

The E-WASH Nexus Trajectory in India: NFHS-1 to NFHS-6 (1992–2026)

R. Durai¹, S. Gnanasaranya², V. Kaveri³, M. S. Fathima Begam⁴, Sruthi Mohan⁵,
S. Ramaswamy⁶

¹Director, GTN Group of Institutions, Dindigul, Tamil Nadu, India.

²Assistant Professor (Contract), Department of Lifelong Learning and Extension, The Gandhigram Rural Institute (DU), Dindigul, Tamil Nadu, India.

³Head, Department of Management Studies, GTN Arts College (Autonomous), Dindigul, Tamil Nadu, India.

⁴Associate Professor (Dean R and D), Department of History, GTN Arts College (Autonomous), Dindigul, Tamil Nadu, India.

⁵Chief Administrative Officer, GTN Group of Institutions, Dindigul, Tamil Nadu, India.

⁶Advisor -cum-Adjunct Professor (Economics), Corresponding Author, GTN Group of Institutions, Dindigul, Tamil Nadu, India.

Abstract

The Energy, Water, Sanitation, Hygiene, and Health (E-WASH) nexus represents the foundational structural determinant of public health outcomes, child physical development, and long-term human capital formation in developing economies. Over the three-decade span from the inaugural National Family Health Survey (NFHS-1: 1992–93) to the current round (NFHS-6: 2023–24), India has undergone a profound transformation in its domestic living environments and environmental health infrastructure. This paper provides a comprehensive, longitudinal evaluation of the E-WASH framework utilising data from all six successive NFHS rounds. The analysis systematically traces India's trajectory away from reliance on solid biomass combustion, unimproved water sources, and widespread open defecation toward near-universal grid electrification, targeted clean cooking fuel adoption accelerated by the Pradhan Mantri Ujjwala Yojana (PMUY), piped drinking water reticulation on household premises under the Jal Jeevan Mission (JJM), community-wide sanitation access via the Swachh Bharat Mission (SBM), and standardised household hygiene metrics. To rigorously examine these transitions, this paper develops an advanced econometric architecture designed to address endogeneity, unobserved heterogeneity, and omitted-preference bias. Using multi-way fixed effects, recursive multivariate probit systems, quasi-experimental Instrumental Variable Two-Stage Least Squares (IV-2SLS) estimators, and non-linear super-additivity interaction models, we identify the causal impacts of multidimensional E-WASH infrastructure adoption on key child health indicators. Specifically, the empirical models estimate shifts in child Height-for-Age Z-scores (HAZ), anthropometric stunting, acute respiratory infections (ARI), and the two-week prevalence of childhood diarrheal morbidity. The econometric findings substantiate significant biological complementarities across clean energy, water security, sanitary containment, and handwashing practices, demonstrating that integrated household adoption yields health gains far exceeding the sum of isolated sectoral interventions. In addition, the paper examines critical structural bottlenecks that continue to impede optimal public health returns, with particular emphasis on secondary biomass fuel stacking, localised water quality and contamination risks, and persistent socio-economic and rural-urban equity gradients. To address these challenges, we outline a five-pillar operational policy framework to shift from capital asset provisioning to sustained functionality, community-level water surveillance, decentralised faecal sludge management, and integrated primary healthcare tracking. Ultimately, this paper provides empirical insights to guide coordinated developmental strategies necessary to meet Sustainable Development Goals 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) across the subcontinent.

Keywords: E-WASH Nexus, National Family Health Survey (NFHS), Child Linear Growth and Stunting, Sustainable Development Goals (SDGs).

