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Developing a regional typology for precision public health using a methodological framework applied to India

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Abstract

Background National health programmes often apply uniform strategies that overlook regional variation in disease burden and ecological context. This paper introduces a planning framework that enables subnational health systems to design precision public health strategies aligned with local epidemiology and risk profiles.

Methods The paper presents a three-step typology method that is well-suited for both practitioners and academicians to use: (1) classify regions based on relative disease prevalence, (2) contextualise with ecological heat mapping, and (3) align evidence-informed strategies across key intervention domains. The method was applied to high blood glucose (HBG) and hypertension (HTN) data from India, using 12 ecological indicators and a synthesis of over 160 peer-reviewed studies to guide strategy development.

Results The framework produced four distinct quadrant profiles, each with tailored public health strategies across five domains (cultural evolution of health, One Health, social determinants, public health services, and healthcare delivery) and two enabling inputs (comparative case studies and implementation pathways). The approach was applied to Indian states, but the method is generalisable to other low- and middle-income countries (LMICs) with decentralised health systems.

Conclusion This typological planning framework provides a practical, data-driven tool for precision public health at the subnational level. It enables national and regional planners to account for local variation while designing scalable, adaptive strategies. The framework is suitable for LMICs and adaptable to a range of health system challenges beyond Non-Communicable Diseases (NCDs) such as diabetes and hypertension.

Highlights

- Introduces a replicable method for subnational public health strategy planning
- Combines disease prevalence classification with ecological heat mappingCombines disease prevalence classification with ecological heat mapping
- Demonstrates application to HTN and HBG in Indian states
- Produces tailored strategies across five domains and two enabling inputs

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- Supports adaptive NCD planning in decentralised LMIC health systems

Keywords High blood glucose, Hypertension, Ecological typology, Insulin insufficiency, Type 5 diabetes, Salt sensitivity, Metabolic epidemiology, Non-communicable diseases

1 Introduction

Non-communicable diseases (NCDs), including hypertension and diabetes, now account for the majority of premature mortality in India [1]. National programmes, such as the National Programme for Prevention and Control of Cancer, Diabetes, Cardiovascular Diseases, and Stroke (NPCDCS), have sought to standardise preventive and curative responses across the country. However, a uniform approach towards addressing these diseases fails to recognise that there is substantial regional heterogeneity in both disease prevalence and underlying risk profiles [2]. Regions differ markedly across multiple dimensions, leading to significant regional variation in the epidemiology of NCDs.

Conventional NCD policies, for example, often treat diabetes and hypertension as universal outcomes of urbanisation, dietary excess, and sedentary lifestyles. Yet emerging research in metabolic epidemiology, genetic predisposition, and ecological adaptation reveals a far more complex picture. Certain populations may develop diabetes in the absence of obesity or hypertension, owing to insulin insufficiency linked to early-life undernutrition or intergenerational famine exposure (referred to as type 5 diabetes). Others may experience hypertension without hyperglycemia, driven by genetic salt sensitivity in historically sodium-scarce environments. Recognising and responding to these differences is essential for the success of any public health efforts.

This paper proposes a general methodological framework to guide the development of a subnational strategy in which distinct epidemiologic zones are identified and sharply defined precision public health strategies are framed for each zone. This method is applied in the paper to hypertension (HTN) and high blood glucose (HBG) to develop a precision public health strategy for India.

2 Methods

The approach proposed in this paper comprises three steps. The three-step approach is intended as a practical, evidence-based guide for regional strategy formulation and implementation in India and other LMICs.

2.1 Step 1: Identify distinct epidemiological zones

Using publicly available data, identify distinct epidemiological zones that have sufficient granularity to capture the variation in disease prevalence. However, the separation between zones would need to be sufficient to allow distinct public health strategies to be developed.

This paper, as an application of this method, focused on hypertension (HTN), an NCD, and high blood glucose (HBG), a surveillance indicator of diabetes risk, as two critical markers in India's evolving NCD profile. Using data from the 5^{th} Round of the National Family Health Survey (NFHS-5) [3], the country was divided into four clusters of states based on the median HTN and HBG (rounded down to generate conservative values)

for men (NFHS-5 reports data separately for men and women – data for men was used in this analysis because of the higher prevalence of these conditions among them). HTN was defined as "systolic blood pressure $\geq$ 140 mmHg, or diastolic blood pressure $\geq$ 90 mmHg at the time of the survey, or currently taking medicine to lower blood pressure." HBG was defined as "random blood glucose $\geq$ 140 mg/dl at the time of the survey". These definitions reflect NFHS-5 survey-based operational criteria and do not constitute repeated clinical diagnostic confirmation. Hypertension is treated as an NCD using the NFHS-5 operational definition. High blood glucose (HBG), as defined in NFHS-5, is used as a surveillance proxy for diabetes risk rather than as a confirmed diagnosis of diabetes. This approach generated four epidemiological zones: Q1 = High HBG + High HTN; Q2 = High HBG + Low HTN; Q3 = Low HBG + High HTN; and Q4 = Low HBG + Low HTN.

2.2 Step 2: Develop determinant and risk factor profiles for each zone

Select appropriate determinants, drivers, and risk factors and examine data on them to identify whether distinct patterns emerge for each zone, which can be used as input into the development of precision public health strategies.

Based on an understanding of the determinants, drivers, and risk factors associated with these conditions and expert consultations, twelve factors were chosen, namely, (i) Urbanisation, (ii) Sedentary Lifestyle, (iii) Energy-Dense Diet, (iv) History of Famine, (v) Lean Body Mass, (vi) Early-life Undernutrition, (vii) Salt Sensitivity, (viii) Tribal Populations, (ix) Manual Labour, (x) Traditional Diet, (xi) Physical Activity, and (xii) Low Caloric Intake as having the potential to help distinguish between the different zones and of relevance to patterns of HTN and HBG prevalence. For conceptual clarity, the twelve factors were grouped into three categories. Structural determinants included urbanisation, history of famine, tribal population composition, and early-life undernutrition, which shape long-term ecological and socio-demographic contexts. Drivers referred to behavioural and occupational pathways such as sedentary lifestyle, manual labour, physical activity, and dietary patterns. Risk factors were defined as biological or physiological characteristics directly associated with hypertension or high blood glucose, including lean body mass and salt sensitivity. While certain variables span categories conceptually, this classification clarifies their role within the analytic framework.

Some factors in the twelve-variable framework are conceptually related — for example, sedentary lifestyle, manual labour, and physical activity. These were nevertheless retained as separate entries to preserve visibility into different aspects of behaviour and occupational structure. While they may overlap statistically, they represent distinct domains in public health practice: sedentary lifestyle pertains to urban desk work, manual labour to occupational exertion, and physical activity to overall movement, including domestic and leisure activity. Their independent inclusion is justified on policy design grounds, where distinct interventions are required to target each domain.

Each factor was assessed using a proxy variable or set of indicators derived from publicly available datasets such as NFHS-5 [3], NSSO [4], Census 2011 [5], NNMB [6], and IHDS [7]. Using data from these datasets, with the help of ChatGPT (4.0), each factor was scored at the state level on a three-point ordinal scale: low (1), medium (2), and high (3). State scores were averaged within each quadrant to generate mean factor values and a Heat Map. From the Heat Map, a disease-prevalence typology for each quadrant

was developed. States near quadrant boundaries or showing mixed characteristics were flagged as edge cases. The details of the Heat Map methodology and the data sources used are given in Section A of the Appendix.

For each of these factors, using multiple approaches, such as keyword search, Boolean search, and semantic search, on databases and search engines such as Google, Google Scholar, PubMed, and ScienceDirect, studies about their relevance to HTN and HBG and their prevalence in the various states were identified. Using insights from these studies, detailed factor-level profiles were developed for each quadrant.

2.3 Step 3: Precision public health Strategy for each zone

Having identified the epidemiologic and associated factor profiles for each zone, select the domains of action and develop an evidence-based precision-public-health strategy for each zone.

Five strategic domains of action, along with country case studies and implementation guidance, were selected as the seven components for which data would be sought. These seven components were: (i) Cultural Evolution of Health (CEH) [8], (ii) One Health [9], (iii) Social Determinants of Health (SDOH) [10], (iv) Public Health [11], (v) Healthcare [12], (vi) Country Case Studies, (vii) Implementation.

To identify studies and extract data, a rapid review approach was employed. For each quadrant, using SciSpace, a database comprising more than 270 million studies, semantic queries were executed, the 40 most-cited studies were selected, and data on each of the seven components mentioned above were extracted. Additional studies were included for information on pharmacy use, implementation guidance, and CEH. Having chosen the studies and extracted the data, a narrative synthesis of the evidence was done to help frame the precision-public-health strategy for each quadrant. The details of the rapid review approach used are provided in Section B of the Appendix.

3 Results

3.1 Step 1: Distinct epidemiological quadrants

Table 1 and Figures 1 and 2 present the quadrant-wise classification of Indian states using data from NFHS-5 [3]. It can be seen from the map in Figure 2 that while the Q4 states (low HBG+Low HTN) are largely in the northern and north-western parts of India, the Q1 states (high HBG+High HTN) are, for the most part, located in southern India. The Q2 states (high HBG+low HTN) are largely confined to the Bengal region in eastern India, potentially including Bangladesh, as well as parts of Jharkhand and Meghalaya. It is also interesting to see from Figure 1 that the states of Andhra Pradesh,

Table 1 HBG-HTN Prevalence among Indian Men (NFHS-5)

Quadrant	States (A–Z)	HTN Prevalence (%)	HBG Prevalence (%)
Q1	Andhra Pradesh, Chandigarh, Gujarat, Karnataka, Kerala, Lakshadweep, Manipur, Mizoram, Odisha, Sikkim, Tamil Nadu, Telangana	30.2	19.3
Q2	Assam, Bihar, Goa, Maharashtra, Puducherry, Tripura, West Bengal	20.3	18.1
Q3	Arunachal Pradesh, Chhattisgarh, Delhi, Haryana, Nagaland, Punjab, Uttarakhand	31.0	13.0
Q4	Himachal Pradesh, Jammu & Kashmir, Jharkhand, Ladakh, Madhya Pradesh, Meghalaya, Rajasthan, Uttar Pradesh	20.9	11.5

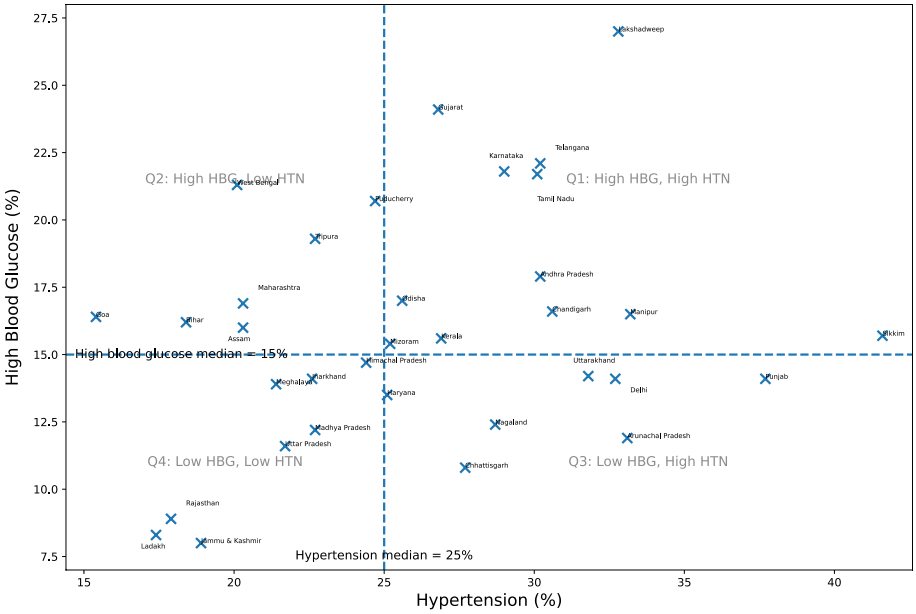


Fig. 1 HBG-HTN Prevalence among Indian Men (NFHS-5). This quadrant plot categorises Indian states based on the prevalence of HTN (X-axis) and HBG (Y-axis) among men as reported in NFHS-5. Conservative prevalence cut-offs of 25% for HTN and 15% for HBG were used to divide states into four typological quadrants: Q1 = High HBG + High HTN; Q2 = High HBG + Low HTN; Q3 = Low HBG + High HTN; Q4 = Low HBG + Low HTN

