.4. Principal component analysis (PCA):

In the PCA of all WaSH indicators (**Fig 3d, Supplementary File 4, Supplementary File 10 S19-S30**), school infrastructure (Wat8) and ODF districts (San1) showed the highest identical contributions (8.75%) in PC1 (25.01% var., infrastructure dominance), indicating that national WaSH variance was primarily driven by target-based school and community infrastructure. High positive indicator scores for Punjab and Haryana on PC1 correlate with high infrastructure achievement, whereas negative scores for Meghalaya and Nagaland indicate significant developmental lags. The PC1 variance rose to 26.64%. While it was a PC1 driver nationwide, urban drainage (San5) became a major contributor to PC2 in States (12.27%), indicating that drainage was a ‘local success’ story for States rather than a national trend. The logistical effectiveness of smaller administrative units was showed in the door-to-door collection (San6) contribution, which was almost three times more than in the national model. Waste management behavior was found to be the secondary differentiator for UTs, with source segregation (San7) dominating PC2 (17.13%). Delhi was a structural anomaly for the UT group, scoring exceptionally high on the urban waste axis.

Groundwater extraction (Wat9) and withdrawal (Wat3) were the most important water-specific contributors to PC1 in the PCA of water sector indicators (**Supplementary File 4**) at the national scale, emphasizing resource dependency. Forest water change (Wat1) was a major loader of PC2 (16.33%), separating mountainous and forest-rich regions from the plains (i.e., Himalayan/environmental variance). The extraction stage (Wat9) was a much stronger driver for states than UTs, reflecting the agricultural economic base. States such as Haryana and Punjab showed extremely positive scores for PWS (Wat6), separating them from the ‘state average’ zone. The contribution of school water (Wat8) reaches a peak of 10.35%, confirming that state-level water policy was most effective when channeled through schools. Arunachal Pradesh showed a severe negative loading on water extraction metrics, identifying it as a unique ‘unexploited but infrastructure-poor’ outlier (i.e., NER coldspot). Improved water source (Wat7) was nearly uniform across UTs, leading to almost zero contribution to the variance. The total absence of Wat2 and Wat3 from the top PC1 loadings confirmed that UTs were not driven by groundwater withdrawal concerns (i.e., non-agrarian). School infrastructure (Wat8) remained a contributor, showed that even in urban UTs, school-based infrastructure was a benchmark for water success. Andaman-Nicobar scores negatively on extraction metrics compared to the high-extraction city-states (Delhi and Chandigarh).

In the PCA of sanitation sector indicators (**Supplementary File 4**), ODF (San1) and urban toilets (San3) were the primary sanitation drivers of PC1, reflecting the success of mission-mode construction. Rural toilets (San4) often load inversely to urban drainage (San5) in scores, showed that states often excel in one but lag in the other (i.e., rural-urban gap). Urban drainage (San5) contribution increased to 12.27% on PC2, identifying it as the primary hurdle (i.e., core differentiator) for large-state sanitation. ODF (San1) showed near-zero variance in many states, indicating that ‘ODF status’ was no longer a useful statistical differentiator between high-

performing states. Waste collection (San6) loading was lower in states than UTs, reflecting the difficulty of implementing door-to-door services in rural areas. Nagaland and Meghalaya showed extremely negative sanitation scores, pulling the PC1 axis toward the infrastructure deficit (i.e., NER sanitation link). Waste collection (San6) and urban toilets (San3) contributed over 30% of the PC1 variance combined (i.e., urban efficiency benchmark), a profile unique to UTs. Unlike States, drainage (San5) was a primary PC1 loader for UTs, indicating that it was an ‘achieved standard’ rather than a ‘secondary challenge’. UTs were the only entities making discernible progress in this area, as seen by the fact that source segregation (San7) loads significantly on PC2 (14.79%). Plastic waste was the key remaining sanitation frontier for UTs, as evidenced by the fact that plastic management (San8) was a significant PC3 loader.

Hazardous waste recycling (Hyg8) was the single biggest contributor to Dimension 2 (39.7%) in the PCA of hygiene sector indicators (**Supplementary File 4**), demonstrating that industrial capacity drives hygiene variance. The school-sanitation-hygiene relationship was reinforced by girls’ restrooms (Hyg7), a major PC1 loader. Dimension 3 was largely influenced by stunting (Hyg4) and underweight (Hyg5), which showed that infrastructure (PC1) and nutritional outcomes were unrelated (i.e., the nutrition-health gap). States with significant urban investment in wastewater treatment were grouped together by strong positive loadings for sewage treatment (Hyg2). Stunting (Hyg4) highlighted the public health concern in rural areas and contributed more to the state-only dimensions than to the national model. Sewage capacity was the main distinction between ‘developed’ and ‘developing’ states, as evidenced by the fact that sewage treatment (Hyg2) was a top PC1 driver for states (8.63%). Hazardous waste (Hyg8) had a much lower contribution in the state model, as recycling was concentrated in a few industrial hubs (Gujarat, Maharashtra). Girls’ toilets (Hyg7) accounts for 19.06% of the primary variance, indicating that UT hygiene success was defined by school facilities. Industrial recycling (Hyg8) remained a major factor for industrial UTs, such as Daman-Diu.

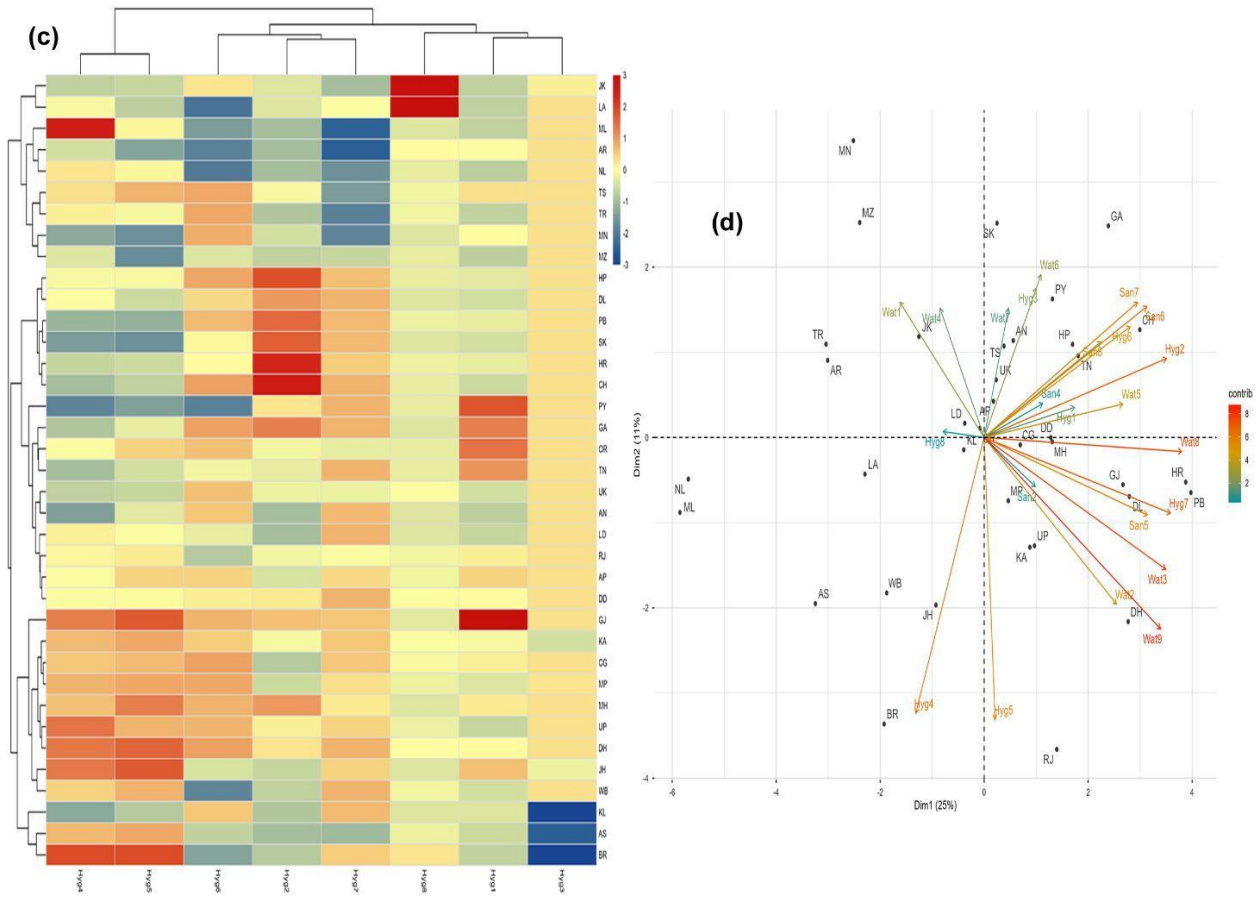
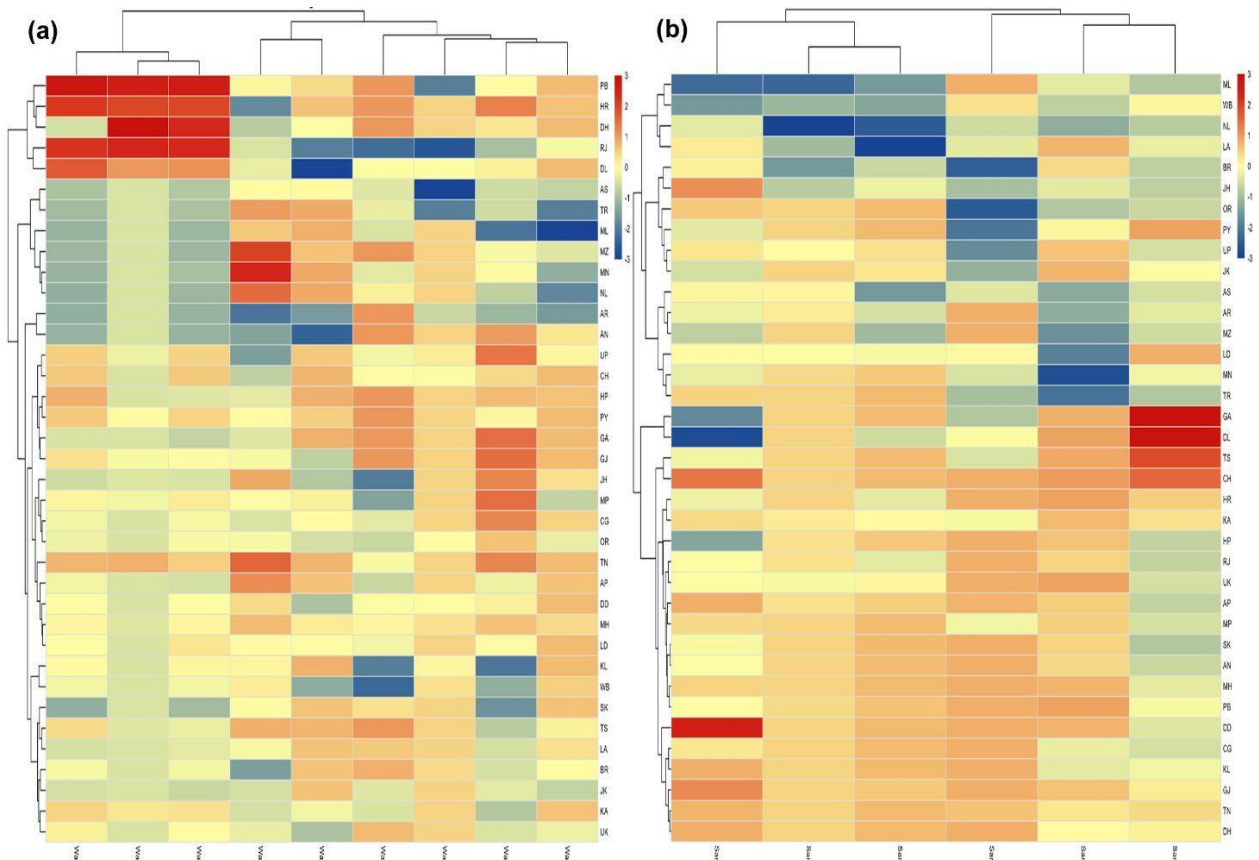