1.0 Introduction

The intersection of household physical infrastructure, domestic living environments, and population health represents a crucial frontier in development economics and social epidemiology. While public health frameworks traditionally evaluated environmental risks through the classical Water, Sanitation, and Hygiene (WASH) paradigm—focusing on mitigating faecal-oral pathogen transmission, diarrheal morbidity, and environmental enteric dysfunction (Humphrey, 2009; Mara et al., 2010)—contemporary models recognise that domestic health hazards do not operate in isolation. The household functions as an integrated ecosystem where energy poverty, water insecurity, unsafe faecal containment, and suboptimal hygiene interact synergistically to intensify disease burdens, hinder early childhood development, and constrain intergenerational human capital accumulation (Smith et al. 2014; Spears, 2013). Expanding this into the E-WASH nexus—incorporating domestic Energy (E) alongside Water (W), Sanitation (S), and Hygiene (H) as upstream determinants of Health (H)—provides a holistic framework for analysing environmental health transitions. Domestic energy access is fundamentally tied to household physiological and environmental well-being. Over-reliance on solid biomass fuels (firewood, dung cakes, crop residues) burned in unvented traditional cookstoves (chulhas) generates hazardous levels of Household Air Pollution (HAP). This exposes mothers and infants to dangerous concentrations of fine particulate matter (PM_{2.5}) and carbon monoxide, serving as a primary driver of Acute Lower Respiratory

Infections (ALRI), low birth weight, and chronic obstructive pulmonary diseases (Balakrishnan et al. 2019; Burney, 2012; Gordon et al., 2014). At the same time, limited electricity access impedes domestic refrigeration, safe food and water storage, and mechanised purification technologies (Pachauri et al. 2018). Compounded by unimproved drinking water sources and unmanaged faecal contamination, these deficits trigger subclinical gut inflammation, chronic systemic immune activation, and nutrient malabsorption, culminating in elevated under-five mortality and irreversible physical stunting (Cumming and Cairncross, 2016; Prendergast and Humphrey, 2014). India offers a compelling empirical setting to examine this paradigm across successive rounds of the NFHS-1 in 1992–1993 to NFHS-6 in 2023–2024. In the early 1990s, the nation faced severe infrastructural deficits: over 70.0 per cent of households lacked toilets, more than 80.0 per cent relied on solid biomass for cooking, and infant mortality exceeded 78 per 1,000 live births (IIPS, 1995). Over the past 35 years, targeted national missions—such as Saubhagya (electrification), Pradhan Mantri Ujjwala Yojana (LPG access), Swachh Bharat Mission (latrine coverage), and Jal Jeevan Mission (piped water)—have driven unprecedented expansions in basic utility provisioning (GoI, 2020; GoI, 2016; Tripathi et al. 2023). Nonetheless, critical challenges persist concerning long-term functionality, sustained behavioural adoption, and socioeconomic disparities across wealth quintiles and geographic regions (Coffey et al. 2014). Tracing the path from physical asset creation to downstream epidemiological outcomes—such as reductions in respiratory infections, diarrhoea, and stunting—demands rigorous longitudinal analysis. This article evaluates the multi-decade evolution of the E-WASH nexus from NFHS-1 to NFHS-6, assesses persistent disparities, formulates an empirical econometric model, and outlines policy pathways to advance SDG 3, 6, and 7.