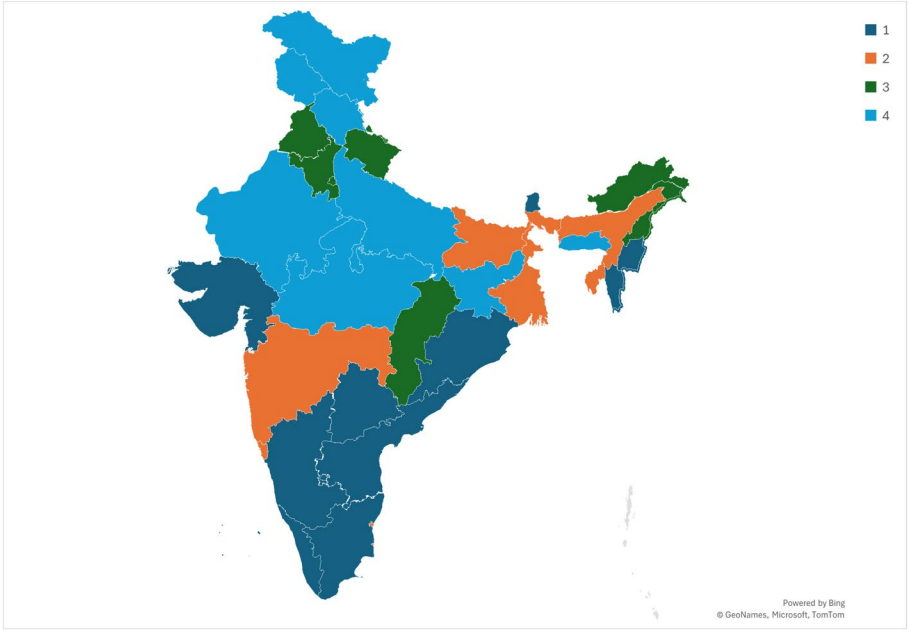


Fig. 2 HBG-HTN Prevalence among Indian Men (NFHS-5). This map categorises Indian states based on the prevalence of HTN and HBG among men as reported in NFHS-5. Conservative prevalence cut-offs of 25% for HTN and 15% for HBG were used to divide states into four typological quadrants: Q1 = High HBG + High HTN; Q2 = High HBG + Low HTN; Q3 = Low HBG + High HTN; Q4 = Low HBG + Low HTN

Karnataka, and Tamil Nadu in Q1 (high HBG+High HTN) are almost the exact opposites of the states of Rajasthan, Ladakh, and Jammu & Kashmir in Q4 (low HBG+Low HTN). Similarly, West Bengal in Q2 (high HBG+low HTN) and Arunachal Pradesh in Q3 (low HBG+High HTN) appear to be exact opposites of each other in terms of the prevalence of HBG and HTN.

3.2 Step 2: Determinant and risk factor profiles for each quadrant

For each of the factors that are likely to be the drivers of disease prevalence, data were extracted from multiple studies for each of the states and quadrants listed in Table 1 and were used to create a Heat Map (Figure 3) and build out risk factor profiles for each quadrant (Table 2). The identified studies are listed in Table 6, and the details of the factor level profiles of each quadrant are given in Section C of the Appendix.

While the focus of this study is on the four quadrants and disease typologies associated with them, it is critical to note that, as shown in Table 2, several states, although formally classified into one of the four quadrants, exhibit characteristics that deviate from the dominant pattern. These *edge case states*, including Goa (classified under Q2), Delhi (under Q3), Sikkim and Mizoram (under Q1), and Ladakh (under Q4), are discussed briefly in Section D of the Appendix.

3.3 Step 3: Precision public health strategy for each quadrant

Using the epidemiologic and factor profiles, a precision public health strategy was developed for each quadrant. Each quadrant calls for a context-specific precision public health strategy spanning five domains and two supportive inputs: (1) the cultural evolution of health (CEH), (2) One Health and planetary health, (3) social determinants of health (SDOH), (4) public health systems, (5) healthcare services, (6) relevant country case studies, and (7) implementation approaches. Table 3 gives the summarised precision-public-health strategy for each of the five domains. The detailed quadrant strategies are presented in Section E, and the studies used to generate these strategies are listed in Tables 7 to 10, in the Appendix.

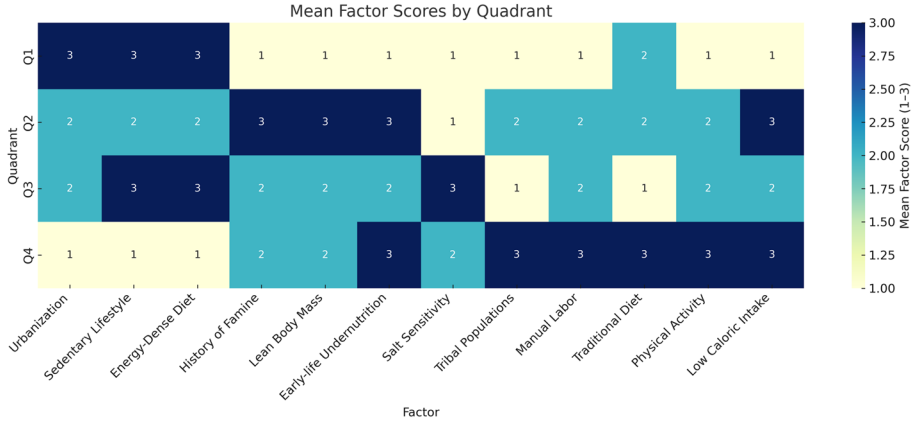


Fig. 3 Heat Map: Mean Score of Twelve Factors by HBG–HTN Quadrant. The Heat Map visualises the average score of the twelve physiologically grounded factors across four HBG–HTN quadrants. Each factor was rated on a scale of 1 (Low), 2 (Medium), to 3 (High) based on available state-level data for each factor

Table 2 Summarised Quadrant Assignment with Proposed Mechanism Labels

Quadrant	Type	States	Edge Case Note	Proposed Label (Dominant Mechanism)
Q1	Typical States	Andhra Pradesh, Chandigarh, Gujarat, Karnataka, Kerala, Lakshadweep, Manipur, Odisha, Tamil Nadu, Telangana		Obesogenic-Urban Syndrome (Metabolic overload, inactivity)
Q1	Edge Case States	Mizoram, Sikkim	Mizoram may align more with Q4 due to tribal traits; Sikkim is a small high-altitude outlier	Possibly Q4 or Independent
Q2	Typical States	Assam, Bihar, Maharashtra, Puducherry, West Bengal		Lean-Insulin Insufficiency Cluster (Epigenetic and famine-induced β-cell failure)
Q2	Edge Case States	Goa, Tripura	Goa has urban and dietary traits of Q1; Tripura has tribal traits similar to Q4	Mixed Phenotype
Q3	Typical States	Arunachal Pradesh, Chhattisgarh, Haryana, Nagaland, Punjab, Uttarakhand		Salt-Sensitive HTN Cluster (Vascular tone dysregulation)
Q3	Edge Case State	Delhi	Urban, high-HBG profile may fit better with Q1	Possibly Q1
Q4	Typical States	Himachal Pradesh, Jammu & Kashmir, Jharkhand, Madhya Pradesh, Meghalaya, Rajasthan, Uttar Pradesh		Traditional-Resilient Cluster (Protective cultural ecology)
Q4	Edge Case State	Ladakh	Small, high-altitude state with unique physiology; warrants separate analysis	Independent/High-Altitude Cluster

3.4 Final outcome

Based on the results presented in Tables 1, 2, and 3 the following epidemiologic-risk-factor-precision-public-health profiles for India were determined:

1. *Quadrant 1: Dual Burden States:* These states, such as Kerala and Tamil Nadu, exhibit high prevalence of both HBG and HTN. They score high on ecological risks, such as being overweight, having sedentary lifestyles, and consuming ultra-processed foods. Precision strategies should focus on re-norming behaviours, integrated risk detection and treatment, and active transport and dietary regulation.
2. *Quadrant 2: Insulin-Deficient States:* These states, such as West Bengal and Bihar, show high HBG prevalence despite low obesity and HTN, pointing to lean phenotypes and developmental origins of insulin insufficiency (or type 5 diabetes). Strategies must prioritise recalibrated screening tools, improved insulin access, and outreach tailored to early-life nutritional vulnerability.
3. *Quadrant 3: Salt-Sensitive States:* These states, such as Chhattisgarh and Jharkhand, have high HTN prevalence but low HBG, with contextual factors including high salt intake, low processed food exposure, and active livelihoods. Interventions should emphasise decentralised blood pressure (BP) control, community-level salt reduction, and culturally rooted health messaging.
4. *Quadrant 4: Prevention-Window States:* These states, such as Rajasthan and Himachal Pradesh, currently show low prevalence of both conditions and maintain protective ecological conditions — high physical activity, low ultra-processed food penetration,

Table 3 Precision Public Health Strategy for Each Quadrant

Domain	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4
Cultural Evolution of Health	Foster lifestyle re-norming via messaging by culturally embedded CHWs, changes in food habits, and increases in physical activity levels.	Reinterpret the culture of fasting by women and promote the eating of dairy, legumes, and iron-rich greens as a sacred duty to future generations.	Shift the perception of salt from a symbol of strength to one of vulnerability.	Frame walking, cycling, and plant-based eating as aspirational, modern behaviours.
One Health	Converge disease prevention with agricultural and food system policies to promote healthier alternatives.	Focus on reversing land degradation and re-enriching soils with micronutrients.	Reverse deforestation and restore access to potassium-rich foods.	Promote approaches that see frugality and ecological wisdom not as obstacles but as opportunities.
Social Determinants of Health	Prioritise modifying the built and transportation environments to make walking a part of daily life.	Alter social and community contexts that invisibilise the health status of women.	Address food insecurity so that people can buy natural potassium-rich foods and reduce their dependence on packaged foods with high salt content.	Take care not to mimic car-centric urban sprawl but to instead build new urban areas as compact, walkable environments.
Public Health	Focus on community education, food labelling, and taxation of unhealthy food products.	Shift disease surveillance from tracking high adult BMI to low birthweight, and focus NCD-related nutritional interventions on adolescent girls and the composition of foods in public systems.	Focus on reducing salt consumption and promoting the use of potassium-based salt substitutes through fiscal subsidies.	Shift focus to "primordial prevention" and work through schools and communities to prevent risk-factor formation.
Healthcare	Introduce task-shifting, proactive risk stratification, and early pharmacologic control at primary and secondary levels.	Ensure access to insulin and point-of-care diagnostics for insulin in rural and peri-urban settings.	Decentralise BP control to pharmacies, CHWs, and tribal health workers using risk stratification protocols.	Avoid prematurely investing in high-cost hospital infrastructure, and build strong gatekeeping at the primary care level.

and resilient food traditions. Precision strategies should focus on frugal innovation, aspirational behavioural reinforcement, and preservation of ecological buffers before risk transition sets in.

4 Discussion

This paper proposes a generalisable methodology for subnational typology construction in public health, designed to support more context-sensitive policy planning in low- and middle-income countries (LMICs). The approach combines (1) epidemiological classification into quadrants based on relative disease burdens, (2) ecological heat mapping to assess contextual variation, and (3) structured evidence synthesis to inform tailored strategy design. While India is the site of its first application, the framework is adaptable to other federal or decentralised health systems with spatial heterogeneity in disease patterns.

The application to India revealed notable epidemiological decoupling: some states face a dual burden of HTN and HBG (Quadrant 1), while others exhibit high HBG but low HTN prevalence (Quadrant 2), or the reverse (Quadrant 3). These patterns challenge assumptions that these two conditions co-occur uniformly or that they share the same

modifiable risk factors. For instance, lean HBG phenotypes suggest insulin insufficiency rather than resistance (indicative of type 5 rather than type 2 diabetes), and salt-sensitive HTN appears to be a key driver in some northern states. These findings reinforce the importance of moving beyond standardised risk-framing towards culturally and biologically specific strategies.

India's health system, with its blend of decentralised implementation and central programme design, provides an ideal case for testing such a typology-driven approach. The quadrant framework, supported by an ecological heat map and evidence synthesis across five domains (and two supportive inputs), offers state-level planners an implementable set of recommendations. These span cultural and behavioural re-norming, One Health linkages, structural determinants, health system design, and implementation pathways. By using publicly available national data (NFHS, Census, NSSO), the framework also demonstrates feasibility in settings with limited real-time surveillance infrastructure.

Importantly, this methodology is not specific to HTN and HBG. It could be applied to other disease clusters that display uneven spatial distribution, such as anaemia and stunting, maternal mortality and facility delivery, mental health and substance use, or cancer (see Section F of the Appendix for a discussion of its application to cancer). Its quadrant logic offers a structured yet flexible approach to planning: one that supports horizontal coherence across policy domains and vertical coherence across health system levels. It enables programme differentiation not only across regions but also across health system functions — from public health to clinical care to community mobilisation.