Figure 3. Hierarchical taxonomy of regional performance and multivariate drivers of WaSH variance.

Heatmaps with dendrograms (a), (b), and (c) display Hierarchical Clustering Analysis (HCA) results for water, sanitation, & hygiene sectors, grouping states and UTs into performance-based tiers such as the ‘SBM core’ leaders and the ‘Eastern Himalayan’ laggard sub-groups.

Panel (d) illustrates the Principal Component Analysis (PCA) biplot, where vector direction and length indicate the contribution of specific indicators to the primary axes of variance (PC1/PC2). The biplot reveals how infrastructure-dominant drivers, such as ODF status (San1), separate high-performing Northern states from infrastructure-poor outliers in the NER.

4.5. Data envelopment analysis (DEA):

Average VRS efficiency was 0.923, indicating a high level of operational efficiency relative to individual scales, although output gaps remain, as expected under VRS. Efficient frontier was 1.0 for 28 entities (out of 37). Inefficient DMUs were: Manipur (0.6217), Kerala (0.6385), Mizoram (0.7204), Tamil Nadu (0.7613), and Jammu-Kashmir (0.7903) (**Fig 4a, Supplementary File 5**). Nearly 75% of DMUs were on the frontier, indicating that when the scale was flexible, most states perform optimally relative to their peers.

In the total WaSH sector (**Supplementary File 5**), inefficient DMUs showed massive shortfalls in hygiene outputs rather than over-utilization of inputs (e.g., Manipur required a 26.8% increase in functional girls’ toilets (Hyg7) to reach the frontier). This means that resource availability was not the bottleneck; rather, the conversion of infrastructure into specific public health outcomes (hygiene) was lagging. Several states showed excessive slack in decadal forest water body change (Wat1) (e.g., Manipur, 78.4; and Mizoram, 47.2). This means that environmental water inputs (forest water bodies) were frequently disconnected from the efficiency of service delivery in the hygiene sector. A few states act as the ‘standard’ (i.e., reference DMUs) for the rest (e.g., Punjab, Gujarat, and Goa appear most frequently in the reference DMUs) (**Fig 4b, Supplementary File 5**). This means that these states provide the most robust operational models for others to emulate under varying scale conditions. Inefficient states like Kerala and Tamil Nadu have high inputs but fail to produce frontier-level hygiene outputs. This means that high-performing states in general development (like Kerala) were penalized by SBM-VRS for not reaching the extreme output heights expected of their high input levels. Kerala was highly inefficient (VRS=0.638) despite high inputs because its stunting/underweight outputs (Hyg4/Hyg5) were lower than what the model predicts for its infrastructure level (i.e., Kerala paradox). Bihar was a 1.0 efficient peer (i.e., efficiency leader) for industrialized states like Karnataka. This means that Bihar’s ‘lean’ input-to-output ratio sets a high efficiency bar for wealthier states. Andhra Pradesh serves as the primary peer ($\lambda=0.51$) for Karnataka, indicating that Karnataka’s pathway to efficiency lies in mimicking Andhra Pradesh’s specific output mix.

In the water sector (**Supplementary File 5**), inefficient states often over-extract groundwater (Wat9) relative to their hygiene outputs (e.g., Jammu-Kashmir needs to reduce the stage of extraction (Wat9) by 5.0 points to align with its peer, Himachal Pradesh). PWS (Wat6) showed high variability among inefficient states (e.g., Jammu-Kashmir at 77.8% vs. targets of 91.7%). Manipur showed a massive 96.5% input slack (i.e., water redundancy) in Wat1. This

means that large forest-based water gains in Manipur were not currently contributing to its operational efficiency in terms of hygiene. Andhra Pradesh serves as the primary benchmark for Karnataka. This means that Andhra Pradesh's balance of PWS (Wat6) and industrial compliance (Wat4) should be the target profile for its neighbors. Inefficient DMUs, such as Jammu-Kashmir, have a target to adjust groundwater extraction (Wat9) but focus primarily on output expansion. This means that water resource management was treated as a fixed constraint that must be matched by higher output.

In the sanitation sector (**Supplementary File 5**), slacks in door-to-door collection (San6) were a primary bottleneck for Manipur and Jammu-Kashmir (e.g., Manipur required an 18.2% increase in collection to become efficient). Plastic management (San8) slacks were common in the most developed states (viz. Karnataka and Tamil Nadu). This means that high urbanization levels create a plastic waste burden that hygiene services cannot yet scale to meet. SBM construction targets (San2) were mostly met across the board (targets >100%) (i.e., ODF saturation), meaning that efficiency was now driven by service delivery (San6/San7) rather than toilet construction. In Jammu-Kashmir, rural toilet coverage (San4, 72.3%) was significantly below the VRS-calculated target (91.7%). Karnataka showed slack in plastic waste generated (San8). This means that Karnataka produced more plastic waste than its hygiene outputs (e.g., BMW treatment) can operationally justify. Surprisingly, Bihar was a 1.0 efficiency benchmark for Karnataka. This means that Bihar's low-input, medium-output profile defines a frontier that 'wealthier' states like Karnataka failed to match in efficiency. Tamil Nadu had high sanitation inputs but required a 25% increase in hygiene outputs to justify them (i.e., infrastructure overhang). This means that Tamil Nadu was currently in a state of 'diminishing returns', where massive infrastructure did not yield equivalent health outcomes. Most inefficient states (viz. Jammu-Kashmir, Kerala, Manipur) had slack in source segregation (San7). This means that incomplete waste segregation was a systemic 'input waste' across inefficient DMUs.