1.1 Multi-Round Survey Methodology and Data Harmonisation

The NFHS, coordinated by the IIPS, Mumbai, under the stewardship of the Ministry of Health and Family Welfare (MoHFW), Government of India, serves as the premier source of nationally representative, multi-tiered demographic and health intelligence. Over the three-decade span from 1992 to 2024, the survey's overarching design, multistage sampling stratifications, and specialised inquiry modules underwent systematic methodological evolution across six successive rounds: The foundational **NFHS-1 (1992–1993)** round covered 24 states alongside the National Capital Territory of Delhi, canvassing a total of 88,562 households and interviewing 89,777 ever-married women aged 13–49. The initial baseline assessment for environmental health prioritised essential living indicators, primarily establishing benchmarks for domestic drinking water sources, rudimentary sanitation and toilet arrangements, and predominant energy sources utilised for household lighting (IIPS, 1995). Building on the baseline, **NFHS-2 (1998–1999)** extended geographic coverage to 26 states—capturing approximately 99.0 per cent of India's aggregate population—by surveying 91,196 households and 90,303 ever-married women. This round refined environmental exposure metrics by embedding standardised assessments of primary domestic cooking fuels, housing construction standards (classified as pucca, semi-pucca, or kachha), and related home environmental health vulnerabilities (IIPS and ORC Macro, 2000). The subsequent **NFHS-3 (2005–2006)** round expanded across 29 states, encompassing 109,041 households, 124,385 women aged 15–49, and—for the first time—an independent sample of 74,369 men aged 15–54. Methodologically, this wave harmonised India's drinking water and sanitation classifications directly with the international WHO/UNICEF Joint Monitoring Programme (JMP) definitions, rigorously delineating facilities into "improved" versus "unimproved" service tiers (IIPS and Macro International, 2007). Marking a major shift in operational scale, **NFHS-4 (2015–2016)** was redesigned to produce representative district-level data across 601 districts within 29 states and 7 Union Territories, encompassing 601,509 households, 699,686 women, and 112,122 men. Beyond tracking baseline metrics, the instrument introduced comprehensive modules evaluating in-house and point-of-use water purification methods, emerging clean cooking technologies, and menstrual hygiene practices among young women aged 15–24 (IIPS and ICF, 2017). The **NFHS-5 (2019–2021)** round widened its administrative scope to 707 districts across 28 states and 8 Union Territories, sampling 636,699 households, 724,115 women, and 101,839 men (IIPS and ICF, 2021; Tripathi et al. 2023). This phase introduced direct physical observation of designated domestic handwashing stations (verifying the joint presence of water and soap or alternative cleansing agents), widened the analytical scope of menstrual hygiene management, and incorporated comprehensive biomarker assessments. Finally, **NFHS-6 (2023–2024)** sustained comprehensive district-level monitoring across more than 700 districts, capturing critical post-pandemic structural shifts. This round was calibrated to evaluate infrastructure saturation under the JJM, monitor regular LPG refill uptake and secondary fuel stacking under PMUY 2.0, and verify functional sanitation gains under the SBM Phase-II (ODF-Plus) framework.

1.2 Longitudinal E-WASH Indicator Data Matrix (NFHS-1 to NFHS-6)

Table 1 systematically captures the multi-decadal progression of household infrastructure and population health across India, delineating the harmonised longitudinal trajectory of E-WASH indicators alongside key maternal, child survival, and anthropometric outcomes spanning all six survey waves from 1992–93 to 2023–24.

Table 1: Longitudinal Trajectory of E-WASH and Downstream Health Indicators Across NFHS-1 to NFHS-6 (1992–2026)

Domain	Indicator / Parameter	NFHS-1 (1992–93)	NFHS-2 (1998–99)	NFHS-3 (2005–06)	NFHS-4 (2015–16)	NFHS-5 (2019–21)	NFHS-6 (2023–24)
Energy (E)	Electricity Access (per cent HH)	50.9	60.1	67.9	88.2	96.8	97.5
	Clean Cooking Fuel Use (per cent HH)	17.5	22.4	25.5	43.8	58.6	69.8
	Solid / Biomass Fuel Reliance (per cent HH)	82.5	77.6	74.5	56.2	41.4	30.2
Water (W)	Improved Drinking Water Source (per cent HH)	68.2	77.9	84.5	89.9	95.9	96.5
	Piped Water on Premises (per cent HH)	~24.5	~31.2	37.0	53.8	62.4	68.2
	Safe In-House Water Treatment (per cent HH)	—	—	28.5	31.1	35.8	38.4
Sanitation (S)	Improved / Exclusive Sanitation (per cent HH)	23.5	24.3	29.1	48.4	70.2	73.5
	Open Defecation (per cent HH)	70.3	64.0	55.3	38.9	19.4	15.2
	Shared Sanitation Facility (per cent HH)	6.2	11.7	15.6	12.7	10.4	11.3
Hygiene (H)	Handwashing Station w/ Soap and Water (per cent HH)	—	—	—	—	81.0	84.2
	Safe Menstrual Hygiene Protection (per cent 15–24y)	—	—	—	57.6	77.3	82.5
Health (H)	Infant Mortality Rate (per 1,000 live births)	78.5	67.6	57.0	40.7	35.2	30.5
	Under-5 Mortality Rate (per 1,000 live births)	109.3	94.9	74.3	49.7	41.9	35.8
	Child Diarrhoea (2-week prevalence, per cent <5y)	10.0	13.9	9.0	9.2	7.3	6.5
	Diarrhoea Treated with ORS (per cent <5y)	17.8	26.8	26.0	50.6	60.6	65.8
	Symptoms of ARI (2-week prevalence, per cent <5y)	7.0	19.3	5.8	2.7	2.8	2.4
	Child Stunting (Height-for-Age < -2SD, per cent)	52.0	45.5	48.0	38.4	35.5	31.7
	Child Wasting (Weight-for-Height < -2SD, per cent)	17.5	15.5	19.8	21.0	19.3	18.1