There are, of course, limitations. The quadrant classifications are based on cross-sectional prevalence and relative thresholds, which may miss intra-state variation and longitudinal dynamics. The ecological heat map, while context-rich, is inherently interpretive. Strategy synthesis relied on literature from diverse LMIC contexts; while this supports generalisability, it may obscure state-specific feasibility constraints. Additionally, while the quadrant strategy recommendations are grounded in evidence, their implementation depends on local political will, bureaucratic bandwidth, and intersectoral coordination.

Nonetheless, the quadrant-based framework offers an actionable model for precision public health planning. It provides a replicable approach to diagnosing subnational variation, aligning strategies with local realities, and generating performance metrics tied to meaningful outcomes. In doing so, it supports not just smarter programme design—but also more equitable and accountable governance of health systems.

5 Limitations

Several limitations should be acknowledged.

First, the quadrant typology and ecological heat map are based on cross-sectional data from NFHS-5 and related sources. As such, the framework captures static snapshots rather than temporal dynamics or transitions between disease states. States undergoing rapid demographic or epidemiological change may not fit neatly into a single quadrant over time.

Second, the classification relies on relative thresholds rather than absolute clinical or policy-driven cut-offs. This makes the typology sensitive to the choice of percentile breakpoints and potentially less comparable across countries or time periods. While this enhances internal coherence for India, it may constrain generalisability unless recalibrated for other contexts.

Third, the ecological heat map and strategic alignment process involve interpretive judgment. While the method is grounded in empirical data and literature synthesis, decisions about what constitutes "contextual fit" for a strategy are ultimately qualitative in nature. Although transparent, this step may vary depending on the research team or policymaker priorities. There is also a significant concern about the choice of determinants and risk factors underlying the heat map. In the paper, expert consultation drove this choice. However, it is vital to recognise that what the paper finds and prescribes depends on the choice of these risk factors. For example, the inclusion of factors related to the commercial determinants of health, especially given the crucial role of the commercial interests of the tobacco, alcohol, and ultra-processed foods industries in shaping these epidemics, could offer additional valuable perspectives but has not been considered in the paper.

Fourth, the framework is designed to accommodate inter-state variation but does not capture within-state heterogeneity. Large states such as Uttar Pradesh or Maharashtra may contain multiple epidemiological zones that are flattened by state-level aggregation. Sub-district or district-level applications, however, would require finer-grained data not just on the disease burden, but also on the risk factors driving it. Given the relative rigidity of the state-level governance structures, it may also be challenging to implement substantially different strategies in different parts of the state. State-level policymakers seeking to apply this framework would be best placed to decide how to balance these different considerations.

Fifth, the feasibility of implementation has not been assessed in this study. While the seven-part strategies draw from real-world case studies and evidence, the actual capacity for health systems to adopt these approaches, especially those requiring multisectoral coordination, cultural adaptation, or community engagement, remains an open question.

Finally, the quadrant typology is not a predictive model. It is a strategic planning heuristic meant to inform differentiated programme design, not to forecast disease risk at the individual or population level.

6 Use of AI in evidence synthesis

Artificial intelligence (AI) tools (Chat GPT 4.0 & SciSpace) were used to support literature screening, annotation, and thematic synthesis during the development of quadrant-specific strategies. AI-assisted workflows accelerated the identification of relevant studies and facilitated the extraction of domain-specific content across multiple thematic dimensions (e.g., cultural framing, public health system responses, healthcare interventions). All AI-generated content was reviewed, edited, and validated by the author. No strategy, citation, or thematic interpretation was used without direct human oversight. This hybrid approach improved efficiency and thematic coherence, but it also introduced new considerations.

7 Conclusion

Uniform strategies are ill-suited to complex federal health systems where disease prevalence and structural conditions vary widely across regions. This paper presents a general methodological framework for constructing regional typologies based on disease prevalence and contextual variation. The Indian case illustrates how this method can

reveal under-recognised patterns, such as insulin-deficient HBG in lean populations or salt-sensitive HTN in non-obese groups, and map them to tailored strategies. The use of publicly available data ensures the approach remains feasible and replicable across LMIC settings. The resulting strategies are practical, modular, and aligned with existing health system structures, but offer a new layer of precision in their regional targeting.

By integrating epidemiology, ecological reasoning, and evidence-informed strategy development, this framework contributes both to the theory and practice of precision public health. It opens the door for smarter programme design, state-level autonomy in implementation, and a stronger link between data and decision-making. Future work should extend the model to other disease clusters, incorporate real-time data where available, and evaluate the operational effectiveness of quadrant-specific strategies. With appropriate institutional support, typology-based planning can transform how national programmes are adapted to serve diverse populations more equitably and effectively.

8 Policy implications

This study introduces a generalisable planning methodology that enables health system actors to classify regions based on disease prevalence and contextual variation, and then match each profile to a differentiated public health strategy. Using publicly available data, the approach combines epidemiological classification with ecological heat mapping and evidence-informed intervention design. It is designed to support adaptive strategy planning in federal or decentralised systems, especially in low- and middle-income countries (LMICs) where spatial heterogeneity is high and real-time surveillance capacity may be limited.

In the Indian case, this methodology was applied to construct a 2×2 quadrant typology for HTN and HBG, but the underlying approach is more flexible. From Figure 1, even with the current data, it can be seen, for example, that Indian states can perhaps be more granularly distributed in a 6x8 matrix, with a state like Rajasthan sitting in the healthiest $C_{1,1}$ cluster; Punjab in $C_{5,3}$, the very-high HTN moderate HBG cluster; Gujarat in $C_{3,7}$, the moderate HTN very-high HBG cluster; and West Bengal in $C_{2,6}$, the low HTN very-high HBG cluster. The method can thus support multiple levels of planning—providing a basic quadrant framework for national programming, and more granular state-level insights for targeted implementation.

For India's Ministry of Health and Family Welfare and state health departments, the framework offers a decision-support tool that aligns public health investment with epidemiological need. It can guide the tailoring of service packages at health and wellness centres, inform differentiated workforce deployment, and structure performance metrics linked to local burden profiles. It also enables adaptive targeting within large-scale programmes such as Ayushman Bharat and the National Programme for Prevention and Control of NCDs (NPCDCS). The quadrant model enables India to transition toward a data-driven, equity-oriented model of preventive health, where strategies are not only scaled nationally but also shaped locally, respecting individual metabolic histories, environmental exposures, and cultural resilience. Over time, it may be extended to a 3×3 or 4×4 matrix at the sub-state level, deepening the granularity and precision of NCD governance in India.

For other LMICs, the approach offers a low-cost, data-accessible framework for subnational health planning. It is applicable to any health outcome with spatial variability

— whether non-communicable diseases, maternal health, malnutrition, or mental health. Its modular structure enables customisation to the local policy environment while preserving a common analytic logic. Operationalising this framework requires a shift in planning culture — from uniform targets to burden-aligned strategies; from siloed interventions to integrated, context-aware design. It can be supported through national health accounts, district planning platforms, and digital public infrastructure that integrates epidemiological and ecological data. With institutional support, this methodology can strengthen the responsiveness, efficiency, and equity of health systems navigating complex, heterogeneous conditions.

A Heat map methodology & results

A.1 Selection of factors

Based on our understanding of the drivers of these conditions, twelve factors, namely, (i) Urbanisation, (ii) Sedentary Lifestyle, (iii) Energy-Dense Diet, (iv) History of Famine, (v) Lean Body Mass, (vi) Early-life Undernutrition, (vii) Salt Sensitivity, (viii) Tribal Populations, (ix) Manual Labour, (x) Traditional Diet, (xi) Physical Activity, and (xii) Low Caloric Intake, were chosen, as having the potential to help distinguish between the different states and of relevance to the HTN and HBG disease prevalence. Some factors in the twelve-variable framework are conceptually related—for example, sedentary lifestyle, manual labour, and physical activity. These were retained as separate entries to preserve visibility into different aspects of behaviour and occupational structure. While they may overlap statistically, they represent distinct domains in public health practice: sedentary lifestyle pertains to urban desk work, manual labour to occupational exertion, and physical activity to overall movement, including domestic and leisure activity. Their independent inclusion is justified from a policy design standpoint, where different interventions are required to target each domain.

A.2 Data extraction & scoring

Each factor was assessed using a proxy variable or set of indicators derived from publicly available datasets such as NFHS-5 [3], NSSO [4], Census 2011 [5], NNMB [6], and IHDS [7]. Using ChatGPT (4.0), data were extracted from these studies, and each factor was scored for each state and quadrant. The scoring was done on a 3-point ordinal scale: 1 (low), 2 (medium), and 3 (high) using the method described in Table 4. The scores for each factor in every state were manually verified to ensure plausibility and are presented in Table 5. Where available, published thresholds (e.g., for urbanisation or body mass index) guided the cut-off points. In other cases, tertile-based splits or qualitative judgments (e.g., historical famine exposure) were used. The scoring method is intended to strike a balance between interpretability and fidelity to public health variation. While simplifications are inherent in ordinal classification, this approach allowed for cross-factor comparability and supported the development of a multidimensional Heat Map and typology.

A.3 Construction of the heat map

State scores were averaged within each quadrant to generate mean factor values (see Table 5 and create a Heat Map. States near quadrant boundaries or showing mixed characteristics were flagged as edge cases. This approach privileges interpretive validity over

statistical generalisability and is intended to support typological hypothesis-building rather than formal causal inference. From the Heat Map, a disease-prevalence typology for each quadrant was developed. States near quadrant boundaries or showing mixed characteristics were flagged as edge cases. While the current typology is anchored in NFHS-5 data, it is intended to evolve. A reclassification protocol should be considered wherein future rounds of NFHS or biomedical survey data can trigger reassignment if (a) prevalence crosses typological thresholds, or (b) dominant factor scores shift substantially. This approach maintains consistency while remaining responsive to state-level epidemiological transitions and policy interventions. An updating framework using either latent class models or decision trees could support this effort.

B Rapid review approach

1. *Semantic Queries for each Quadrant on SciSpace*: SciSpace has over 270 million studies, and a decision was taken to restrict the search to SciSpace for identifying the studies needed to develop the precision-public health strategies for each quadrant. For each quadrant carefully designed semantic queries were submitted to SciSpace: `Integrated care for diabetes and hypertension in primary health systems in LMICs` for Q1, `Community-level interventions for the prevention and treatment in famine-exposed populations with epigenetic changes and beta-cell damage of diabetes resulting from low insulin secretion` for Q2, `Effective community-level interventions for preventing and treating salt-sensitive hypertension in tribal and other high-risk populations` for Q3, and `Effective community-based interventions for the long-term prevention of diabetes and hypertension in the future in lean, healthy populations, in low-income countries` for Q4.
2. *Identification of included studies*: Using these semantic queries, SciSpace presented between 300 and 600 relevant studies for each query. The 40 most cited studies were chosen from that list, and a few more studies in specific areas were added.
3. *Creating a Library of all the PDF files*: While SciSpace can identify the necessary studies, it does not have the full text of all the studies. Using multiple search approaches, the full-text PDFs for the included studies were uploaded onto SciSpace.
4. *Creating an Evidence Table*: Using the unique capabilities of SciSpace, data was extracted from each study for the following 17 fields: (i) Summary of the paper; (ii) Insights on the Semantic query; (iii) Name of the country where the study was based and the number of participants in the study, where relevant; (iv) Health condition targeted by the intervention; (v) Intervention description; (vi) Platform used to deliver the intervention; (vii) Setting (rural, urban, or tribal); (viii) target population; (ix) Diagnostic tools used in the study; (x) Main outcome measured; (xi) Evidence of effectiveness; (xii) Implementation notes; (xiii) cultural ecology of health; (xiv) One health; (xv) Social determinants of health; (xvi) Public health; (xvii) healthcare. This was followed by creating an evidence summary for each quadrant.
5. *Development of Precision-Public Health Strategy*: A narrative synthesis of the evidence generated from the included studies was then used to develop a precision-public-health strategy for each quadrant on the following seven parameters: (i) Cultural Evolution of

Health (CEH); (ii) One Health; (iii) Social Determinants of Health (SDOH); (iv) Public Health; (v) Healthcare; (vi) Country Case Studies; and (vii) Implementation.

C Detailed quadrant level factor profiles

For each of these factors, using multiple approaches such as keyword search, Boolean search, and semantic search on databases and search engines such as Google, Google Scholar, PubMed, ScienceDirect, and ChatGPT (4.0), the studies about their relevance to HTN and HBG and their prevalence in the various states were identified. Using insights from these studies, detailed factor-level profiles were developed for each quadrant. The identified studies are listed in Table 6, where each row represents the factor used to create the quadrant-level Heat Map.