In the hygiene sector (**Supplementary File 5**), stunting/underweight (Hyg4/Hyg5) were the 'binding constraints' (e.g., Kerala required an improvement of 12.8 points in underweight scores (Hyg5) to reach its frontier peer, Goa). Efficient states such as Gujarat and Maharashtra maintained 100% BMW treatment (Hyg3) (e.g., Jammu-Kashmir showed a 12.9% slackness in biomedical waste treatment). Functional girls' toilets (Hyg7) were a major output slack in Himalayan states (e.g., Jammu-Kashmir required a 10.2% increase in this metric to match Himachal Pradesh). Under VRS, inefficient states were penalized more for output deficits in child health than for excessive infrastructure spending. For nearly all inefficient DMUs, stunting (Hyg4) and underweight (Hyg5) were the primary output slacks (e.g., Manipur required +14.12 in Hyg4 and +20.25 in Hyg5). This means that SBM-VRS identified child health outcomes as the most 'under-served' output relative to WaSH inputs. Despite high social scores, Kerala was only 0.63 efficient because its Hygiene outputs (Hyg4/Hyg5) were lower than what the frontier (e.g., Goa or Himachal Pradesh) produced with similar inputs. This means that the VRS showed that Kerala's WaSH infrastructure was not translating into superior stunted growth prevention (i.e., Kerala paradox). Efficient states such as Gujarat and Maharashtra showed that 100% BMW treatment (Hyg3) was the 'entry fee' for the frontier. This means that high efficiency was synonymous with clinical waste management. Manipur and Jammu-Kashmir were significantly below the frontier for functional girls' toilets (Hyg7). This means that school-level hygiene was the most immediate path to improving VRS efficiency in these states.

4.6. Inequality analysis:

We have performed a multi-level Theil index decomposition, which focuses on the Theil Index (T), where higher values indicate greater regional disparity and the contribution of individual indicators to the overall sectoral inequality. Most unequal (Theil) WaSH indicators were: Hyg1 (hazardous waste - UTs, 1.902 i.e., extreme outlier), Wat9 (groundwater extraction - UTs, 0.485), Wat3 (groundwater withdrawal - UTs, 0.329), San8 (plastic waste - UTs, 0.295), Hyg6 (MSW processed - States, 0.223). Most unequal states & UTs (as per regional inequality score) were: Delhi (in hygiene, 1.411), Tripura (in hygiene, 1.076), Bihar (in hygiene, 1.069 and sanitation, 0.782), Assam (in hygiene, 1.049), and Meghalaya (in sanitation, 0.932). States drive higher overall WaSH inequality (0.0195) compared to UTs (0.0079), while the hygiene sector exhibited the highest national disparity across all sub-indices.

In the total WaSH sector (**Fig 4c, Supplementary File 6**), inequality within States (0.0195) was nearly 2.5 times higher than that within UTs (0.0079), indicating that the ‘state’ cohort was the primary source of national WaSH divergence. Sectoral disparity was highest in hygiene (0.031), followed by sanitation (0.023) and water (0.021). High individual inequality scores in Assam & Bihar suggest that the national hygiene average was heavily skewed by a few extreme laggards. The overall national WaSH inequality (0.017) was significantly lower than the individual indicator inequality, suggesting that high performance in one indicator (e.g., PWS) often offsets poor performance in another (e.g., MSW processing) within the same region. While Meghalaya usually performs well in environmental metrics, its sanitation inequality score (0.932) was the highest among all states, indicating extreme internal pockets of deprivation. Unlike other sectors, Jharkhand showed higher inequality in water (0.527) than many smaller states, highlighting a severe rural-urban divide in water access. The national average inequality (0.053) acted as a dividing line; most states in the NER exceed this, signaling regional ‘clustering’ of inequality.

In the water sector (**Supplementary File 6**), with an inequality of 0.485 in UTs, groundwater extraction (Wat9) was the most unequal component of the water sector. UTs showed high inequality in groundwater withdrawal against availability (0.329), likely due to the contrast between water-rich islands and water-stressed urban UTs, such as Delhi. Improved rural water sources (Wat7) showed the lowest inequality (0.001), indicating that basic access programs had successfully achieved national equity. School infrastructure (Wat8) inequality remained a secondary but consistent driver of disparities in the water sector. Punjab had the lowest water inequality (0.04) despite being a high-stress state, indicating that while resources were low, access was distributed evenly. UTs had more equitable water indices (0.01) but more unequal ‘specific indicators’ (Wat9=0.485) than states, showed extreme variance in resource types. Telangana showed a higher water inequality score (0.399), diverging from its high performance in sanitation.

In the sanitation sector (**Supplementary File 6**), inequality in toilet construction against targets (San2, 0.071) showed that the ‘final mile’ of the Swachh Bharat Mission (SBM) was progressing at uneven speeds across states. Plastic waste generation (San8) was an urban-concentrated issue with significant diversity among UTs, as evidenced by the substantial inequality (0.295). In UTs, the disparity between rural and urban home toilet coverage (San4) was still much greater (0.137). Door-to-door collection (San6) disparity was unexpectedly low in UTs (0.005),

indicating that the ‘standardized’ service was successful. The substantial discrepancy in ‘difficult’ sanitation tasks like source segregation was concealed by the low inequality in UTs (0.014). Bihar’s sanitation disparity (0.78) was ten times greater than Karnataka’s, indicating a structural breakdown in fair service scaling. Sikkim demonstrated considerable sanitation disparity (0.695) despite being the first ODF state, most likely as a result of waste management scaling problems. Sikkim demonstrated considerable sanitation disparity (0.695) despite being the first ODF state, most likely as a result of waste management scaling problems. One of the main causes of inequality within the UT group was urban drainage (San5), which set high-infrastructure Delhi apart from the rest. When compared to water equity, sanitation disparity was disproportionately high in Meghalaya, indicating a separation of liquid and solid waste management.

A national hygiene urgency resulted from the extreme inequality of 1.902 in UTs indicating hazardous waste (Hyg1), which was nearly totally concentrated in 1-2 entities (e.g., Delhi). Hygiene inequality was significantly influenced by MSW processing (Hyg6) in states (0.223), which distinguished states with sophisticated circular economies from those that relied on landfills. Stunting (Hyg4) inequality (0.156) remained a stubborn driver of hygiene sector divergence among states. Disparity in girls’ school toilets (Hyg7) was low in UTs, suggesting a successfully implemented national standard. Delhi’s internal hygiene inequality score of 1.41 was the highest, driven by hazardous waste and MSW volume. Assam and Tripura exhibited ‘hygiene inequity spikes’ (>1), likely due to the lack of centralized MSW processing in hilly terrains. Hygiene inequality in states (0.036) was driven more by health outcomes (stunting) than by infrastructure. The hygiene sector was the most sensitive to ‘inter-state’ differences, where one state’s policy shift significantly impacted the national inequality coefficient.

4.7. Evenness analysis (EIS & MIS):

$EIS < 0.7$ indicating an ‘imbalanced’ state. At the total WaSH level, all entities scored >1.0 , indicating a high cross-sector balance. However, at the Sectoral level (Water, Sanitation, Hygiene), scores consistently fall below 0.7, indicating localized indicator-specific imbalances.

Across all 3 individual sectors (Water, Sanitation, & Hygiene, **Fig 4d-f, Supplementary File 7, Supplementary File 10 S31-S34**), 100% of entities score $EIS < 0.7$ (Avg: ~ 0.15), showed that ‘performance silos’ were rampant within specific WaSH domains (i.e., universal sectoral imbalance). In Water and Sanitation, the states with the highest performance (MIS) often had the lowest evenness (EIS) (e.g., Punjab and Haryana). Meghalaya and Nagaland were ‘balanced laggards’ because they regularly lead in Evenness ($EIS \sim 0.13-0.31$) across sectors but fall short in Performance. In terms of hygiene, Jammu-Kashmir and Ladakh exhibit almost nil evenness (0.001), meaning that one dominant indicator drives their results while others were ignored. Sanitation EIS was the lowest and most restricted (0.06 to 0.13) (i.e., sanitation homogeneity), indicating that this sector was the most susceptible to ‘target chasing’ (e.g., focus on toilet count over waste processing).

From the evenness index score (EIS) perspective, in the total WaSH sector (**Fig 4g, Supplementary File 7**), Puducherry (21.84) and Telangana (20.63), exhibited the highest evenness, suggesting that their WaSH policies were the most non-discriminatory across indicators (i.e., symmetry leaders). Jammu-Kashmir and Ladakh showed the lowest evenness (1.6 and 1.66),

suggesting that while they achieve high marks, their progress was concentrated in a few specific ‘hero indicators’ (i.e., Himalayan imbalance). Puducherry (EIS=21.84) was the most balanced entity in India; its performance was remarkably consistent across all WaSH indicators. Bihar (3.74) was a significant outlier among large states; its low evenness suggested a ‘fragmented’ WaSH model with massive gaps between different indicators. Telangana (20.63) showed exceptional state-level balance, outperforming many UTs that usually benefit from smaller geographic areas.

Across all 3 individual sectors (Water, Sanitation, & Hygiene, **Fig 4d-f, Supplementary File 7**), Punjab leads the water sector with a massive MIS (1199.2), nearly 4 times the score of Meghalaya (335.9) (i.e., Punjab water peak). Despite being a health leader, Kerala was in the bottom 5 (i.e., hygiene dip) for Hygiene MIS (346.1), trailing far behind states like Gujarat (635.8). Bihar (1229.7) ranks in the for the Hygiene performance, defying its lower rankings in Water and overall WaSH.

From the mean index score (MIS) perspective, in the total WaSH sector (**Fig 4g, Supplementary File 7**), Jammu-Kashmir (135.68) and Ladakh (105.59) report scores exceeding 100, suggesting that specific indicators (likely rural water or school infrastructure) far exceed national benchmarks. Meghalaya (46.37) was the only state falling below the 50% ‘poor’ threshold, identifying it as the primary national priority for WaSH intervention. With an MIS of 56.8, West Bengal was the lowest-performing major state in the Eastern belt, trailing behind Bihar (64.9). A majority of states (e.g., Gujarat, Karnataka, and Maharashtra) cluster around the 70% MIS mark (i.e., 70% club), indicating a stabilized middle-tier performance.