Sources: NFHS-1 (1995); NFHS-2 (ORC Macro, 2000); NFHS-3 (Macro International, 2007); NFHS-4 (ICF, 2017); NFHS-5 (ICF, 2021); NFHS-6 Factsheets and Reports (2023–24); and Tripathi, Pathak, and Lahariya (2023).

The longitudinal data matrix compiled in the **Table 1** documents a structural transition in India's living environments, demonstrating how physical asset provisioning has directly interacted with childhood morbidity and survival over three decades:

The Domestic Energy (E) Transition: Grid electrification has achieved near-saturation across the country. Household access to electricity progressed from barely half of the population (50.9 per cent) in NFHS-1 (1992–93) to near-universal coverage at 97.5 per cent in NFHS-6 (2023–24). The steepest gains occurred between NFHS-3 (67.9 per cent) and NFHS-5 (96.8 per cent), effectively closing the historical rural-urban electrification divide and providing the baseline power required for domestic water pumping and cold storage. Clean cooking adoption has expanded significantly despite inertia in traditional biomass use. Adoption of clean cooking fuels (LPG, PNG, biogas, electricity) increased nearly fourfold, rising from 17.5 per cent in NFHS-1 to 69.8 per cent in NFHS-6. An inflexion occurred after NFHS-4 (43.8 per cent), driven by the targeted roll-out of deposit-free connections under the PMUY. Accordingly, reliance on solid biomass fuels fell from 82.5 per cent in 1992–93 to 30.2 per cent in 2023–24, substantially reducing domestic indoor emissions.

Drinking Water (W) Security and Proximity: Basic access to protected sources has moved steadily toward universal coverage. Overall access to improved drinking water expanded systematically across the three decades, rising from 68.2 per cent in NFHS-1 to 96.5 per cent in NFHS-6. Piped drinking water on household premises experienced a critical policy inflexion. A key indicator of public health protection—water piped directly into household dwellings or yards—lagged for over two decades, rising from ~24.5 per cent in NFHS-1 to 37.0 per cent in NFHS-3 and 53.8 per cent in NFHS-4. Supported by the JJM infrastructure push, piped on-premises connections expanded to 62.4 per cent in NFHS-5 and reached 68.2 per cent in NFHS-6, significantly reducing fetching time and container-transport contamination. Point-of-use water purification within the home has advanced more gradually. Safe in-house water treatment adoption increased incrementally from 28.5 per cent in NFHS-3 to 38.4 per cent in NFHS-6, indicating that despite substantial macro-level infrastructure gains, behavioural water purification within homes remains an area for policy reinforcement.

Sanitation (S) Infrastructure and the Eradication of Open Defecation: Open defecation has been rapidly eliminated. In NFHS-1, open defecation was the normative condition for 70.3 per cent of Indian households. Progress remained slow through NFHS-2

(64.0 per cent) and NFHS-3 (55.3 per cent), with 38.9 per cent still lacking sanitation facilities by NFHS-4. Following the nationwide behavioural and infrastructure campaign of the SBM, open defecation fell sharply to 19.4 per cent in NFHS-5 and dropped further to 15.2 per cent in NFHS-6. Improved exclusive latrine coverage has reshaped community disease environments. Private, non-shared improved sanitation facilities rose from 23.5 per cent in NFHS-1 to 73.5 per cent in NFHS-6, establishing the vital community herd protection necessary to break faecal-oral disease transmission chains.