C.1 Quadrant 1 (Q1): obesogenic-urban syndrome

States in this quadrant show a high prevalence of both HBG and HTN. This pattern is associated with urbanisation, sedentary living, and energy-dense diets.

- **Urbanisation:** Kerala (47.7%) and Tamil Nadu (48.5%) are among the most urbanised states [5].
- **Sedentary lifestyle:** Prevalent employment in service sectors with low physical activity [7].
- **Energy-dense diet:** High fat and calorie intake from processed foods [4, 6].
- **Low physical activity and manual labour:** Limited engagement in physically intensive work [7]. The "hinge" of insulin resistance that connects HTN and HBG [13] is likely a key driver of the twin burden, along with factors such as high salt consumption, energy-dense diets, and low levels of physical activity in these states.

C.2 Quadrant 2 (Q2): lean-insulin insufficiency cluster

States in this quadrant show a high prevalence of HBG but not HTN. This quadrant represents a lean HBG phenotype, often driven by insulin insufficiency (indicative of type 5 diabetes).

- **Famine history:** It is now well understood that South Asians are generally more likely to develop diabetes at a younger age relative to European and North American populations on account of what is referred to as a "thrifty metabolic profile" [14, 15]. However, it is apparent from the work of Singh, Shukla, and others [16] that even within this group, the residents of Bengal and Bihar are at a higher risk of developing diabetes. The unusually high exposure the region has had to repeated famines, such as the 1943 and the 1974 famines [17], and the epigenetic changes that have resulted from it appear to have exacerbated diabetes risk by further impairing insulin production in these populations relative to other South Asians [18–20]. While other parts of South Asia have also experienced periodic food shortages, especially during colonial rule (such as the Deccan famine and the Orissa famine), the recurrence and intensity of famines in this region were unusually high.
- **Early-life undernutrition:** High stunting in children (Bihar 42.9%, WB 32.5%) [3].
- **Lean body mass:** High prevalence of BMI < 18.5 among adults [3].
- **Low caloric intake:** Average rural intake below 2100 kcal/day [4].
- **Traditional diet:** Low-fat, rice-based diets with minimal processing [21].

C.3 Quadrant 3 (Q3): salt-sensitive hypertension cluster

High HTN with low HBG prevalence, suggestive of salt-sensitive hypertension.

- **Manual labour decline:** Mechanised farming is reducing physical workload, but physical activity levels still continue to be high [7].
- **Urbanisation:** National Capital Region (Delhi) and Chandigarh showing increased suburbanisation, but the states, as a group, are still predominantly rural [5].
- **Energy-dense diet:** Rich in wheat, animal fats, and dairy [6].
- **Tribal populations:** There is a high proportion of tribal populations in Arunachal Pradesh, Chhattisgarh, and Nagaland [5]. Tribal populations evolving in inland or forested zones (e.g., central India, sub-Saharan Africa), such as those in these three states, had limited access to dietary sodium. Over generations, these groups developed *salt-conserving physiology* [22, 23]. In modern settings with increased salt exposure, this predisposition results in higher blood pressure [24–26]. In contrast, coastal populations (e.g., Kerala, Goa) had regular access to salt from fish, salt pans, and trade, and consequently experienced less evolutionary pressure to retain sodium and possibly lower baseline salt sensitivity. However, it is critical to note that even tribal populations that have developed salt sensitivity span a spectrum of ecological integration. In states like Jharkhand, Madhya Pradesh, and Meghalaya, they still maintain high physical activity, low-sodium diets, and coarse grains — leading to low HBG and HTN [6] and preserved *ecologies*. However, in states like Chhattisgarh, Odisha, and parts of Maharashtra, tribal groups are experiencing *transitional ecologies* due to increased market access to refined foods, decline in manual labour, and rising salt intake. As a result, these areas report a higher prevalence of HTN even among lean adults with low caloric intake [27].
- **Salt sensitivity:** HTN is prevalent among normal-weight individuals even without a tribal ancestry in Haryana, Punjab, and Uttarakhand [27]. Salt-sensitivity in these states could be driven by factors such as a high reliance historically on pickled, salted, and preserved foods, especially in traditional Punjabi and Haryanvi diets (e.g., achars, salted dairy, lassi with salt) and low potassium intake (due to reduced fruit/vegetable consumption) that can amplify salt sensitivity by affecting sodium-potassium balance, increasing vascular resistance. In Uttarakhand, high-altitude physiology may increase susceptibility to salt-related blood pressure elevation [28].

C.4 Quadrant 4 (Q4): traditional-resilient cluster

Low disease prevalence supported by traditional subsistence lifestyles.

- **Tribal populations:** High tribal populations in Jharkhand, Meghalaya, and Madhya Pradesh [5], potentially with higher salt-sensitivity but with *preserved ecologies*.
- **Traditional diets:** Millet and tuber-based diets with low glycemic index [21].
- **Manual labour:** Agrarian and forest-based occupations [4].
- **Physical activity:** High daily activity from subsistence work [7].
- **Low caloric intake:** Minimal consumption of energy-dense foods [6].

D Discussion of edge cases

While the focus of this study is on the four quadrants and their disease typologies identified above, it is critical to note that, as shown in Table 2, several states, although formally classified into one of the four quadrants, exhibit characteristics that deviate from the dominant pattern. These *edge case states*, including Goa (classified under Q2), Delhi (under Q3), Sikkim and Mizoram (under Q1), and Ladakh (under Q4), serve as analytically valuable exceptions. Such cases often reflect *transitional ecologies* or *heterogeneous internal profiles*. For instance, Goa exhibits urban dietary patterns similar to Q1 but is classified under Q2 due to its relatively lean metabolic profile. Delhi, with its high levels of urbanisation, could easily fall under Q1 but is retained in Q3 due to a high HTN prevalence along with a relatively lower HBG prevalence, a pattern not typically associated with insulin resistance. Similarly, small, high-altitude regions like Sikkim and Ladakh introduce unique physiological and logistical variables — altitude adaptation, climatic constraints, or localised food ecologies — that resist quadrant generalisation. These edge cases underscore the importance of local context and suggest that quadrant-based strategies should be applied with nuance, flexibility, and allowance for subregional targeting. In future typologies, such states may warrant their own transitional or hybrid classification or serve as early warning indicators of quadrant migration.

E Precision public health strategies

E.1 Strategy for quadrant 1 (Q1): obesogenic-urban syndrome

Building on the quadrant-level typology developed earlier, this section outlines a comprehensive public health strategy tailored to the states classified in Q1, drawing on the evidence generated (summarised in Table 7). A total of 40 studies were identified from SciSpace, and three additional ones were added to provide a pharmacy perspective.

1. **CEH**: The shared, deeply held beliefs and norms with which human beings operate, also referred to as our *accumulated culture*, have evolved during times of severe scarcity and an appreciation only of visible threats. The current reality in these states, as discussed above, is very different, but, despite the urgency of the need for change, our *accumulated culture* has not yet adapted to this new reality. The use of culturally embedded community health workers to deliver chronic disease messaging in local languages, within familiar social networks in Ethiopia [29] and Tanzania [30]; the participatory design of patient education materials and the inclusion of peer supporters in group care models in South Africa [31]; family-based cooking sessions [32]; and community-based self-management programs addressing salt, fat, and sugar consumption in Iran [33] have had some success in shifting the accumulated culture as it relates to hypertension and diabetes. For durable change in the states in this quadrant, additional mechanisms drawing on CEH will need to be urgently developed to address entrenched habits such as tobacco use, excessive calorie intake, and a lack of physical activity.
2. **One health**: The One Health perspective calls for a convergence of disease prevention with agriculture and food system policy so that healthier alternatives gradually replace the production of low-priced, energy-dense foods.

3. **SDOH**: Steps in the domains of *education*, *social and community context*, and *economic stability* are all likely to be helpful, but for this quadrant, it would be crucial to act with urgency in the *neighbourhood and built environment* domain. There is a need to prioritise the development of public transport linked with walkable pavements in the states in this quadrant, so that physical activity becomes a default behaviour, leading to a reduction in insulin resistance levels [34, 35].
4. **Public health**: For Q1 states, the widespread co-occurrence of HBG and HTN demands a shift from reactive, individual-level interventions to robust, population-based preventive systems. Health education and lifestyle counselling were also recurrent themes. In Iran, a community-based intervention combining group-based health education, visual tools, and culturally adapted dietary messaging led to significant reductions in blood pressure and blood glucose at the population level [33]. In Uganda, integrating lifestyle counselling into NCD follow-up visits, rather than relegating it to separate sessions, was perceived by patients as more relevant and actionable [36]. Evidence from multi-country syntheses indicates that regulatory measures, such as sodium reduction in processed foods, front-of-pack labelling, and sugar-sweetened beverage taxation, are effective at the population scale when combined with mass communication [37]. These are essential reforms for states in this quadrant to prioritise.
5. **Healthcare**: Amongst all the levers, this is perhaps the one that has the potential to yield immediate benefits, even as the other levers discussed above become operational.

    (a) *Risk Stratification*: In Q1 states, where the burden of both HBG and HTN is high and long-term, population-wide disease control depends not only on early detection but on sustained, high-quality curative services. Yet many public health systems in these states remain configured for acute episodic care, with weak infrastructure for chronic follow-up, adherence monitoring, and risk-based treatment adjustment. The strategic pivot in healthcare must centre around early detection, structured follow-up, and risk stratification embedded within the architecture of primary healthcare and task shifting [38–41]. Evidence from multiple settings, such as South Africa [31] and Ethiopia [29], supports this shift in healthcare strategies.

    (b) *Task Shifting*: In Tanzania, nurses and clinical officers using protocol-driven management of hypertension and diabetes were able to safely initiate and titrate medications, with physicians serving a supervisory and referral role [40]. Similarly, in South Africa, nurse-led clinics supported by structured forms and algorithmic guidance produced improvements in both glycemic and blood pressure control, especially in settings where physician availability was limited [31]. Several studies addressed the issue of treatment adherence and therapeutic inertia—both common challenges in Indian public facilities [33, 38].

    (c) *Clinical Integration*: Clinical integration across diseases is also vital. The Ugandan experience with co-management of HIV, hypertension, and diabetes demonstrates that vertical silos can be dismantled in favour of multimorbidity clinics, improving efficiency and reducing stigma [36]. In India, where separate lines for each NCD

are often maintained at PHCs, this suggests a potential direction for service reorganisation.

(d) *Technology Enablement*: In this context, technology-enabled strategies hold considerable promise [39, 42, 43]. In Bangladesh, a multicomponent digital health intervention enabled CHWs to track patient status, send appointment reminders, and flag patients for physician escalation, improving retention and medication adherence [44]. Similar systems piloted in Kenya and Nigeria demonstrated how simple SMS tools improved appointment adherence and empowered patients to self-monitor blood pressure and glucose levels [43, 45].

(e) *Medical Supply Chains & Pharmacies*: Several studies emphasise the importance of medication supply chain reliability. Stockouts and inconsistent dosing regimens were reported as major causes of non-adherence and patient dissatisfaction [46, 47]. These findings highlight the need for curative strategies to include backend logistics reform, such as demand forecasting, digital inventory systems, and tiered distribution models — especially in Q1 states with large rural hinterlands. In this context, pharmacies have shown potential not only as an integral part of the supply chain but as decentralised nodes for preventive screening and access to advanced treatments [48, 49]. In Portugal, pharmacist-led medication therapy management significantly improved blood pressure outcomes in hypertensive patients [50]. Formally incorporating pharmacists into India's primary care continuum could bolster capacity to manage stable chronic patients in Q1 states.

6. **Country case studies**: There are several examples from Bangladesh [44]; Uganda [36], Tanzania [40], Ethiopia [29], South Africa [31], India [39, 41, 42, 46, 48, 49], and Brazil and Canada [50], that are worthy of careful study.
7. **Implementation**: Operationalising the Q1 strategy requires not only clear clinical models but a robust implementation architecture. It must move beyond isolated pilots to a structured, statewide operational framework. This requires leadership, workforce alignment, reliable data systems, and responsive supervision mechanisms—all built on the evidence base from diverse LMIC contexts, including India.