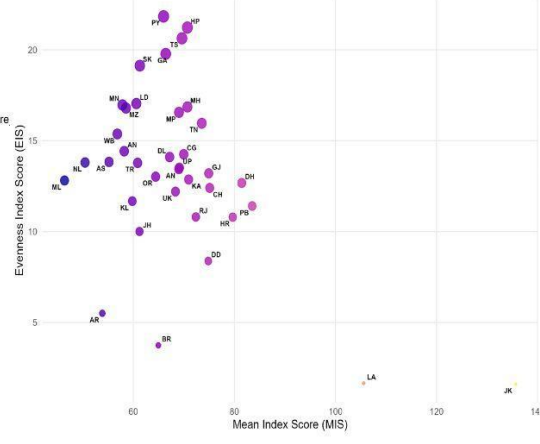
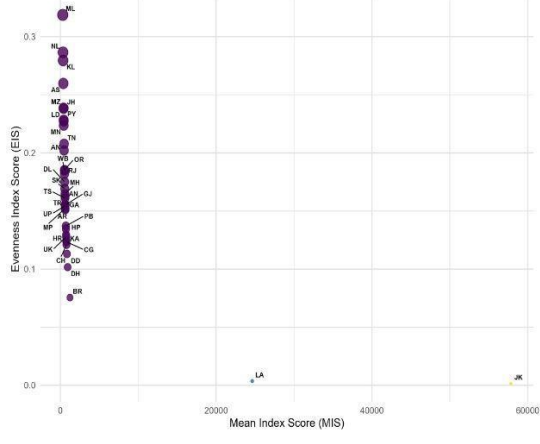
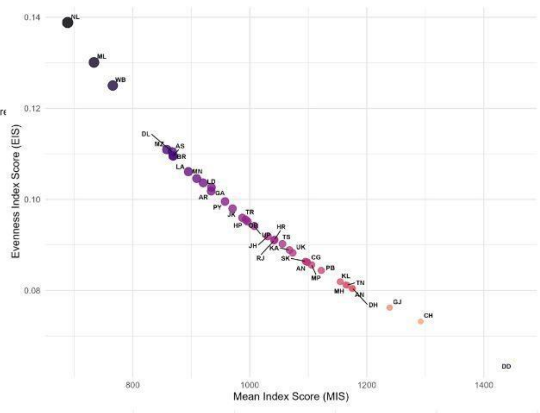
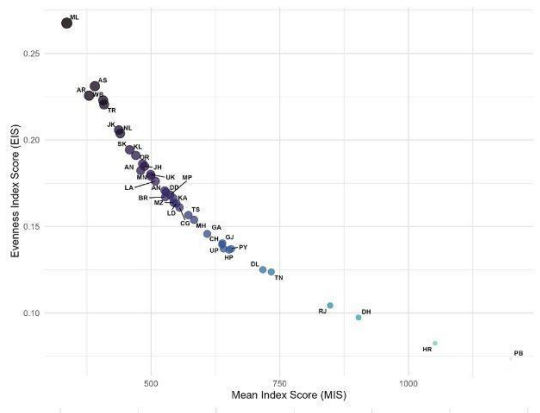
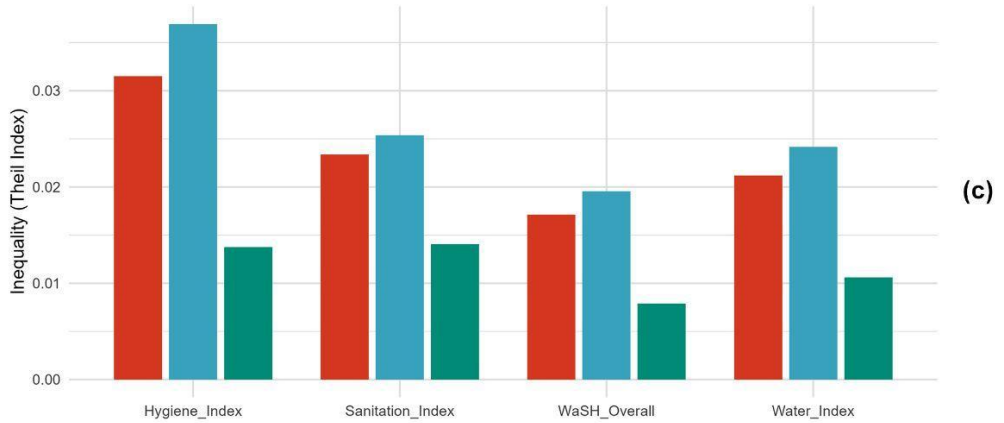
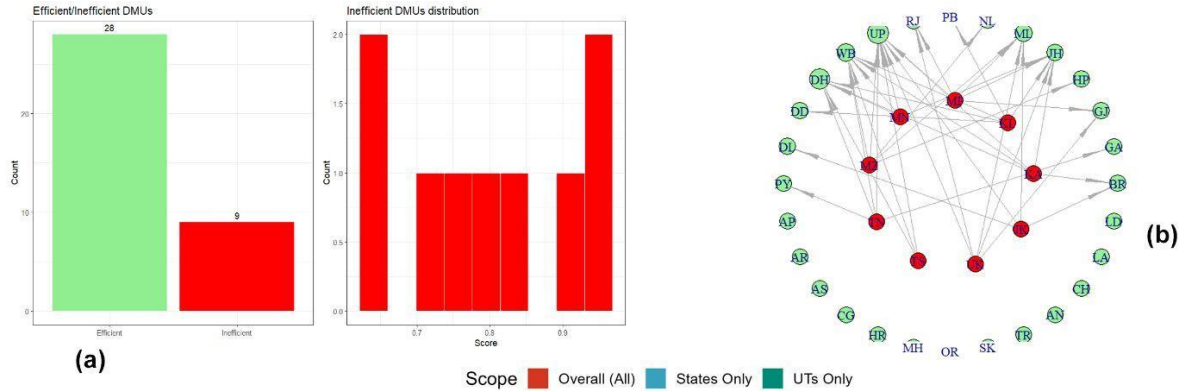


Figure 4. Operational efficiency, inequality decomposition, and the performance-evenness nexus.

Panel (a) showed the distribution of efficient versus inefficient Decision-Making Units (DMUs) using an output-oriented SBM-DEA model.

Panel (b) identified reference DMUs (efficient frontiers) like Uttar Pradesh and West Bengal that serve as benchmarks for laggard states.

Bar chart (c) presents Theil Index scores, quantifying the extreme inequality in hazardous waste (Hyg1) and groundwater extraction (Wat9).

Scatter plots (d) through (g) correlate Mean Index Scores (MIS) with Evenness Index Scores (EIS) for 3 domains of WaSH (viz. Wat, San, Hyg) & overall WaSH sector, distinguishing between ‘balanced leaders’ (e.g., Puducherry) and ‘skewed performers’ experiencing internal service silos.

4.8. Spatial additive decomposition analysis (SAD):

In the total WaSH sector (**Fig 5a, Supplementary File 8**), Punjab and Haryana exhibited the highest positive total deviation (362.4 and 266 respectively), indicating a dominant high-performance hotspot in the Northwest (i.e., Northwest spatial powerhouse). Meghalaya (-566.2) and Nagaland (-464.6) showed extreme negative spatial deviations, suggesting that poor WaSH infrastructure was geographically contagious in the NER (i.e., NER coldspot cluster). Spatial dependence in the Water sector contribution accounts for the largest portion of the total deviation in most states, identifying water as the primary spatial driver of WaSH. Gujarat (147.2) and Maharashtra (41.9) form a positive spatial cluster, where neighbors’ progress likely facilitates industrial and infrastructure synergies (i.e., Western corridor resilience). Jammu-Kashmir showed a WaSH of 3392.2 and a deviation of 1666.5, an extreme outlier driven by disproportionate hazardous waste metrics that do not spill over to neighbors. West Bengal showed a negative deviation of -305, acting as a performance ‘sink’ between the relatively higher-performing Bihar and Odisha. Arunachal Pradesh showed a deviation of -379.3; its extreme terrain likely turns proximity into a hindrance for infrastructure connectivity (i.e., negative spillover).

In the water sector (**Supplementary File 8**), groundwater extraction’s (Wat9) contribution showed massive positive clustering in Jammu-Kashmir (1795.7) and Ladakh (1113.7), indicating a high-altitude regional reliance on specific water sources. High spatial autocorrelation in groundwater extraction was observed in Punjab (Wat9 contribution: 112.7) and Haryana (84.7), indicating a common regional irrigation model (i.e., agricultural water hub). The rural PWS (Wat6) contribution consistently showed a negative spatial lag in Kerala (-30.9) and Jharkhand (-31.4), indicating a regional concentration of infrastructural impediments. While neighbors showed positive Wat1 trends, Arunachal Pradesh had a negative Wat1 contribution of -54.6, identifying it as a local environmental outlier. Rajasthan showed a massive Wat3 contribution (89.4) but a negative Wat6 contribution (-35.6), indicating high resource extraction that failed to translate into piped supply for neighbors. Despite high rainfall, Kerala showed a negative Wat6 contribution of -45.1, an unexpected local effect given its high human development indicator (i.e., water body sink).