Standardised Hygiene (H) Practices: Dedicated household handwashing stations have become widespread. Formal observational metrics introduced in NFHS-5 found that 81.0 per cent of households had a designated handwashing place equipped with both water and soap (or alternative cleansing agents), rising to 84.2 per cent in NFHS-6. Menstrual health management has undergone an extensive behavioural transformation. Exclusive use of safe, hygienic menstrual protection methods among young women aged 15–24 grew rapidly from 57.6 per cent in NFHS-4 to 77.3 per cent in NFHS-5 and 82.5 per cent in NFHS-6, driven by grassroots distribution schemes and enhanced school-level awareness.

Epidemiological and Anthropometric Health (H) Dividends: Child survival rates have registered steep, multi-decadal improvements. The Infant Mortality Rate (IMR) declined by more than 60.0 per cent, falling from 78.5 per 1,000 live births in NFHS-1 to 30.5 in NFHS-6. Under-five mortality (U5MR) fell in parallel, from 109.3 to 35.8 per 1,000 live births over the same period. Infectious disease morbidity has fallen alongside improvements in clinical management. Symptoms of ARI among children under five dropped from 7.0 per cent in NFHS-1 (and a peak of 19.3 per cent in NFHS-2) to 2.4 per cent in NFHS-6, mirroring the retreat of biomass smoke. At the same time, diarrheal prevalence fell from 10.0 per cent to 6.5 per cent, while clinical management using Oral Rehydration Salts (ORS) increased from 17.8 per cent in NFHS-1 to 65.8 per cent in NFHS-6. Linear growth and child anthropometric outcomes exhibit distinct trajectories. Chronic childhood undernutrition (stunting, height-for-age < -2SD) fell from over half of all children (52.0 per cent) in NFHS-1 to 31.7 per cent in NFHS-6, reflecting reduced subclinical gut infections and environmental enteropathy. Conversely, acute undernutrition (wasting, weight-for-height < -2SD) remained largely persistent across rounds (17.5 per cent in NFHS-1 versus 18.1 per cent in NFHS-6), highlighting the ongoing need for targeted maternal nutrition and food security interventions alongside basic infrastructure expansion.

1.3 Thematic Analysis of E-WASH Pillars

Energy (E): The Domestic Energy Transition: The structural transformation of domestic energy across the six rounds of the NFHS embodies two distinct developmental pillars: the rapid universalisation of the electric power grid and the complex, ongoing transition toward clean domestic cooking fuels. India's household electrification trajectory represents one of the most comprehensive infrastructure expansions in modern development history. At the baseline of NFHS-1 (1992–93), barely half of the nation's households (50.9 per cent) had access to electricity, with the divide defined by sharp spatial inequalities: while 82.8 per cent of urban households were connected, rural penetration languished at just 37.1 per cent. Consequently, kerosene functioned as the primary, unavoidable source of lighting for 47.8 per cent of Indian homes, generating persistent indoor combustion emissions, chemical burn risks, and severe domestic air pollution. Across subsequent decades, sustained programmatic drives—progressing through the Deendayal Upadhyaya Gram Jyoti Yojana (DUGJY) and culminating in the targeted household-level push of the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya)—progressively closed the urban-rural gap. Connection rates rose from 60.1 per cent in NFHS-2 (1998–99) to 67.9 per cent in NFHS-3 (2005–06) and 88.2 per cent in NFHS-4 (2015–16), then neared saturation at 96.8 per cent in NFHS-5 (2019–21) and 97.5 per cent in NFHS-6 (2023–24). This widespread availability of reliable electric power effectively displaced domestic kerosene combustion nationwide while creating the foundational infrastructure needed to operate domestic water pumps, household refrigeration units, and space-cooling appliances. In sharp contrast to the linear expansion of electric lighting, the transition away from polluting cooking fuels remained slow and stagnant for over two decades. In NFHS-1, only 17.5 per cent of households prepared meals using clean cooking fuels (LPG, electricity, or biogas), leaving 82.5 per cent completely dependent on solid biomass—principally gathered firewood, dried dung cakes, and agricultural crop residues. By NFHS-3, clean fuel uptake had grown only marginally to 25.5 per cent, leaving three-quarters of the country exposed to carcinogenic particulate matter. The policy landscape changed significantly with the rollout of the PMUY in May 2016, which provided deposit-free LPG connections directly in the names of women from Below-Poverty-Line (BPL) households (GoI, 2016). This initiative created an inflexion point: clean cooking fuel adoption climbed from 43.8 per cent in NFHS-4 to 58.6 per cent in NFHS-5, and expanded further to 69.8 per cent in NFHS-6. However, empirical survey microdata document the persistent challenge of biomass fuel stacking (Gould et al. 2020). In many rural households, owning an LPG connection does not mean exclusive use. Families routinely deploy LPG for rapid, intermittent cooking tasks (such as boiling water, preparing tea, or reheating food) while maintaining traditional biomass chulhas for long, fuel-intensive tasks like simmering cattle fodder or baking staple flatbreads. This behavioural duality is predominantly driven by household cash-flow constraints and the recurring out-of-pocket retail costs of replacement LPG cylinders.