Taken together, these strategic directions for Q1 acknowledge that controlling the dual burden of HBG and HTN in high-burden regions necessitates a shift from reactive disease management to a systems-level transformation grounded in cultural, clinical, and institutional realignment. By integrating frontline pharmacies, investing in digital follow-up tools, supporting community health workers (CHWs) and nurses in care coordination, and grounding prevention efforts in local ecologies of risk, states like Kerala, Tamil Nadu, and Gujarat can model how a decentralised, resilient, and equitable non-communicable disease (NCD) strategy may be operationalised. The lessons drawn from diverse national and international implementations also provide a replicable roadmap for other high-burden settings.

E.2 Strategy for quadrant 2 (Q2): lean insulin-insufficiency cluster

Q2 states—such as West Bengal, Bihar, Assam, Tripura, Maharashtra, and Goa—present a paradox in India's metabolic landscape: high HBG prevalence coexists with low rates of HTN and obesity. Standard risk models, which rely on anthropometric cues and lifestyle proxies, systematically overlook these populations. The result is a growing cohort of undi-

agnosed, insulin-deficient individuals whose symptoms are misrecognised or missed altogether. This strategy addresses the unique typology of HBG in Q2: a phenotype shaped by foetal undernutrition, ecological deprivation, symbolic invisibility, and systemic neglect. Precision public health in this context must move beyond universal guidelines and recalibrate across seven key domains: cultural adaptation, ecological framing, social determinants, public health surveillance, healthcare system readiness, international learning, and implementation logistics. The development of the strategy draws on the evidence generated (summarised in Table 8. 40 studies were identified from SciSpace; one duplicate was removed, and nine additional studies were added, resulting in a total of 48 studies.

1. **CEH**: Here, the accumulated culture around HBG is rooted not in visible affluence or excess, but in long-standing traditions of austerity, food restraint, and intergenerational undernutrition [51–53]. While standard HBG messaging emphasises sedentary lifestyles and excessive intake, such framings create dissonance in communities shaped by famine, food scarcity, and structural deprivation. Within this dissonant landscape, public health efforts must address not just behaviours but the *accumulated culture* that gives those behaviours moral and symbolic weight. Here, austerity and thrift are culturally coded as virtues, contributing to the invisibilisation of diabetes risk among lean individuals who do not fit biomedical risk archetypes. The legacy of famine and undernutrition in these populations is well documented; yet, because their external body appearance does not match dominant disease imagery, risk recognition is delayed by individuals, families, and healthcare providers alike [54, 55]. To resolve this dissonance, cultural innovation is required — shifting the metaphorical framing of diabetes from *a disease of excess* to *a wound of survival*. Studies in India and China demonstrate that health narratives grounded in famine memory and ancestral endurance can re-legitimise the physiological impact of deprivation [56, 57]. Health promotion efforts can draw on these insights to create storytelling formats, through theatre, radio, or oral histories, that frame beta-cell failure not as moral weakness but as a hidden legacy of resilience. Such reframing can reduce stigma, facilitate disclosure, and mobilise community solidarity. In kinship-dense environments, behavioural change does not flow through individuals, but through socially embedded channels [55, 58], and new behaviours are more likely to be sustained when encoded in ritual and symbolic systems. For example, repositioning beta-cell supportive foods like dairy, legumes, and iron-rich greens—as "protective offerings" in household rituals can confer sacred legitimacy [59, 60]. The normative logic of fasting, frugality, and self-sacrifice, especially among women, must be carefully reinterpreted rather than dismantled. Programs may promote dietary replenishment as a sacred duty to future generations, thereby aligning care-seeking and nutritional restoration with existing value systems [61, 62]. Studies on maternal and foetal nutrition have emphasised how caregiving practices often reflect deep moral imperatives that, if rewritten, can support metabolic prevention across generations [63–65].
2. **One health**: Diets in rural Bengal and Bihar have been shown to be deficient in key micronutrients such as B12, zinc, and iron—nutrients essential for insulin biosynthesis and foetal pancreatic development [59, 66]. These deficiencies are often inherited intergenerationally, creating a cumulative nutritional debt. Studies from China and Africa echo this pattern, in which land degradation has led to population-wide

micronutrient deprivation and a rising non-communicable disease burden [67, 68]. Despite its origins in infectious disease surveillance, One Health can inform chronic disease strategies by highlighting how degraded environments create metabolic vulnerability. In Q2 states, this means integrating micronutrient mapping, soil health metrics, dietary diversity surveys, and sanitation indices into NCD surveillance systems. Data platforms could converge human, animal, and ecological data to identify "metabolic risk zones" requiring cross-sectoral action [61, 62, 68].

3. **SDOH**: Steps in the domains of *education*, *economic stability*, and *neighbourhood and built environment* are all likely to be helpful, but for this quadrant, it would be crucial to act with urgency in the *social and community context* domain. Social hierarchies and gendered expectations influence who reports symptoms, who receives support, and who gets taken seriously by both families and providers. In many Q2 settings, older women are praised for restraint, thinness, and sacrifice — qualities that may conceal metabolic distress and inhibit care-seeking [54]. Studies show that community-based platforms, such as women's SHGs (self-help groups) [69], religious networks, and peer educators, can help counter this invisibility if appropriately mobilised [70, 71].
4. **Public health**: In these states, standard public health protocols calibrated to obesity and HTN will not only fail to detect risk in these populations but also actively reinforce diagnostic neglect. Current NCD surveillance programs often use BMI (Body Mass Index) and blood pressure as entry points, leading to under-detection of lean diabetic individuals. Evidence from multiple famine and foetal programming studies shows that early-life deprivation, independent of adult anthropometry, is a major risk factor for beta-cell failure [72–74]. Surveillance algorithms must therefore integrate life-course indicators such as birthweight (where recorded) or visible stunting, maternal undernutrition history, and exposure to famine or seasonal hunger. Additionally, micronutrient deficiency, especially in zinc, B12, and iron, is a key ecological contributor to insulin insufficiency [59, 62]. Rather than treating malnutrition and NCDs as separate domains, strategies in these states will need to merge surveillance streams from the ICDS (Integrated Child Development Scheme), mid-day meal schemes, and anaemia control programs, and public distribution systems will need to prioritise the availability of food items such as green vegetables, dairy, and pulses. In these states, adolescent girls represent both a high-risk group and a strategic prevention opportunity - nutritional status during adolescence has direct intergenerational effects on foetal beta-cell development [57, 61]. They will need to be a particular focus of public health strategies in these states.
5. **Healthcare**: This section focuses on system-level reforms required to improve detection, diagnosis, and disease management for insulin-deficient patients, particularly those who do not present with traditional NCD flags such as obesity or HTN.

    (a) *Training to recognise Lean Diabetes*: Healthcare providers at primary care centres and community hospitals are trained to look for visual signs of excess: obesity, abdominal girth, and HTN. As a result, lean individuals, especially women and elders, are often dismissed as *not at risk* despite classic symptoms of insulin

deficiency [53, 62]. This misrecognition delays diagnosis until complications (e.g., neuropathy, vision loss) become unavoidable. Several studies from India, China, and Sri Lanka describe how provider bias reinforces diagnostic inertia [70, 75].

(b) *Appropriate Diagnostics in Primary Settings*: Glucose testing kits, HbA1c analysers, and insulin assays are rarely available at the primary care level in Q2 states. Even when glucose tests are present, follow-up pathways are unclear for individuals who are not hypertensive or overweight. In China and East Africa, the absence of simple diagnostic protocols for lean adults led to missed therapeutic windows and underutilisation of care [52, 76]. Integrating simple fasting glucose or 2-hour OGTT (Oral Glucose Tolerance Test) protocols and C-Peptide testing [77] into routine adult and adolescent health programs can improve early detection.

(c) *Ensuring Insulin Availability*: Insulin is inconsistently available at rural facilities, often limited to emergency or hospital use. Providers hesitate to initiate insulin in underweight patients, citing adherence concerns, stigma, and fear of hypoglycemia [61, 74]. This therapeutic nihilism leaves lean diabetic individuals under-treated for long periods. Mobile outreach clinics and SHC (sub-health centre)-based weekly insulin days have shown promise in increasing reach and confidence among both providers and patients.

(d) *Gender- and Caste-Sensitive Provider Engagement*: As highlighted earlier, care-seeking is shaped by gendered and caste-based moral codes. But health systems themselves must also overcome their own biases. Studies in India show that providers often under-test or under-treat women, especially those who appear physically *compliant* with cultural norms of leanness and restraint [55, 58]. Provider sensitisation should include training on cultural misrecognition, social position–based risk adjustment, and syndromic detection, including symptoms such as fatigue, blurred vision, and amenorrhea.

(e) *Differentiated Care Pathways for Non-Classical Presentations*: Health systems need care algorithms that reflect the metabolic diversity of diabetes. This includes tiered risk scores that flag lean but symptomatic individuals for glucose testing, structured insulin initiation pathways in low-BMI adults, and community-based adherence models. China's experience with metabolic phenotyping and Sri Lanka's integration of insulin delivery at the primary level suggest operational models worth adapting [78, 79].

6. **Country case studies**: While lean, insulin-deficient diabetes presents a unique challenge in Q2 Indian states, international experiences offer practical insights. This section presents selected case studies from countries where health systems have adapted to foetal-origin diabetes phenotypes, addressed famine-linked metabolic risk, or innovated in detection and care models for underserved, lean populations.

(a) *Sri Lanka: Community-Based Insulin Care and Provider Training*: Sri Lanka's national diabetes strategy emphasises early detection and insulin initiation at the primary care level. Despite resource constraints, the system integrates diabetes care into routine services through task-sharing with nurses and community volunteers. Notably, provider education initiatives include modules on atypical

phenotypes and social sensitivity [70, 79]. These measures have improved early insulin initiation, even in lean, low-income patients, echoing the structured insulin care pathways previously recommended.

(b) *China: Famine Cohorts and Lean Diabetes Surveillance*: China's extensive longitudinal data on cohorts exposed to the 1959–1961 famine have yielded deep insights into foetal programming of metabolic disease. Multiple studies document that adults born during the famine—despite low BMI—face higher rates of insulin-deficient diabetes and metabolic syndrome [72, 73, 78, 80]. These findings informed public health messaging that reframed diabetes not as a disease of affluence, but of developmental loss.

(c) *Kenya: Syndromic Screening for Lean Adults*: Kenya has piloted syndromic screening checklists for lean adults based on fatigue, blurred vision, and food insecurity history [71].

(d) *Ethiopia: Soil Micronutrient Mapping for Precision Nutrition Planning*: Ethiopia has invested in multisectoral approaches linking soil health to human nutrition outcomes. District-level soil zinc and selenium data are combined with dietary diversity metrics to identify high-risk populations for metabolic and growth disorders [68]. This integrative approach supports the ecological surveillance recommendations for building One Health–style public health data platforms in Q2.

(e) *Chennai (India): Recognition of Lean Diabetes in Urban South India*: Urban research from Chennai has confirmed that a significant proportion of young adults with diabetes have a lean phenotype with insulin deficiency (type 5 diabetes), independent of lifestyle risk factors [52, 81]. These findings led to calls for non-BMI-based screening protocols and broader clinical definitions. While concentrated in Tamil Nadu, the research offers direct validation of the metabolic patterns described in West Bengal, Bihar, and Assam, and highlights the need for subnational phenotyping to guide care pathways.

7. **Implementation**: Several steps would need to be taken by Q2 states to address the high prevalence of type 5 diabetes amongst their populations. These would include developing block-level NCD heatmaps using ecological and dietary risk factors (aligned with One Health models); reframing diabetes as a legacy of survival, not excess, using local stories and symbols; targetting adolescent girls with micronutrient supplementation, menstrual tracking, and nutrition counselling; retraining and equipping providers to detect and treat lean diabetes through syndromic and social cues; and using gender- and caste-sensitive engagement to overcome moral misrecognition and care avoidance.

HBG in Q2 states cannot be treated as a downstream expression of lifestyle excess. It is the biological imprint of intergenerational deprivation, ecological fragility, and cultural invisibility. A strategy focused solely on obesity, HTN, and behaviour change will bypass the most vulnerable. Precision public health in this context demands a model of care that is culturally resonant, socially equitable, and ecologically grounded. The strategy outlined here offers a roadmap for shifting the diagnostic gaze, recalibrating the system, and preventing a silent epidemic in some of India's most neglected metabolic frontiers.

E.3 Strategy for quadrant 3 (Q3): salt-sensitive hypertension cluster

Q3 states face a unique metabolic profile: high rates of HTN in relatively lean populations, often without accompanying HBG or obesity. As discussed above, emerging evidence suggests that genetically and epigenetically driven salt sensitivity is a central mechanism, shaped by centuries of adaptation to low-sodium forest ecologies [82, 83]. This distinct pathophysiology renders conventional non-communicable disease (NCD) strategies focused on obesity and urban diets insufficient. A tailored precision public health approach for these regions must integrate ecological, cultural, behavioural, and institutional dimensions. It must simultaneously realign dietary norms, enable early detection, support culturally congruent clinical care, and leverage One Health principles to address upstream ecological risks. The development of the strategy draws on the evidence that has been generated (summarised in Table 9). A total of 40 studies were identified from SciSpace, and five additional ones were included to provide an added pharmacy, primary care, and social determinants perspective.