In the sanitation sector (**Supplementary File 8**), Uttar Pradesh (10.8) and Bihar (6.5) showed positive spatial clustering in Waste Collection (San6), indicating a regional success in SBM-U implementation (i.e., Gangetic sanitation belt). Meghalaya (-69.5) and Nagaland (-9.5) showed a significant negative spatial lag in toilet construction (San2), identifying a regional laggard cluster (i.e., NER sanitation gap). Delhi (16.2) and Haryana (16.1) showed a high positive spatial lag in San5, reflecting the shared drainage infrastructure of the National Capital Region (NCR) (i.e., urban drainage synergy). Nagaland (-45.6) and Tripura (-36.8) showed clustered negative San7 contribution, indicating that waste segregation was a significant regional challenge in the East. Daman-Diu showed a San2 contribution of 76.8, the highest in the country, suggesting a localized administrative ‘sprint’ that had not yet influenced its neighbors. West Bengal showed a San2 contribution of -46.3, a stark local outlier compared to the positive progress in neighboring Bihar and Odisha. Sikkim showed a negative San4 contribution of -35.2, unexpected for a state often cited as a sanitation leader, indicating a specific local bottleneck in rural households. Telangana had a disparity between rural infrastructure deficiencies and urban trash success, as seen by its high San6 contribution (14.8) and negative San4 contribution (-6.5).

In the hygiene sector (**Supplementary File 8**), Jammu-Kashmir and Ladakh showed hygiene contributions of 1766.1 and 1021.5, driven entirely by localized hazardous waste processing outliers (i.e., ‘mountain hygiene’ explosion). Chhattisgarh (30.2) and Madhya Pradesh (29.1) showed positive spatial lags in Hyg6, suggesting a successful regional model for solid waste processing (i.e., central solid waste hub). Meghalaya (-48) and Nagaland (-65.7) showed clustered negative Hyg7 contribution, indicating a regional lack of functional girls’ toilets in schools (i.e., NER infrastructure coldspot). Andhra Pradesh (14.2) and Telangana (28.5) showed positive spatial lags in solid waste management, indicating a ‘cluster of excellence’ in the Deccan (i.e., southern hygiene synergy). Punjab (53.8) and Himachal Pradesh (63.4) showed positive spatial lags in Hyg2, suggesting shared regional investments in treatment plants (i.e., sewage treatment disparity). Despite high literacy, Kerala showed a hygiene contribution of -147.7, the 2nd lowest in India, driven by local failures in sewage capacity (Hyg2). Sikkim showed a negative Hygiene contribution (-150.7, highest negative), identifying a critical local failure in industrial waste management. Bihar showed a positive Hyg8 contribution (97.4), a massive local effect that makes it a regional hygiene leader despite lower water/sanitation scores.

4.9. Relative performance analysis:

We have analyzed the relative performance deviations for Indian states & UTs (**Fig 5b, Supplementary File 9**). The data reflect the extent to which each entity deviates from the national average benchmark (0). Positive values indicate outperformance, whereas negative values indicate a performance deficit.

With Dadra-Nagar Haveli and Delhi continuously sustaining a $>+0.5$ premium, the UTs exhibit a persistent positive deviation across core sectors in the overall WaSH sector (**Supplementary File 9**), particularly in urban sanitation and recycling. A significant degree of performance convergence at the national average for integrated WaSH was indicated by the fact that almost 70% of large states cluster within variances of -0.2 and +0.2 (‘70% plateau’). In the water and sanitation pillars, there was a consistent pattern of negative deviations (<-0.5) in the Eastern and NER states, particularly Meghalaya and Arunachal Pradesh. High positive variations

in urban waste collection and individual toilet construction were most closely associated with high total WaSH deviations (e.g., in Haryana or Punjab). Arunachal Pradesh exhibited a near-total deficit in groundwater extraction metrics and piped water supply (-0.99), the most significant negative deviation in the water sector. Telangana showed an extremely positive outlier in hazardous waste recycling (Hyg8) (+3.13), indicating a specialized industrial hygiene model far exceeding the national norm. In a counterintuitive turn, Bihar showed a major positive deviation (+3.51) in hazardous waste recycling despite negative deviations in piped water supply. Despite leading social indicators, Kerala showed a major negative deviation (-0.94) in decadal forest water body change (Wat1), trailing significantly behind its neighbors. Goa maintains an extreme outperformance in recycling (+3.41), yet showed a -1.0 deviation in industrial wastewater compliance (Wat4), highlighting a split in the industrial environmental policy.

In the water sector (**Supplementary File 9**), 45% of states showed a deviation of <-0.4 in PWS (Wat6), identifying rural piped water connectivity as the most significant laggard sub-sector nationally. Northern states (e.g., Punjab, Haryana, Rajasthan) showed extreme positive deviations ($>+4.0$) in groundwater extraction, indicating a resource-intensive agricultural model. Forest water bodies (Wat1) exhibited the widest range of deviations, from +2.86 (Mizoram) to -2.83 (Arunachal Pradesh), reflecting localized climate and conservation impacted. Punjab/Rajasthan states represent the 95th percentile cap for groundwater withdrawal (+5.4), indicating extraction rates at the absolute limit of the national spectrum. Mizoram leads the nation in forest water conservation (+2.86), a major outperformance compared to the regional NER average. While performing near average in most areas, Uttar Pradesh showed a persistent negative gap in rural piped water (-0.21) compared to neighboring Haryana. Assam showed a significant positive deviation in water availability against withdrawal (+0.51), identifying it as a 'water-surplus' outperformer in the eastern belt.

In the sanitation sector (**Supplementary File 9**), 62% of states report negative deviations (<-0.4) in urban drainage facilities (San5), marking it as the primary infrastructure bottleneck in Indian cities. High positive deviations in SBM-U construction (San3) were concentrated in western states (Gujarat at +1.64), indicating faster-than-average urban toilet construction. States like Sikkim and Mizoram showed significant negative deviations (-0.33) in rural household toilets, lagging behind the national SBM-G momentum. Source segregation (San7) showed the lowest national average performance, with the majority of eastern states showed negative deviations between -0.3 and -0.4. Daman-Diu act as extreme outperformers in sanitation construction against targets (+1.74), with nearly double the performance of the surrounding regional average. West Bengal showed a significant performance gap in SBM-G construction targets (-0.42) compared to its high performance in hygiene metrics. Delhi leads the nation in urban waste collection deviations (+1.28), setting a benchmark for MSW logistics. Jharkhand showed a strong positive reversal in sanitation construction (+0.41), moving from a historical laggard to a modern outperformer in sanitation. Nagaland exhibited an extreme negative deviation in waste recycling (-0.91), indicating a total lack of municipal processing infrastructure.

In the hygiene sector (**Supplementary File 9**), hazardous waste recycling (Hyg8) showed the highest variance, with several states exceeding +3 deviations, indicating highly concentrated industrial recycling hubs in these states. The trend for sewage treatment (Hyg2) was bifurcated, with states like Meghalaya showed the largest disparity in hygiene services (-1) and UTs showed

+0.8 deviations. The efficacy of the national school sanitation mandates was demonstrated by the nearly zero variation of functional girls' restrooms (Hyg7) across the mainland. A successful national specialized waste regime was demonstrated by the fact that the majority of large states (Andhra Pradesh, Tamil Nadu, Gujarat) had achieved 'positive parity' (deviation >0) for BMW treatment. The most significant hygiene gap found in the investigation was Meghalaya's complete lack of sewage treatment capability (-1). As the top performance in urban solid waste processing (+2.58), Chandigarh was a national leader in the field. As the top performance in urban solid waste processing (+2.58), Chandigarh was a national leader in the field. The recycling of hazardous waste in Ladakh showed an exceptional maximum deviation (+7.2), indicating a distinct and highly specialized alpine waste regime. In terms of sewage treatment capacity, Haryana demonstrated a significant positive deviation (+1.62), far surpassing the performance of neighboring agricultural states. Puducherry was the best-performing hygiene UT because it combines high variances in BMW treatment and recycling (+1.69).