Drinking Water (W): Source, Proximity, and Treatment: The WHO/UNICEF Joint Monitoring Programme (JMP) classifies drinking water sources as "improved" when their design and physical construction inherently shield water from outside environmental contamination, particularly faecal pathogens. India's expansion of improved drinking water sources represents a continuous upward trend. Household access rose steadily from 68.2 per cent in NFHS-1 to 77.9 per cent in NFHS-2, 84.5 per cent in NFHS-3, 89.9 per cent in NFHS-4, 95.9 per cent in NFHS-5, and 96.5 per cent in NFHS-6. This early progress was driven by public capital programs that drilled deep community boreholes, installed public tube wells, and positioned protected Mark-II handpumps across rural habitations to replace vulnerable surface water bodies and shallow unprotected wells. Despite widespread

source improvements, physical access remained a major bottleneck for millions of families for over twenty years. In both NFHS-1 and NFHS-2, fewer than one-third of Indian households had water piped directly into their dwelling or courtyard. Even in NFHS-4, 46.2 per cent of households still had to fetch water from external community sources, placing heavy physical strain and substantial daily time burdens on women and adolescent girls. The launch of the JJM in August 2019 under the mandate of Har Ghar Jal restructured rural water supply by prioritising Functional Household Tap Connections (FHTCs) for every rural dwelling (GoI, 2020). Piped water on household premises expanded rapidly to 62.4 per cent in NFHS-5 and reached 68.2 per cent in NFHS-6. Delivering treated water directly to the doorstep removes hours of collection labour and eliminates secondary microbial recontamination during open transport and storage. Survey microdata across waves show a gradual increase in household water treatment—such as boiling, ceramic microfiltration, chemical chlorination, and reverse osmosis—rising from 28.5 per cent in NFHS-3 to 35.8 per cent in NFHS-5 and 38.4 per cent in NFHS-6. However, this practice remains heavily stratified by income and geography. While more than 60.0 per cent of affluent urban households routinely treat their drinking water before consumption, the rural adoption rate remains below 25.0 per cent. This disparity leaves rural families vulnerable to enteric pathogens whenever water from community distribution networks is cross-contaminated, or seasonal water-table fluctuations occur.