1. **CEH**: There is now a growing dissonance between the lived experience of elevated blood pressure and the cultural scripts that valorise salt as strength, hospitality, or climate resilience [84, 85]. Health-enhancing innovation requires reframing salt awareness within locally meaningful symbols. In tribal settings, revival of millet-based ceremonial cooking, or seasonal feasts using fermented greens, can act as low-sodium anchors. In agrarian households, substitution of ritualised salted buttermilk with spiced potassium-rich drinks (e.g., coriander or cumin-infused water) may be introduced during festivals [83, 86]. Such innovations succeed not by negating tradition but by realigning health with ancestral logics. In patriarchal food systems where men regulate salt-rich foods and dismiss early hypertension symptoms, the CEH strategy involves shifting the metaphor: from *salt as strength* to *salt as stealth threat*. Peer leaders and youth collectives can rewrite these scripts using local storytelling and performance traditions [83]. Trusted community figures, such as folk musicians, temple cooks, panchayat health workers, can model these practices through participatory gatherings and narrative re-enactments. Rather than external campaigns, CEH emphasises transmission via observation, imitation, and embedded performance [85, 86]. The performative aspect, such as community members publicly preparing salt-light meals or role-playing hypertensive symptom narratives, accelerates diffusion without resistance. As repetition stabilises these behaviours, symbolic markers—naming practices, ritual calendars, visual motifs—can seal them into cultural memory. For instance, a weekly *Paani Shanti* ceremony, honouring water and restraint, may gradually replace salt offerings in some regions. Where once salt represented vitality, it now represents vulnerability. Through such shifts, the community internalises restraint not as deprivation, but as reverence [83].
2. **One Health**: In Q3 states, One Health strategies offer an integrated, multi-sectoral pathway to address both the *biological susceptibility* and the *ecological disruptions* that amplify salt-related risks. One Health frameworks recognise that such health burdens are not only medical but ecological in origin [84] - deforestation and ecosystem degradation reduce access to traditional potassium-rich foods (e.g., wild greens, tubers), while increasing exposure to high-sodium market substitutes [85]. A One Health approach to salt-sensitive HTN would entail involving forest departments

in restoring access to indigenous potassium-rich foods that counterbalance sodium intake, promoting potassium-rich indigenous diets through ecological food mapping and community kitchen revival [87], and preventing forest encroachment that disrupts traditional dietary access and increases commercial food dependence [88].

3. **SDOH**: Q3 regions are often marked by high levels of informal employment, subsistence farming, and fragile household incomes. *Economic instability* limits access to fresh, potassium-rich produce and increases dependency on cheap, high-sodium processed foods. Studies show that food affordability shapes HTN risk profiles, particularly when local economies are flooded with low-cost commercial snacks and condiments [86]. *Fiscal interventions* such as subsidies for salt substitutes and targeted nutritional transfers have been recommended to reverse this nutritional drift [89, 90]. The 3D Commission report highlights how zoning, licensing, and labelling regulations can reduce population-level salt exposure through *environmental levers* [91]. Reformulating mid-day meals and ICDS rations in high-risk areas offers a policy route to mitigate built environment–induced dietary risks [89].
4. **Public health**: Routine HTN screening in tribal and forest-adjacent populations is limited by access barriers and systemic neglect. Evidence from co-created screening programs [82] and participatory NCD interventions [86] suggests that integrating screening with local outreach utilising tribal health workers and culturally embedded events can enhance early detection. Mobile BP check-up camps linked to local festivals and panchayat days may increase participation and retention. Policy-level interventions are also crucial in shifting population-level salt exposure. A conducive policy landscape must enable subsidies for potassium-based salt substitutes targeted at tribal and remote areas, public procurement reforms (such as ICDS and mid-day meals) to reduce sodium content, and tax incentives or regulatory nudges for food manufacturers to reformulate high-sodium packaged goods sold in these states [89]. Evidence also supports promoting salt substitutes through front-line health workers and pharmacies in high-risk zones [90, 92]. Q3 states should develop sub-state public health plans that formally recognise salt-sensitive HTN as a strategic priority [93], which includes ring-fenced funding for salt substitution programs and communication campaigns, integration of salt sensitivity screening into Health and Wellness Centres, and establishment of District HTN Prevention Task Forces that coordinate across food, education, health, and tribal welfare departments.
5. **Healthcare**: Primary care providers must become the frontline for HTN detection and management. Studies emphasise that culturally aligned, task-shifted care models using community health workers improve uptake, especially when integrated with broader health promotion efforts [39, 94]. Standard NCD protocols must be adapted to reflect the high salt sensitivity in these populations. Interventions must prioritise early initiation of treatment at pre-hypertensive stages, non-pharmacological management through dietary counselling focused on salt avoidance and potassium enhancement [90], use of culturally acceptable salt substitutes integrated into routine clinical advice [89], and point-of-care devices for creatinine and potassium testing to monitor antihypertensive side effects in remote settings [92]. Given the limited tertiary infrastructure in Quadrant 3 regions, curative strategies must prevent the avoidable progression of HTN complications. However, for cases requiring specialist care (e.g., hypertensive retinopathy, stroke), contracts with mission hospitals,

government medical colleges, and PPP-mode teleconsultation hubs can expand reach without diverting resources from primary care [93]. A digital HTN registry at the block or district level can facilitate tracking and follow-up. Evidence shows that digital dashboards linked to NCD clinics improve continuity of care when combined with local ownership and feedback loops [86]. These registries should include ethnicity, diet type, and known salt sensitivity flags to inform care. In tribal and peri-urban regions, pharmacies often serve as the first point of contact in the care pathway. Implementation research [48] shows that trained pharmacists, equipped with BP monitors, counselling scripts, and telemedicine tools, can play a pivotal role in screening for salt-sensitive HTN in culturally embedded ways, providing patient education and low-salt dietary advice, ensuring treatment adherence and follow-up through app-based coordination, and supporting prescription continuity during seasonal migration and healthcare disruptions. Their proximity, trust, and embeddedness make them ideal anchors for culturally safe chronic disease management, particularly where formal health infrastructure is weak.

6. **Country case studies**: Four case studies offer practical lessons in delivering HTN-related interventions to populations with cultural, dietary, or ecological similarities to India's Q3 states.

   (a) *Bangladesh: Culturally Anchored CHW-Led Lifestyle Interventions*: In Bangladesh, a community-based lifestyle intervention led by community health workers (CHWs) demonstrated significant reductions in systolic blood pressure among adults at risk for HTN. The intervention combined dietary counselling, physical activity promotion, and tobacco cessation within a framework of community health worker (CHW) home visits, community meetings, and locally adapted health education tools. Cultural tailoring was evident in the use of Islamic idioms for health messaging, gender-concordant interactions, and the adaptation of salt reduction advice to match regional cooking practices. This study highlights the importance of integrating HTN control into trusted, culturally resonant delivery systems [95].

   (b) *Indonesia: Faith-Based and Traditional Anchors for Public Health Messaging*: Indonesia illustrates how deeply religious contexts can be leveraged for effective chronic disease prevention. Health messages are integrated into Islamic Friday sermons and supported by community health cadres trained to engage families on nutrition and mental health. Traditional communication forms, such as Wayang (shadow puppetry), are repurposed to convey NCD-related advice to young audiences. Collaborative engagement with traditional healers, rather than displacing them, improves referral uptake. These models reflect the CEH framework's tenets of epistemic inclusivity and the role of spiritual authority in health behaviour change [96].

   (c) *India: Decentralised Governance and Panchayat-Led Behaviour Change*: Evidence from India highlights the effectiveness of involving panchayati raj institutions in public health governance. Behaviour change interventions addressing salt reduction and HTN control were more successful when locally legitimised

through village leadership structures. These programmes used participatory learning approaches, folk theatre, and visual narratives to reinforce dietary changes. India's experience underscores the need to harness decentralised political capital and pre-existing community platforms when designing culturally congruent strategies for chronic disease prevention [97].

(d) *Ghanaian Immigrants in the Netherlands: Culturally Tailored Risk Communication*: Although implemented in the Netherlands, this cluster-randomised trial targeting Ghanaian immigrants offers key insights into culturally adapted HTN prevention. The intervention employed group counselling, ethnic-specific dietary advice, and social identity–affirming communication techniques. Challenges included maintaining participant retention and bridging biomedical messages with culturally anchored beliefs. The findings affirm that even in diaspora contexts, cultural salience improves the uptake of salt reduction advice and justifies deeper investment in tailored communication approaches for tribal and indigenous populations [98].

7. **Implementation**: The successful implementation of a salt-sensitive HTN strategy in Q3 requires integrating three overlapping elements: (1) field-tested delivery mechanisms; (2) population trust and cultural alignment; and (3) coordination across sectors and care levels. These would include enhancing the role of CHWs as comprehensive providers doing careful risk stratification and follow-up [39], actively engaging pharmacies [48] where the formal infrastructure is weak, and alignment with local epistemologies and trust networks through programs that integrated tribal knowledge systems, dietary rituals, and social norms into HTN counselling.

Salt-sensitive HTN in Quadrant 3 is both a sentinel condition and a structural signal, pointing to ecological imbalance, dietary transition, and systemic exclusion. A successful response must go beyond generic lifestyle advice or vertical pharmacological programs. It requires an integrative framework that links salt reduction to cultural evolution, community empowerment, ecological stewardship, and intersectoral care delivery. By grounding strategies in local knowledge systems and embedding them in robust delivery platforms—from tribal health workers to pharmacies to One Health units, Q3 states can pioneer a model of cardiovascular prevention that is scientifically sound, culturally embedded, and institutionally scalable.

E.4 Strategy for quadrant 4 (Q4): traditional-resilient cluster

Q4 states in India represent a paradoxical strength: despite economic vulnerability, rural character, and limited medical infrastructure, they have sustained remarkably low burdens of HBG and HTN. As these regions modernise, the central challenge is not treating illness but preserving health. This strategy document proposes a comprehensive, evidence-based framework for safeguarding the metabolic resilience of Q4 communities (see Table 10 for the thematic evidence summary). By investing in cultural evolution, structural determinants, ecological alignment, and frugal healthcare, Q4 states can define a new development model—one where prosperity reinforces, rather than erodes, public health.

Table 4 Scoring method for each factor

Factor	Proxy or source	Scoring logic	Reference
Urbanization	% Urban Population from Census 2011	Low (1): <30%, Medium (2): 30-50%, High (3): >50%	[5]
Sedentary Lifestyle	IHDS/NSSO occupational category, urbanisation, and leisure time data	Low: manual labour dominant; High: desk jobs and urban professions dominate	[7]
Energy-Dense Diet	NSSO food expenditure + NFHS frequency of oil/sugar/fried intake	Low: coarse grains, pulses; High: refined foods, fried/oily/sweet foods	[3, 4]
History of Famine	Historical records and secondary famine literature	High (3): major exposure in 19th/20th century (e.g., Bengal, Bihar)	[17]
Lean Body Mass	NFHS-5 BMI <18.5 prevalence among men	High (3): >20%, Medium: 10-20%, Low (1): <10%	[3]
Early-life Undernutrition	NFHS-5 stunting and underweight prevalence	High: >35%, Medium: 25-35%, Low: <25%	[3]
Salt Sensitivity	% Tribal populations (Census) + lean HTN phenotype (NFHS)	High: lean + hypertensive + tribal ecology	[6, 27]
Tribal Populations	Scheduled Tribe % from Census 2011	High: >15%, Medium: 5-15%, Low: <5%	[5]
Manual Labour	% working in agriculture/construction/mining (IHDS, NSSO)	High: >50%, Medium: 30-50%, Low: <30%	[4, 7]
Traditional Diet	NNMB and NFHS dietary intake (millets, pulses, etc.)	High: local/coarse foods dominate; Low: refined cereals dominate	[6, 21]
Physical Activity	Time use and occupation from IHDS/NFHS-5	High: mostly active work; Low: sedentary work	[3, 7]
Low Caloric Intake	NSSO calorie consumption, NNMB rural nutrition studies	High: <1800 kcal/day, Medium: 1800-2400, Low: >2400	[4, 6]

1. **CEH**: In Quadrant 4 states, where NCD prevalence is still low, but social transitions are accelerating, a CEH perspective is essential. Numerous studies highlight a disparity between aspirational health outcomes and prevailing norms. For example, communities in Bangladesh and sub-Saharan Africa express a desire to control diabetes and HTN but lack shared expectations around preventive behaviour [99–101]. Gendered perceptions, stigma, and fatalism further exacerbate this mismatch [55, 102]. This dissonance between what communities want and what their cultural environment supports, creates an opportunity space for innovation. As incomes rise and urbanisation accelerates, cultural expectations around success and modernity are increasingly shaped by high-consumption, sedentary lifestyles, aspirational shifts that threaten to unravel the frugal health-protective norms that currently prevail in many Q4 settings [44, 103]. However, it is possible to steer this dissonance in a direction that deliberately protects health. Programs in Rwanda, Vietnam, and South Africa have succeeded by framing walking, cycling, plant-based eating, and green spaces not as symbols of deprivation but as globally admired behaviours [104–106]. Storytelling and peer-led interventions have helped communities reflect on the hidden costs of unhealthy modernity and recognise continuity between local traditions and international health trends [100, 107–109]. Cultural reframing transforms frugality into an aspiration, enabling dissonance to steer communities away from consumerism of cars, malls, and highways, and toward a more sustainable yet ultra-modern model of urban health. Where transmission succeeds, behaviours shift from being novel to being normative. Programs in Brazil, Rwanda, and Vietnam show that repeated exposure, inclusive design, and reinforcement through formal and informal systems allow health-positive behaviours to become community expectations [104, 108, 110]. In

some contexts, these changes have persisted across programs and administrations, indicating their entrenchment in accumulated culture [106, 111].