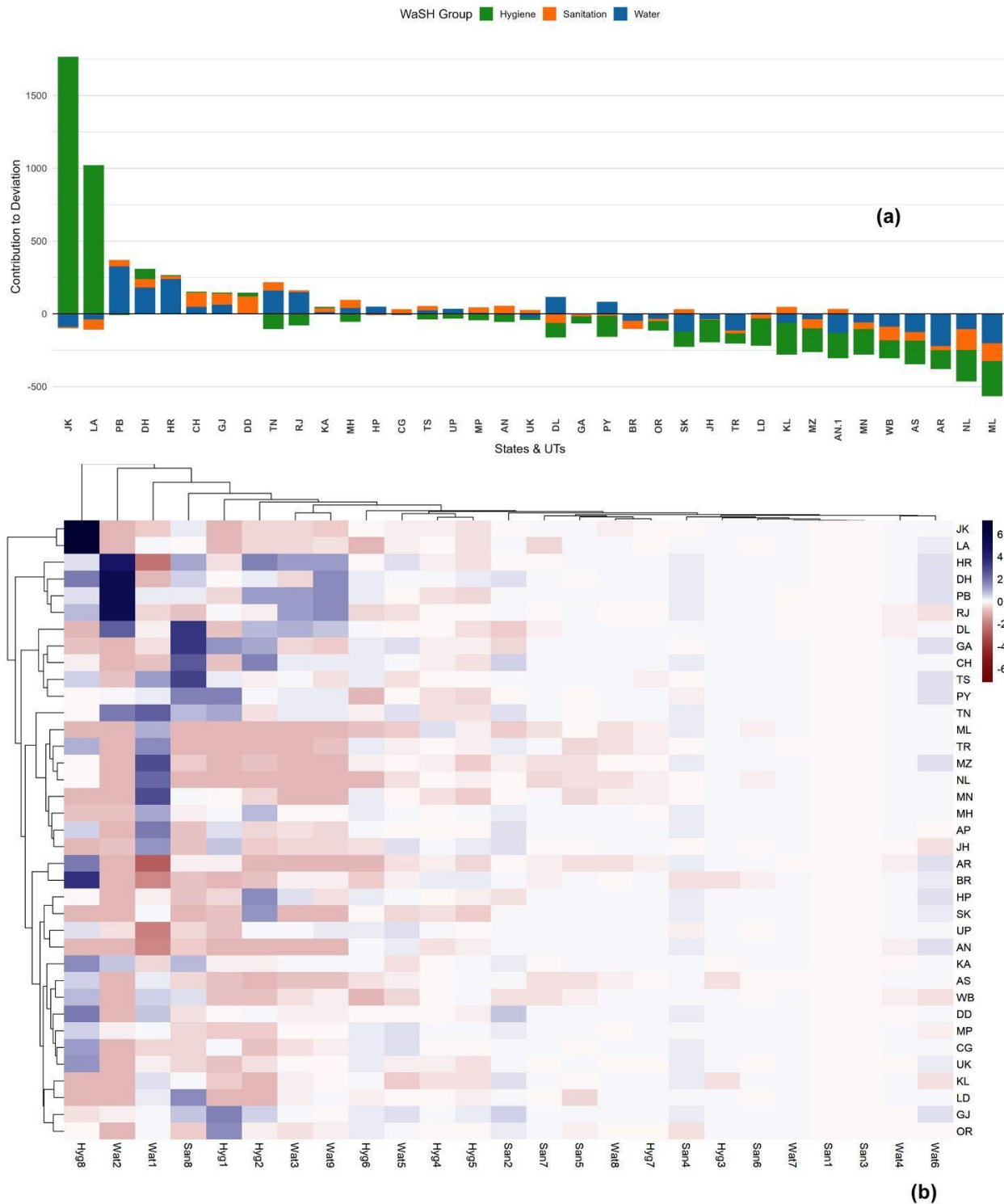


Figure 5. Performance deviations and sub-national WaSH benchmarking.

Panel (a) utilizes Spatial Additive Decomposition (SAD) to quantify the contribution of Water, Sanitation, and Hygiene domains to total regional deviation from the national mean. It highlighted geographically ‘contagious’ coldspots in the NER versus high-performance hotspots

in the Northwest.

Panel (b) presents the relative performance analysis, visualizing each entity's deviation from the zero-benchmark (national average) across 25 indicators. This heatmap identified critical sub-sectoral bottlenecks, such as the widespread rural piped water connectivity gap (Wat6) and localized 'toxic sinks' in hazardous waste processing.

5. Discussion:

HCA and SAD demonstrated a substantial difference between state and UT trajectories, indicating a 'UT performance premium'. States showed substantially larger internal performance differences, but UTs showed standardized, high-density urban efficiency in garbage collection and cleanliness. This implies that, in contrast to the varied topographical and socioeconomic difficulties encountered by larger governments, the controllable administrative scale of UTs permits more consistent policy execution. Biswas et al. (2024) reinforce our identification of eastern and NER states as geographic coldspots by identifying Jharkhand, Odisha, Tripura, Assam, and Rajasthan as trailing behind in SDG-6 accomplishment.

The 'efficiency-output gap' in socially developed states like Kerala and Tamil Nadu was a crucial finding from the DEA. These areas were penalized for failing to translate hardware into anticipated hygiene-health results, including decreased stunting, despite having significant infrastructure inputs. Due to this gap, 'construction-heavy' aims must give way to 'outcome-based' interventions that combine nutrition and WaSH. Li et al. (2020) support our conclusion that hygiene infrastructure did not always translate to health outcomes by showing that community-level sanitation practices explain greater inter-state variation in childhood stunting than individual nutrition behaviors. Kerala's infrastructure-outcome dissociation was consistent with Choudhary et al. (2021), who showed that child nutrition was impacted by family water insecurity through mechanisms unrelated to WaSH facilities, corroborating our conclusion that hardware did not always equate to health.

We found the almost ideal connection between specialist hygiene facilities and school infrastructure. The main 'bridge node' in the national network was functional girls' restrooms, indicating that educational settings were the most effective force multipliers for concurrent improvements in gender-sensitive development and public health. Our conclusion that functional girls' restrooms act as the main network bridge node was supported by Pednekar et al. (2024), who emphasize that insufficient school WaSH data obscures the real influence on girls' attendance. According to Nizamuddin (2025), 61% of schools lack disposal facilities and 51% lack sanitary vending machines, which supports our conclusion that school hygiene was essential infrastructure.

Significant 'coldspots' where subpar performance was geographically concentrated were found in the NER, especially in Meghalaya and Nagaland, according to SAD. To overcome terrain-induced obstacles in basic sanitation and school-level hygiene, these findings question the effectiveness of isolated state-level planning and support 'regional WaSH corridors'. Roy et al. (2023b) validate our result that sanitation poverty showed spatially contagious patterns by using LISA clustering to show that open defecation hot locations were concentrated in India's north-central belt.

According to our findings, high-GDP states like Gujarat and Maharashtra frequently lag behind in terms of solid waste processing and behavioral hygiene. This suggested that, to close the gap between financial affluence and behavioral health, certain social marketing techniques were needed as economic progress did not immediately address hygiene inadequacies.

In agricultural states like Punjab and Haryana, a resource-intensive growth strategy was highlighted by the strong association between over-exploited blocks and extraction stages. PCA confirmed that although water access was uniform, extraction limitations were rapidly endangering its sustainability, making interstate water compacted necessary to preserve long-term ecological health. Our identification of Punjab-Haryana as an extraction-driven performance cluster was supported by Tobochnik et al. (2025), who report favorable correlations between groundwater utilization and physical asset accumulation in northwest India. Bhallamudi et al. (2019), who reported that dense toilet construction in hard rock regions resulted in fecal coliform pollution up to 100m depth, directly harming child health, were supported by the correlation between groundwater extraction and stunting (Wat2↔Hyg4).

According to EIS, almost all entities experience localized imbalances in particular sectors. The propensity to pursue building goals (like ODF) at the expense of managing liquid and solid waste results in ‘success silos’, where infrastructure was present but drainage or processing systems were not operational.

Hazardous waste, which was mostly concentrated in a small number of industrial hubs, was identified by inequality analysis as the most unequal indicator in our dataset. To prevent localized ‘toxic sinks’, specialized waste treatment must be decentralized, as this concentration produced a statistical skew that hides more extensive infrastructure failures in other areas. According to Siddique (2024) on the Brahmapuram waste plant fire in Kerala, hazardous waste was the most uneven indicator (1.902 in UTs), illustrating how concentrated industrial waste created localized ‘toxic sinks’ that disproportionately afflict vulnerable areas. Gini coefficient (0.29) revealing significant inequality in sanitation coverage across Indian districts (Biswas et al., 2024) aligned with our Theil index decomposition showed sanitation as the second-most unequal sector after hygiene.

There were a few significant contributions of our WaSH analysis of India:

- This research introduced a pioneering multi-method framework., integrating network analysis, DEA, and spatial decomposition, to capture the multidimensional complexities of WaSH performance that single-method studies overlook.
- By identifying specific ‘bridge nodes’ like functional girls’ toilets, this study provided a prioritized roadmap for high-ROI investments that simultaneously accelerate SDG 6 and educational outcomes.
- The application of DEA identified specific output slacks in laggard states, allowing policymakers to transition from construction-heavy targets to outcome-based hygiene and health interventions.
- This analysis quantified the extreme performance variations between states and UTs, providing evidence to move beyond national averages that mask critical localized infrastructure deficits.

- The NER's spatially 'contagious' coldspots were identified using the spatial additive decomposition, supporting the need for regional infrastructural corridors as opposed to discrete state-level design.
- The study provided state governments with a standardized benchmarking tool to assess their success in comparison to their regional counterparts by creating statistical anchors and performance quadrants.
- The results showed a 'hygiene-economy gap', where high-GDP states frequently fall behind in behavioral measurements. This calls for a tactical change to focus on social marketing and hygiene education.
- To prevent secondary groundwater pollution, this paper highlighted important policy silos between SBM-G and SBM-U and promotes unified waste collection and drainage systems.