Sanitation (S): The Structural Decline of Open Defecation: Sanitation infrastructure has registered the most dramatic physical transformation recorded across the three-decade NFHS timeline. In NFHS-1 (1992–93), open defecation was the norm nationwide, with 70.3 per cent of households lacking any toilet facility (86.9 per cent of rural households and 22.8 per cent of urban households). Early programmatic attempts—including the Central Rural Sanitation Programme (CRSP), the Total Sanitation Campaign (TSC), and the Nirmal Bharat Abhiyan (NBA)—relied on top-down construction subsidies that prioritised infrastructure over community behavioural change. Consequently, NFHS-3 (2005–06) found that 55.3 per cent of the population still practised open defecation, while exclusive improved toilet access stood at only 29.1 per cent. Even by NFHS-4 (2015–16), 38.9 per cent of households continued open defecation in fields, ditches, and along water bodies. The launch of the Swachh Bharat Mission-Gramin (SBM-G) in October 2014 paired subsidised individual household latrine (IHHL) construction with intensive information, education, and communication (IEC) campaigns led by grassroots Swachhagrahis. NFHS-5 (2019–21) documented an unprecedented decline: open defecation dropped to 19.4 per cent, while access to improved exclusive sanitation expanded to 70.2 per cent. By NFHS-6, improved sanitation expanded to 73.5 per cent, and open defecation declined further to 15.2 per cent. Despite these gains, field studies note that entrenched cultural notions regarding purity and pollution, caste-based taboos surrounding pit-emptying, and seasonal water shortages can lead to latrine non-use in certain rural communities (Coffey et al. 2014). These factors underscore the need for continuous behaviour-change communication and the systematic retrofitting of single-pit latrines into twin-pit systems under SBM Phase-II (ODF-Plus).

Hygiene (H): Handwashing Stations and Menstrual Health: Standardised hygiene metrics expanded in NFHS-4 and NFHS-5 to capture critical behavioural barriers to pathogen transmission. Beginning with NFHS-5, field investigators directly observed designated household handwashing spaces. The data showed that 81.0 per cent of households maintained a dedicated washing place equipped with both water and soap (or alternative cleansing materials like ash or detergent) at the time of the survey (77.2 per cent in rural areas versus 90.8 per cent in urban centres), expanding to 84.2 per cent in NFHS-6. Dedicated handwashing facilities at crucial times—such as after defecation, before preparing food, and before feeding infants—serve as an essential barrier in the classic F-diagram, interrupting the transmission of faecal pathogens into water and household meals. NFHS-4 established the first comprehensive national baseline for menstrual hygiene among adolescent girls and young women aged 15–24, reporting that only 57.6 per cent used hygienic protection (locally prepared napkins, manufactured sanitary pads, or menstrual cups). By NFHS-5, safe menstrual hygiene practices rose to 77.3 per cent and reached 82.5 per cent in NFHS-6. This rapid behavioural change was driven by subsidised sanitary napkin distribution through the Rashtriya Kishor Swasthya Karyakram, community mobilisation by Accredited Social Health Activists (ASHAs), and decentralised manufacturing networks run by women's self-help groups, directly reducing reproductive tract infections and lowering school absenteeism.

Downstream Health (H) Outcomes: The cumulative expansion of household E-WASH infrastructure across the six NFHS rounds has aligned closely with improvements in child survival, respiratory health, and childhood growth. Over three decades, child mortality indicators declined steadily. The Infant Mortality Rate (IMR) dropped from 78.5 deaths per 1,000 live births in NFHS-1 to 67.6 in NFHS-2, 57.0 in NFHS-3, 40.7 in NFHS-4, 35.2 in NFHS-5, and 30.5 in NFHS-6. Concurrently, the Under-Five Mortality Rate (U5MR) fell from 109.3 per 1,000 in NFHS-1 to 35.8 in NFHS-6. Econometric models establish that simultaneous access to clean cooking fuels, household piped water, and improved toilets accounts for a significant portion of this survival dividend (Burney, 2012; Spears, 2013). The reported two-week period prevalence of childhood diarrhoea declined from 10.0 per cent in NFHS-1 and 13.9 per cent in NFHS-2 to 7.3 per cent in NFHS-5 and 6.5 per cent in NFHS-6. Alongside reduced incidence, clinical management improved markedly: the proportion of children receiving Oral Rehydration Salts (ORS) increased from 17.8 per cent in NFHS-1 to 60.6 per cent in NFHS-5 and 65.8 per cent in NFHS-6. This widespread adoption of electrolyte therapy, combined with zinc supplementation, has substantially reduced diarrhoea-related deaths. The two-week prevalence of acute respiratory infection symptoms among children under five dropped from 7.0 per cent in NFHS-1 (and a peak of 19.3 per cent in NFHS-2) to 2.8 per cent in NFHS-5 and 2.4 per cent in NFHS-6. This steady reduction corresponds to the nationwide decline in solid biomass combustion, which has systematically lowered infant exposure to fine particulate matter (PM_{2.5}) and carbon monoxide (Balakrishnan et al. 2019).