2. **One health**: Conventional approaches to One Health have typically prioritised zoonotic disease prevention through inter-ministerial coordination across health, agriculture, and animal welfare sectors. In Q4 states, the Ministry of Tribal Affairs could establish a Tribal Health One Health Unit focused on preserving bio-cultural knowledge and reducing zoonotic risks associated with deep-forest exposure. Urban agencies could simultaneously invest in rodent control and sanitation infrastructure that maintains microbial safety in growing towns. A One Health strategy for Q4 must be a foundational design principle of modernisation itself. By investing in institutions, behaviours, and aspirations that see frugality and ecological wisdom not as obstacles but as opportunities, Q4 states can leapfrog the public health burdens seen in more industrialised regions.
3. **SDOH**: As Q4 populations begin to urbanise and accumulate wealth, the risk is that rising incomes and modern lifestyles may erode rather than strengthen metabolic health. The goal, therefore, is not simply to improve social determinants of health (SDOH) but to shape them in ways that preserve the protective cultural and ecological conditions already in place. *Education* is a powerful predictor of long-term health, but the mechanism is not simply literacy: it is the creation of aspirational identity. Studies from India and sub-Saharan Africa show that when education programs foster critical thinking, civic engagement, and health literacy, they also anchor preventive health behaviours [105, 108]. In particular, school-based interventions that integrate wellness themes, physical activity, and cultural narratives of resilience build an ecosystem of protection around young people [71, 107]. The *Neighbourhood and Build Environment* domain offers perhaps the most powerful structural lever for chronic disease prevention. As Q4 states modernise, they face a pivotal choice: whether to mimic car-centric urban sprawl or to preserve and enhance the frugal, compact, and walkable environments that already exist in many of their towns and villages. Studies from Ethiopia, Ghana, and Vietnam highlight how the built environment influences long-term metabolic outcomes by shaping everyday exposure to green spaces, walkability, food access, and pollution [99, 110, 112]. Q4 states already resemble the walkable, low-pollution, active-transport urban utopias that cities like Paris and Geneva are trying to build. The opportunity is to leapfrog the development model of highways and malls and instead evolve toward a model of distributed, mixed-use, ecologically embedded growth [104, 106]. Several studies highlight the protective role of green corridors, co-located services, low particulate matter exposure, and informal gathering spaces in reducing stress and increasing physical activity [113, 114].
4. **Public Health**: In Q4 states, where metabolic resilience remains largely intact, the public health challenge is one of preservation rather than recovery. The dominant risk is not disease prevalence but the erosion of health-protective behaviours through unregulated urbanisation, economic transition, and cultural displacement. Therefore, public health systems must be reoriented toward *primordial prevention*, i.e., intervening upstream of risk factor formation, anchored in cultural, ecological, and spatial contexts. Unlike in high-prevalence areas, where tertiary and

Table 5 State & quadrant level factorScoring

State	Quadrant	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
Andhra Pradesh	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Chandigarh	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Gujarat	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Karnataka	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Kerala	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Lakshadweep	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Manipur	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Mizoram	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Odisha	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Sikkim	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Tamil Nadu	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Telangana	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Assam	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Bihar	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Goa	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Maharashtra	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Puducherry	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Tripura	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
West Bengal	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Arunachal Pradesh	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Chhattisgarh	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Delhi	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Haryana	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Nagaland	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Punjab	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Uttarakhand	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Himachal Pradesh	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Jammu & Kashmir	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0

Table 5 (continued)

State	Quadrant	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
Jharkhand	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Ladakh	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Madhya Pradesh	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Meghalaya	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Rajasthan	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Uttar Pradesh	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0
Quadrant Average	Q1	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Quadrant Average	Q2	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0
Quadrant Average	Q3	2.0	3.0	3.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	2.0
Quadrant Average	Q4	1.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0	3.0	3.0

The table includes twelve factors (i) Urbanisation, (ii) Sedentary Lifestyle, (iii) Energy-Dense Diet, (iv) History of Famine, (v) Lean Body Mass, (vi) Early-life Undernutrition, (vii) Salt Sensitivity, (viii) Tribal Populations, (ix) Manual Labour, (x) Traditional Diet, (xi) Physical Activity, and (xii) Low Caloric Intake. The table reports the ordinal scores (1 = Low, 2 = Medium, 3 = High) assigned to each state across the twelve factors. The final rows include the average scores for each quadrant, which were used to construct the quadrant-level Heat Map

Table 6 Studies analysing impact of factors

Factor	Count	Cited studies
Urbanisation	1	[5]
Sedentary Lifestyle	2	[13, 116]
Manual Labour	2	[117, 118]
Physical Activity	3	[7, 116, 119]
Energy-Dense Diet	3	[3, 120, 121]
History of Famine	4	[17–20]
Early-life Undernutrition	6	[3, 14, 15, 81, 122, 123]
Traditional Diet	3	[4, 6, 21]
Low Caloric Intake	6	[4, 6, 21, 124–126]
Lean Body Mass	2	[52, 127]
Salt Sensitivity	9	[22–27, 128–130]
Tribal Populations	4	[5, 24, 28, 131]

Table 7 Quadrant 1: Thematic evidence summary

Theme	Count	Cited studies
Cultural competence/stigma reduction	8	[29–32, 36, 46, 48, 50]
One Health/environmental risk integration	5	[33, 34, 40, 43, 46]
Social determinants/equity	8	[30, 32, 41, 45, 50, 132–134]
Preventive screening/risk stratification	6	[29, 31, 38, 42, 43, 48]
Digital decision support/registries	7	[40, 43, 44, 47, 49, 135, 136]
CHW/nurse-led care	6	[29, 31, 33, 41, 46, 136]
Adherence/therapeutic continuity	6	[33, 43, 44, 47, 49, 134]
Pharmacy-based service delivery	3	[48–50]
Country case studies/health systems models	8	[29, 31, 36, 40, 41, 44, 46, 50]
Policy/fiscal and regulatory tools	1	[37]
Health system readiness/other LMIC models	8	[137–144]
Task-shifting/workforce redesign	4	[145–148]
Multimorbidity/care coordination	3	[149–151]
Service quality/patient experience	3	[152–154]

Table 8 Quadrant 2: Thematic evidence summary

Theme	Count	Cited studies
Early-life undernutrition and insulin insufficiency	15	[51–53, 61–63, 72, 74, 122, 123, 155–159]
Cultural adaptation and lean diabetes framing	5	[54, 55, 58, 62, 75]
Access and equity in diabetes care	7	[52, 53, 55, 58, 76, 81, 155]
Micronutrients, dietary diversity, and metabolic risk	8	[59–62, 66, 67, 72, 155]
Public health system readiness and provider response	7	[52, 53, 75, 76, 155, 160, 161]
Urbanization, environment, and built infrastructure	5	[72, 75, 156, 162, 163]
Maternal-child health and intergenerational prevention	8	[53, 57, 58, 61, 63, 164–166]
Epigenetics and foetal programming	8	[56, 57, 63–65, 73, 78, 166]
Country case studies and subnational policy relevance	11	[52, 68, 70–72, 79, 156, 167–170]
Famine exposure and metabolic risk in lean populations	10	[72, 73, 75, 78, 80, 160, 165, 168, 169, 171]
Social Determinants of Health	6	[54, 55, 58, 63, 80, 162]

Table 9 Quadrant 3: Thematic evidence summary

Theme	Count	Cited studies
Salt Sensitivity & Cultural Diets	12	[82, 83, 85, 86, 95, 172–178]
Salt Substitution & Fiscal Policy	5	[87, 89–92]
One Health & Ecological Strategies	7	[9, 84, 85, 88, 93, 94, 179]
Community-Based Prevention & CHWs	7	[83, 86, 87, 92, 94, 179, 180]
Culturally Adapted Clinical Care	7	[83, 89, 90, 92, 96, 98, 181]
Pharmacy and Hybrid Delivery Models	2	[39, 48]
Governance, Scale-Up, and Implementation	5	[39, 48, 91, 93, 182]
Other Relevant Studies	15	[97, 99, 112, 114, 183–193]

Table 10 Quadrant 4: Thematic evidence summary

Theme	Count	Cited Studies
Hypertension Awareness and Referral	3	[99, 100, 101]
Diabetes Management in Underserved Populations	8	[103, 102, 194, 195, 71, 196, 55, 111]
Community-Led Cardiovascular Risk Control	9	[112, 108, 197, 198, 134, 199, 114, 182, 44]
Chronic Disease Control in LMICs	13	[200, 115, 201, 104, 134, 202, 203, 204, 42, 105, 205, 44, 111]
Systematic Reviews of LMIC Diabetes Strategies	11	[206, 200, 107, 112, 110, 202, 109, 204, 114, 205, 182]
Lifestyle Prevention by Local Health Workers	18	[207, 200, 107, 112, 106, 197, 208, 209, 134, 203, 71, 199, 210, 55, 204, 205, 113, 111]

secondary care must absorb the disease load, Q4 public health systems have the luxury (and responsibility) of focusing upstream. Programs in Vietnam, Rwanda, and Kenya demonstrate that surveillance, education, and primary prevention can be institutionalised as dominant mandates of public health infrastructure [100,

Table 11 Regional phenotypes of cancers

Regional phenotype	Dominant cancer type(s)	Dominant risk factor(s)
Northeast Highlands (Mizoram, Nagaland, Manipur, Meghalaya, Arunachal)	Nasopharyngeal, oesophageal, lung (NPC/UADT)	Epstein–Barr virus [212], smoked/fermented meats [213], biomass fuel
Gangetic Belt (Uttar Pradesh, Bihar, West Bengal, Assam plains)	Gallbladder, digestive tract	Arsenic in groundwater, chronic infection–stone pathogenesis, female predominance [214]
Western–Central States (Gujarat, Maharashtra, Madhya Pradesh)	Oral cavity, tongue	Smokeless tobacco, areca nut, betel quid
Southern Metros (Tamil Nadu, Karnataka, Telangana, Kerala districts)	Lung (men), rising breast	Smoking, ambient air pollution, biomass fuels, reproductive transition [215]
Urban Cohorts (Delhi, Mumbai, Bangalore, other metros)	Breast (rising), cervical (falling), prostate	Fertility transition [215], HPV prevalence, metabolic risk factors