Although this study offers a thorough sub-national evaluation of the WaSH environment in India, its limitations present a strategic road map for further research. These results should be used in future studies to shift from descriptive evaluations to functional and predictive modeling.

- *Transitioning to Longitudinal Analysis*: To assess the long-term durability of infrastructure improvements and the development of sub-national WaSH trajectories, future research should go beyond the current static, cross-sectional dataset and include temporal dynamics.
- *Verification of Causal Pathways*: Longitudinal investigations were necessary to offer causal verification for the revealed multi-method interrelationships, even though this study finds high synergy between school utilities and hygiene.
- *Refinement of Performance Weighting*: By creating weighted frameworks that take into consideration the disproportionate systemic influence of 'bridge nodes', such functional girls' restrooms, on national development ROI, future indices could enhance the equal-weighting approach.
- *Granular and Transboundary Spatial Modeling*: Future study should use district-level data to identify more precise 'coldspots' and incorporate transboundary groundwater flow dynamics that exist outside of state and UT administrative boundaries, to address the Modifiable Areal Unit Problem (MAUP).
- *Advanced Efficiency Benchmarking*: The results of DEA indicate that comparative models that test alternative returns to scale were necessary, particularly to make sure that companies operating on lean input-output ratios, such as Bihar, were not unfairly credited with overstated efficiency under VRS assumptions.
- *Incorporating Behavioral and Functional Metrics*: Future frameworks should incorporate measurements that capture real functional utilization and the long-term durability of behavioral hygiene habits, rather than infrastructure-centric indicators like toilet building.

5.4. Policy Suggestions

This section presents our analysis's main policy recommendations that deal with the three WaSH areas. Policymakers may create a more equitable and sustainable environmental future by focusing on these factors.

(a) For Water sector:

- *Targeted PWS Infrastructure Blitz*: Give Arunachal Pradesh and Jharkhand priority for emergency Piped Water Supply (PWS) funding to reduce the 40% rural connectivity gap and solve severe performance deficiencies (deviations of -0.99) (Ministry of Jal Shakti).
- *Northwest Groundwater Regulatory Compact*: To reduce severe resource over-exploitation, Punjab, Haryana, and Rajasthan should implement a cross-state strategy that targets areas that are now at the 95th percentile (+5.4 deviation) of national extraction limits (Ministry of Water Resources).
- *Scaling School-Based 'Statistical Anchors'*: Use this metric as the main motivator to improve national WaSH performance and accomplish SDG 6 by requiring integrated water-electricity packages for schools in laggard regions.
- *Regional Forest-Water Conservation*: To stabilize regional water tables and guard against climate-induced depletion, NE states should be encouraged to follow Mizoram's forest-water conservation strategy (+2.86 deviation) through 'Environmental Performance Grants'.
- *UP Rural Water Connectivity*: To close the deviation gap (-0.21) in rural PWS compared to nearby high-performers like Haryana, initiate a targeted 'Har Ghar Jal' secondary phase.
- *Desalination Equity for Island UTs*: Standardize desalination and storage infrastructure to guarantee fair access across remote administrative divisions to address the substantial internal water inequality (T=0.439) in archipelagos.

(b) For Sanitation Sector:

- *National Urban Drainage Mission*: Create a special fund for the 62% of states that currently have major lagging status (deviations < -0.4) in urban drainage facilities (San5) (Ministry of Housing and Urban Affairs, MoHUA), including West Bengal and Uttar Pradesh.
- *Efficiency-Driven Municipal Logistics*: Manipur and Jammu-Kashmir should get fleet and technical support to eliminate the 18.2-26% slack in door-to-door garbage collection (San6) that the DEA frontier analysis found.
- *Leveraging the 'UT Performance Premium'*: Use Delhi's superior waste collection performance (+1.28 deviation) as a national standard and training center for states (like West Bengal) shifting from building infrastructure to logistics for service delivery.
- *Regional Sanitation Equity Scaling*: Funding should be redirected to address the severe internal inequalities in Meghalaya (0.932) and Bihar (0.782), with an emphasis on localized 'inequality pockets' rather than statewide averages.
- *Behavioral Source Segregation Blitz*: To solve the persistent -0.3 to -0.4 performance disparity in source segregation (San7) and advance the industry beyond simple toilet construction, launch aggressive behavioral campaigns in Eastern states.
- *SBM-G Momentum Recovery*: To meet national saturation targets, targeted interventions were implemented in West Bengal and Sikkim to overcome negative deviations (-0.42 to -0.33) in rural home toilet building (San4).

(c) For Hygiene Sector:

- *Decentralized Sewage Treatment for the NER*: To address regional public health instability and bridge the crucial -1.0 hygiene gap, implement localized solutions in Meghalaya and Nagaland.
- *Nutrition-Integrated WaSH Interventions*: Close the 12.8-point child underweight (Hyg5) gap by combining WaSH with nutrition initiatives to address the ‘Kerala paradox’ (poor efficiency despite large inputs).
- *Prioritizing National ‘Bridge Nodes’*: As the main structural hub (betweenness: 13) for producing the best ROI across public health and education, make significant investments in operational girls’ restrooms in schools (Hyg7).
- *Inter-State Hazardous Waste Corridors*: Take care of the extreme 1.902 to prevent localized ‘toxic sinks’, waste treatment corridors between industrial hubs and lagging areas should be established.
- *High-GDP Behavioral Transformation*: To close the ‘hygiene-economy gap’ in MSW processing, implement specialized social marketing in economically powerful states like Gujarat and Maharashtra (Hyg6).
- *North-East Regional WaSH Corridors*: Create regional infrastructural corridors in the NER to get over obstacles caused by topography that led to spatially ‘contagious’ low school hygiene performance.

6. Conclusion:

By showing that the shift from infrastructural saturation to functional sustainability was the main frontier for attaining WaSH, this study contributed to our understanding of India’s public health environment. The ‘construction-outcome paradox’, as our analyses showed, was a crucial new finding: the existence of physical hardware, like piped water connections and home toilets, did not always result in better public health outcomes, especially stunted growth and enteric infection rates. This implies that ‘WaSH poverty’ was increasingly characterized by the inability to combine infrastructure with behavioral maintenance and nutrition-sensitive interventions rather than by a lack of resources. A strategic force multiplier where targeted institutional expenditures produce a disproportionate rippling impact across gender parity, educational attendance, and community hygiene standards was highlighted by the identification of ‘bridge nodes’, particularly functional girls’ restrooms in schools.

Policy frameworks must shift from national aggregations to granular, sub-national localization to expedite the advancement of WaSH. This study’s ‘UT performance premium’ offers a paradigm for success, indicating that decentralized, high-density urban governance models outperform centralized state mandates in handling intricate waste and hygiene networks. To counteract terrain-induced logistical sinks, larger governments must create ‘regional WaSH corridors’ in geographically limited regions like the NER. To close the gap between industrial growth and public health outcomes, future strategies must shift toward sophisticated social marketing and behavioral hygiene education. The identified ‘hygiene-economy gap’ in high-GDP states indicating financial wealth was an insufficient proxy for behavioral health.

In the end, India needs to go beyond national averages and focus on regional ‘statistical laggards’ like Meghalaya to meet UN SDG 6 & WaSH by 2030. The government may transition from a phase of ‘universal access’ to one of ‘equitable and functional sustainability’ by

concentrating on the designated ‘statistical anchors’ and ‘bridge nodes’, guaranteeing that no subnational region was left behind in the nation’s public health reform.

List of Abbreviations:

BMW=Bio Medical Waste	CPCB=Central Pollution Control Board
EIS=Evenness Index Score	HDI=Human Development Index
JJM=Jal Jeevan Mission	MICE=Multivariate Imputation by Chained Equations
MIS=Mean Index Score	MoHUA = Ministry of Housing and Urban Affairs
MSW=Municipal Solid Waste	NCR=National Capital Region
NDAP=National Data and Analytics Platform	NSSO=National Sample Survey Office
ODF=Open Defecation Free	PC=Principal component
PWS=Piped Water Supply	ROI=Return on Investment
SBM-G=Swachh Bharat Mission (Grameen)	SBM-U=Swachh Bharat Mission (Urban)
SDG=Sustainable Development Goal	SMB=Slack-Based Measure
VRS=Variable Returns to Scale	WaSH=Water, Sanitation & Hygiene

References:

- Ashrit, R. R., & Joshi, S. (2025). Analysis of NSSO data sets for a spatial evaluation of water and housing inequality in India. *Environmental Development*, 55, 101104. <https://doi.org/10.1016/j.envdev.2024.101104>
- Bhallamudi, S. M., Kaviyarasan, R., Abilarasu, A., & Philip, L. (2019). Nexus between sanitation and groundwater quality: case study from a hard rock region in India. *Journal of Water, Sanitation and Hygiene for Development*, 9(4), 703-713. <https://doi.org/10.2166/washdev.2019.002>
- Biswas, J. K., Mondal, B., Priyadarshini, P., Abhilash, P. C., Biswas, S., & Bhatnagar, A. (2022a). Formulation of water sustainability index for India as a performance gauge for realizing the United Nations sustainable development goal 6. *Ambio*, 51(6), 1569-1587. <https://doi.org/10.1007/s13280-021-01680-1>
- Biswas, S., Adhikary, M., Alam, A., Islam, N., & Roy, R. (2024). Disparities in access to water, sanitation, and hygiene (WASH) services and the status of SDG-6 implementation across districts and states in India. *Heliyon*, 10(18). <https://doi.org/10.1016/j.heliyon.2024.e37646>
- Biswas, S., Dandapat, B., Alam, A., & Satpati, L. (2022b). India's achievement towards sustainable Development Goal 6 (Ensure availability and sustainable management of water and sanitation for all) in the 2030 Agenda. *BMC Public Health*, 22(1), 2142. <https://doi.org/10.1186/s12889-022-14316-0>
- Biswas, S., Khanam, Z., Alam, A., & Satpati, L. (2025). Progress and determinants of household access to improved drinking water in India using a Water Access Index: insights from the National Family Health Survey towards achieving SDG 6.1. *BMJ Open*, 15(6), e091269. <https://doi.org/10.1136/bmjopen-2024-091269>
- Chaudhuri, S., & Roy, M. (2017). Rural-urban spatial inequality in water and sanitation facilities in India: A cross-sectional study from household to national level. *Applied Geography*, 85, 27-38. <https://doi.org/10.1016/j.apgeog.2017.05.003>
- Choudhary, N., Schuster, R. C., Brewis, A., & Wutich, A. (2021). Household water insecurity affects child nutrition through alternative pathways to WASH: evidence from India. *Food and Nutrition Bulletin*, 42(2), 170-187. <https://doi.org/10.1177/0379572121998122>
- Chouhan, N. S., Nielsen, M. O., Singh, P., Manchikanti, S., Pandey, V., Walters, J. P., & Kadyan, K. (2022). A systems approach to improving access to water, sanitation, and hygiene (WASH) in schools in Odisha, India. *H2Open Journal*, 5(3), 395-411. <https://doi.org/10.2166/h2oj.2022.044>
- Dadhich, A. P., Dadhich, P. N., & Goyal, R. (2022). Synthesis of water, sanitation, and hygiene (WaSH) spatial pattern in rural India: an integrated interpretation of WaSH practices. *Environmental Science and Pollution Research*, 29(57), 86873-86886. <https://doi.org/10.1007/s11356-022-21918-z>
- Das, M., Verma, M., Sahoo, S. S., & Gupta, M. (2022). Regional water availability and WASH indicators as predictors of malnutrition in under-5 children: analysis of the national family health survey, India (2015–16). *Journal of Tropical Pediatrics*, 68(3), fmac030. <https://doi.org/10.1093/tropej/fmac030>
- Garai, N., Roy, A., & Pramanick, K. (2025). Unravelling sustainable development at the sub-national scale in India. *Environmental Development*, 101336. <https://doi.org/10.1016/j.envdev.2025.101336>

- Ghosh, P., Hossain, M., & Alam, A. (2022). Water, sanitation, and hygiene (WASH) poverty in India: a district-level geospatial assessment. *Regional Science Policy & Practice*, 14(2), 396-417. <https://doi.org/10.1111/rsp3.12468>
- Ghosh, P., Hossain, M., & Sarkar, S. (2023). Inequality among social groups in accessing improved drinking water and sanitation in India: a district-level spatial analysis. *The Professional Geographer*, 75(3), 361-382. <https://doi.org/10.1080/00330124.2022.2124181>
- Li, T., Liu, Y., Li, M., Qian, X., & Dai, S. Y. (2020). Mask or no mask for COVID-19: A public health and market study. *PloS One*, 15(8), e0237691. <https://doi.org/10.1371/journal.pone.0237691>
- Mondal, D. (2022). Access to Latrine Facilities and Associated factors in India: an empirical and spatial analysis. *Indian Journal of Human Development*, 16(3), 528-547. <https://doi.org/10.1177/09737030221141248>
- Nizamuddin, A. (2025). Adolescent Health and Menstrual Well-Being: Insights from School Students in West Bengal, India. *Journal of Science and Knowledge Horizons*, 5(02), 382-397. <https://doi.org/10.34118/jskp.v5i02.4454>
- Pednekar, S., Desouza, S., & Mukhopadhyay, P. (2024). Monitoring WASH and school dropouts in India: Is there adequate data? An assessment of four national databases. *Journal of Water, Sanitation and Hygiene for Development*, 14(1), 56-68. <https://doi.org/10.2166/washdev.2024.195>
- Pradhan, M. R. (2020). Water, sanitation, and hygiene (WASH) conditions and their association with selected diseases in urban India. *Journal of Population and Social Studies*, 28 (2), 103 – 115. <https://doi.org/10.25133/JPSSv28n2.007>
- Rani, S. (2022). Evaluating the regional disparities in safe drinking water availability and accessibility in India. *Environment, Development and Sustainability*, 24(4), 4727-4750. <https://doi.org/10.1007/s10668-021-01631-6>
- Roy, A. (2024). Charting uneven progress of sustainability: A multi-dimensional assessment of the SDGs in Northeast India. Authorea Preprints. <https://doi.org/10.22541/au.173083541.13969991/v2>
- Roy, A., & Pramanick, K. (2019). Analysing progress of sustainable development goal 6 in India: Past, present, and future. *Journal of Environmental Management*, 232, 1049-1065. <https://doi.org/10.1016/j.jenvman.2018.11.060>
- Roy, A., Garai, N., & Biswas, J. K. (2023a). Exploration of urban sustainability in India through the lens of sustainable development goals. *Discover Sustainability*, 4(1), 41. <https://doi.org/10.1007/s43621-023-00158-2>
- Roy, A., Rahaman, M., Adhikary, M., Kapasia, N., Chouhan, P., & Das, K. C. (2023b). Unveiling the spatial divide in open defecation practices across India: an application of spatial regression and Fairlie decomposition model. *BMJ Open*, 13(7), e072507. <https://doi.org/10.1136/bmjopen-2023-072507>
- Roy, A., Rahaman, M., Bannerji, R., Adhikary, M., Kapasia, N., Chouhan, P., & Das, K. C. (2023c). Spatial clustering and drivers of open defecation practice in India: findings from the fifth round of National Family Health Survey (2019-21). *Global Transitions*, 5, 55-63. <https://doi.org/10.1016/j.glt.2023.05.002>
- Roy, C., Sati, V. P., Biswas, A., & Kumar, S. (2023d). Status of drinking water, sanitation facilities, and hygiene in West Bengal: evidence from the National Family

- Health Survey of India (NFHS), 2019–2021. *Journal of Water, Sanitation and Hygiene for Development*, 13(1), 50-62. <https://doi.org/10.2166/washdev.2023.228>
- Sarkar, S. K., & Bharat, G. K. (2021). Achieving sustainable development goals in water and sanitation sectors in India. *Journal of Water, Sanitation and Hygiene for Development*, 11(5), 693-705. <https://doi.org/10.2166/washdev.2021.002>
 - Saroj, S. K., Goli, S., Rana, M. J., & Choudhary, B. K. (2020). Availability, accessibility, and inequalities of water, sanitation, and hygiene (WASH) services in Indian metro cities. *Sustainable Cities and Society*, 54, 101878. <https://doi.org/10.1016/j.scs.2019.101878>
 - Siddique, S. M. M. (2024). The Political Ecology of Risk: Problematising the Risk Distribution of Solid Waste Treatment Plants. In: El Khoury, R. (eds) *Anticipating Future Business Trends: Navigating Artificial Intelligence Innovations*. Studies in Systems, Decision and Control, vol 536. Springer, Cham. https://doi.org/10.1007/978-3-031-63402-4_3
 - Tirkey, C., Gurung, R., Rai, R., & Takri, K. K. (2025). Factors influencing access to safe drinking water and sanitation in Northeast India: evidence from National Family Health Survey (NFHS-5). *International Journal of Social Economics*, 1-16. <https://doi.org/10.1108/IJSE-03-2025-0228>
 - Tobochnik, H., Zaveri, E., & Fishman, R. (2025). Mixed correlations between groundwater extraction in India and accumulation of physical and human capital. *Environmental Research Letters*, 20(7), 074044. <https://doi.org/10.1088/1748-9326/addd32>
 - Tripathi, V., GS, P., & Swain, S. (2024). Tracking water, sanitation, and hygiene (WASH) indicators in tribal districts of India: a secondary data analysis through 2015–2020. *Journal of Water, Sanitation and Hygiene for Development*, 14(1), 40-55. <https://doi.org/10.2166/washdev.2024.119>
 - Trivedy, A., & Khatun, M. (2024). Water, Sanitation, and Hygiene (WaSH) condition in West Bengal, India: Exploring geospatial inequality, patterns, and determinants. *GeoJournal*, 89(1), 32. <https://doi.org/10.1007/s10708-024-11034-5>
 - Van Buuren, S., & Groothuis-Oudshoorn, K. (2011). mice: Multivariate Imputation by Chained Equations in R. *Journal of Statistical Software*, 45(3), 1-67. <https://doi.org/10.18637/jss.v045.i03>
 - Vatsa, R., Ranjan, M., Bhandari, P., & Gayawan, E. (2023). Analyzing effect of WASH practices and district-level spatial effects on acute respiratory infections and diarrhoea among under-five children in India. *Applied Spatial Analysis and Policy*, 16(4), 1299-1316. <https://doi.org/10.1007/s12061-023-09512-3>