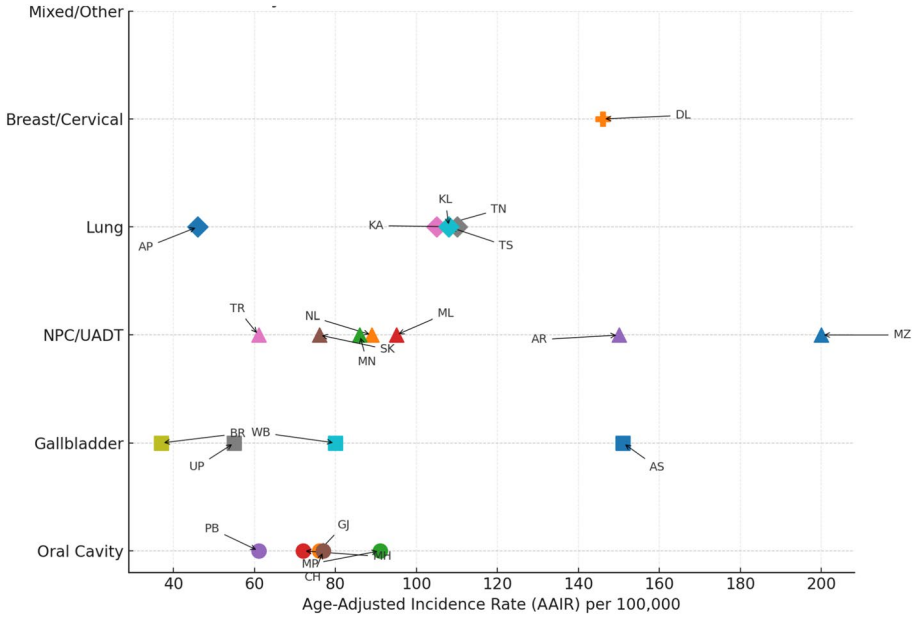


Fig. 4 Cancer Typology by State. **Note:** This figure presents a state-level cancer typology for India, plotting overall cancer burden (all-site age-adjusted incidence rate [AAIR], World Standard Population) on the horizontal axis against the predominant cancer phenotype on the vertical axis. Each state is positioned according to its estimated all-cancer AAIR and classified by the dominant cancer pattern observed across constituent population-based cancer registries (PBCRs) during the period 2015–2019, as reported by the National Cancer Registry Programme (NCRP). Source: National Cancer Registry Programme data as reported by Mathur and colleagues [211]. The phenotype categories (e.g., oral cavity–upper aerodigestive tract, gallbladder–digestive, nasopharyngeal/upper aerodigestive tract, lung–breast in southern urbanised states, and breast–cervical transition in large metropolitan areas) are intended to capture regionally durable cancer regimes, rather than to identify a single site with the numerically highest AAIR in each state. For states with multiple PBCRs, phenotype assignment reflects the most frequently leading cancer sites across registries, informed by NCRP site-specific incidence rankings and regional clustering patterns, rather than strict state-level aggregation. All-cancer AAIR values shown are derived from NCRP PBCR summaries and graphical outputs and should be interpreted as approximate indicators of relative cancer burden, not as precise point estimates. The purpose of the figure is therefore analytical and typological—to illustrate systematic regional variation in cancer profiles relevant to precision public health strategy—rather than to provide definitive epidemiological rankings. X-axis: age-adjusted all-cancer incidence rate (AAIR) per 100,000. Y-axis: dominant cancer site, grouped into five regional phenotypes: (1) Oral cavity (Western–Central states); (2) Gallbladder (Gangetic belt); (3) Nasopharyngeal Carcinoma (NPC)/Upper Aero-Digestive Tract (UADT) (Northeast highlands); (4) Lung (Southern metros); (5) Breast/Cervical (Urban cohorts). State labels: Andhra Pradesh (AP), Arunachal Pradesh (AR), Assam (AS), Bihar (BR), Chandigarh (CH), Delhi (DL), Gujarat (GJ), Karnataka (KA), Kerala (KL), Madhya Pradesh (MP), Maharashtra (MH), Manipur (MN), Meghalaya (ML), Mizoram (MZ), Nagaland (NL), Punjab (PB), Sikkim (SK), Tamil Nadu (TN), Telangana (TS), Tripura (TR), Uttar Pradesh (UP), and West Bengal (WB)

110, 114]. This requires reorienting health departments toward environmental monitoring, nutrition support, school-based wellness, and urban planning partnerships. Rather than waiting for HTN and diabetes to emerge, Q4 states can build a system that sustains their current health advantage.

5. **Healthcare**: In Q4 states, where the burdens of HBG and HTN remain low, healthcare infrastructure must be designed not around curative overload but preventive foresight. As modernisation advances, health systems can either reinforce ecological and behavioural buffers or undermine them through fragmentation, over-medicalisation, and inaccessibility. The challenge is to design a tiered healthcare strategy that sustains resilience, prevents risk formation, and equips providers to act early without pathologising normal life. Primary care in Q4 states should be designed as a forward-looking, community-integrated platform. Studies from Ethiopia, Ghana, and West Bengal illustrate how primary

Table 12 Anchoring dimensions and precision public health responses

Regional phenotype (states)	Anchoring dimension	Observed historical/cultural /ecological factors	Potential precision public health responses
Northeast Highlands (MZ, NL, MN, ML, AR, SK, TR)	CEH	Smoked/fermented meats, betel nut, strong cultural acceptance of tobacco	Community-led cultural substitution campaigns; oral health education in schools; alternative livelihood for areca cultivation
	One Health	Biomass smoke, forest/hill ecology, high EBV prevalence	Clean-fuel interventions; ventilation programmes; targeted ENT surveillance for nasopharyngeal cancer
	Public Health	Patchy registry coverage; weak oncology services; late presentation	Build oncology units in regional medical colleges; community referral pathways; strengthen PBCRs
	SDOH	Tribal isolation, transport barriers, literacy gaps	Mobile cancer clinics; patient navigator schemes; health literacy campaigns
	Health Systems	Weak specialist capacity; reliance on Kolkata/Guwahati for advanced care	Invest in regional oncology centres; integrate cancer detection into PHC; tele-oncology links
Gangetic Belt (UP, BR, WB, AS plains)	CEH	Betel quid and smokeless tobacco embedded in rural life	Behaviour-change via cultural influencers; school-based bans; oral cancer screening
	One Health	Arsenic contamination in groundwater; chronic infections driving gallbladder cancer	Safe water supply; arsenic remediation; hepatobiliary screening pilots
	Public Health	Low coverage of organised screening; weak hepatobiliary services	Establish district cancer detection units; expand surgical oncology capacity
	SDOH	Poverty, caste stratification, poor sanitation, high female labour burdens	Women's health empowerment; cash/transport incentives for screening
	Health Systems	Tertiary overload in Patna/Kolkata; weak district-level oncology	Hub-and-spoke model for hepatobiliary surgery; expand cancer registries in rural Bihar
Western–Central States (GJ, MP, MH, PB, CH)	CEH	Strong cultural acceptance of smokeless tobacco and areca nut	Vendor regulation; culturally adapted quitlines; religious/community leader involvement
	One Health	Agricultural pesticide residues in some belts	Monitor exposures; occupational health campaigns
	Public Health	Established PBCRs (Mumbai, Barshi); pilots of oral visual inspection	Scale oral inspection nationally; integrate into ASHA/PHC workflows
	SDOH	High illiteracy in rural chewing populations; urban–rural gaps	Targeted outreach to rural workers; strengthen urban–rural referral links
	Health Systems	Strong tertiary centres (Tata Mumbai, Gujarat Cancer Centre), but weak PHC integration	Expand prevention programmes; integrate oral cancer care into insurance packages
Southern Metros (TN, KA, TS, KL, AP)	CEH	Urban lifestyle transition; later marriage, fewer children, sedentary work	Health promotion for metabolic risk; reproductive health education
	One Health	Air pollution (Chennai, Bangalore, Hyderabad); biomass fuel in rural Kerala/Andhra	Enforce clean-air standards; LPG/clean fuel subsidies; indoor air interventions
	Public Health	Better registry coverage (Chennai, Bangalore, Kerala districts); HPV and breast screening pilots	Expand HPV vaccination; scale breast diagnostic capacity; digital registries
	SDOH	Higher literacy and empowerment, but urban inequities persist	Target slum populations with screening; equity-focused outreach

Table 12 (continued)

Regional phenotype (states)	Anchoring dimension	Observed historical/cultural /ecological factors	Potential precision public health responses
	Health Systems	Strong cancer centres (Adyar, Kidwai, NIMS); public insurance schemes (Arogyasri, CMCHIS)	Leverage state insurance to fund screening and early detection; strengthen survivorship care
Urban Cohorts (DL, MH metros, WB-Kolkata, KA-Bangalore, CH)	CEH	Fertility transition; decline in cervical cancer; obesity/diabetes rise	Promote HPV vaccination and metabolic health; lifestyle modification campaigns
	One Health	Severe ambient air pollution in Delhi, Mumbai	Multi-sectoral clean air policies; smoking cessation synergy
	Public Health	Metro registries with long data; active NGOs for breast cancer	Formalise NGO activity into public programmes; public–private partnerships for early detection
	SDOH	Intra-urban inequities: slums vs affluent	Deploy targeted screening in slums; reduce financial barriers to treatment
	Health Systems	Strong tertiary hospitals but fragmented primary prevention	Integrate systematic cancer screening into metro PHCs; expand survivorship and palliative care

health centres can offer culturally aligned counselling, dietary guidance, risk screening, and behavioural reinforcement [55, 99, 112]. Rather than focusing on pharmacological management, primary care in these contexts can prioritise motivational interviewing, family-based lifestyle change, and age-appropriate tracking of blood pressure, glucose, and waist circumference. When equipped with a modest supply of essential medicines and diagnostics, such systems can serve as a sensitive net to detect upward trends in risk before they become unmanageable. In contrast to high-burden states, Q4 regions should avoid prematurely investing in high-cost hospital infrastructure for the management of chronic diseases. Instead, hospital care should be designed as a scalable backbone, capable of rapid capacity expansion if risk trends accelerate. Evidence from South Africa and Kenya illustrates how regional centres can function as resource hubs for training, referral triage, and complex diagnostics without becoming the de facto entry point into care [106, 114]. Q4 states can use this window to set a new norm: care that is close to home, minimally invasive, and ecologically aligned.

6. **Country case studies**: In addition to the country cases referred to above, Vietnam's case illustrates how primary care modernisation can occur without undermining continuity or access. Vietnam prioritised service quality at commune-level health stations while integrating them into a national referral system [110]. Importantly, Vietnam maintained horizontal coordination with public health programs and utilised schools and local governments as allies in prevention efforts. The result is a relatively low NCD burden, despite rapid urbanisation. Educational interventions around diet, tobacco, and physical activity are culturally grounded and delivered through trusted local systems.

7. **Implementation**: To operationalise the prevention-first strategy for Q4, implementation must focus on early institutionalisation, cross-sectoral alignment, and community embeddedness.

   (a) *Build Prevention into Every System*: Public health, education, agriculture, and urban planning must be explicitly tasked with health prevention mandates. Evidence from Ghana and Vietnam shows that food systems and land use policies, when aligned with public health goals, support long-term metabolic resilience [99, 110]. Similarly, infrastructure design must embed walkability, air quality standards, and zoning to preserve traditional activity patterns [104, 106].
   (b) *Use Schools and Youth as Anchors of Norm Change*: The evidence from India, Kenya, and Brazil emphasises the role of school-based wellness programs and youth-led health clubs in reinforcing protective norms [71, 107, 115]. Implementation should include curricular integration of One Health, frugality, and chronic disease prevention; school gardens and cooking labs can foster experiential learning.

The Quadrant 4 precision public health strategy is rooted in a simple yet powerful conviction: that the best way to address the rising tide of NCDs is to prevent them from emerging in the first place. This is neither a minimal nor a passive vision. It demands anticipatory investment, cultural humility, institutional innovation, and unwavering political commitment. It requires recognising the strengths already present in Q4 communities — not only their walkable environments and frugal diets, but their intergenerational solidarities, ecological embedment, and adaptive cultural forms. By using these assets as launchpads for preventive action across seven strategic domains, Q4 states can chart a health trajectory fundamentally different from that of more industrialised regions. They can show that the future of public health in India lies not in crisis response, but in strategic foresight.

F Cancer typology for precision public health

This Appendix demonstrates how the approach used in the main paper for HTN and HBG can be extended to cancer. Using state-level aggregation of the 43 Population-Based Cancer Registries (PBCRs) in India (2015-2019) [211], durable, geographically-anchored patterns in cancer type (Figure 4 and causation (Table 11) can be observed. These are expressed here as a four-part chain: *regional phenotype → cancer type(s) → dominant risk factor(s) → precision public health implication*.

The typology shows that Indian cancer patterns are not random but anchored in long-standing ecological and socio-cultural determinants. Expressing them as *regional phenotype → cancer type → risk factor* makes explicit the causal logic and facilitates the design of precision public health strategies. For example, a high AAIR (Age-Adjusted Incidence Rate) in Mizoram is not merely *high cancer burden* but specifically *high nasopharyngeal*

burden due to EBV and fermented diets, which points directly to ENT pathways and clean fuel as targeted interventions (Table 12). This causal anchoring mirrors the HTN/HBG quadrants and demonstrates the portability of the approach.

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