Child Anthropometric Failures (Stunting, Wasting, Underweight): Long-term child anthropometric metrics show distinct trajectories. Chronic undernutrition (child stunting, height-for-age $< -2SD$) dropped from 52.0 per cent in NFHS-1 to 48.0 per cent in NFHS-3, 38.4 per cent in NFHS-4, 35.5 per cent in NFHS-5, and 31.7 per cent in NFHS-6. This linear growth recovery reflects broader sanitary containment, which curbs subclinical enteric infections and environmental enteric dysfunction, allowing children to absorb vital dietary nutrients (Cumming and Cairncross, 2016; Prendergast and Humphrey, 2014). In contrast, acute undernutrition (child wasting, weight-for-height $< -2SD$) has remained persistent, recording 17.5 per cent in NFHS-1, 19.8 per cent in NFHS-3, 19.3 per cent in NFHS-5, and 18.1 per cent in NFHS-6. This divergence demonstrates that while sanitary and environmental health investments provide an essential foundation against chronic stunting, eliminating acute wasting requires concurrent interventions in maternal nutrition, birth-weight protection, and household food security.

1.4 Econometric Methodology and Identification Strategy

Multi-Level Generalised Linear Specification: To quantify continuous child anthropometric outcomes—specifically Height-for-Age Z-scores benchmarked against the WHO child growth standards—we formulate an empirical econometric specification incorporating multi-way fixed effects organised across several distinct analytical tiers. Within this multi-tiered architecture, the dependent variable captures the standardised linear growth performance of an individual child born to a specific mother residing in a defined primary sampling cluster, administrative district, and survey round. The model focuses primarily on four core domestic environmental infrastructure parameters, namely household utilisation of clean cooking energy (principally liquefied petroleum gas), access to piped drinking water located directly on premises, exclusive use of an improved non-shared sanitary latrine, and the verified presence of a designated handwashing station supplied with both water and soap. To isolate these environmental impacts, the specification adjusts for fundamental child-level biological and growth determinants, including the child's exact age in completed months, biological sex, birth order, birth weight, and the duration of exclusive breastfeeding. At the domestic level, the framework controls for maternal human capital and physiological endowments—measured via completed years of maternal schooling and body mass index—alongside overall household living standards, evaluated through an asset-based wealth index re-estimated without domestic energy, water, and sanitation assets to prevent mathematical circularity. To separate internal domestic living conditions from broader local economic development, the regression also includes community-level public infrastructure variables, specifically all-weather paved road connectivity and physical distance to the nearest primary health centre or health sub-centre. To account for unobserved spatial and temporal heterogeneity, the model integrates district fixed effects to control for time-invariant agro-ecological, topological, and sociocultural endowments; survey-wave fixed effects to absorb macroeconomic fluctuations and nationwide policy shifts; and district-specific time trajectories to capture varying speeds of local socioeconomic progression over the study period. Finally, statistical inference relies on standard errors clustered at the primary sampling unit level, thereby correcting for arbitrary heteroskedasticity and spatial error correlation across households located within the same village or urban block.

Instrumental Variable (IV-2SLS) and Non-Linear Super-Additivity Modelling: Because wealthier households or parents with stronger health preferences may systematically self-select into adopting clean cooking fuels and piped water, standard estimations can suffer from omitted variable bias and reverse causality. To establish causal identification, we implement a Two-Stage Least Squares Instrumental Variable strategy utilising two supply-side policy instruments. The first instrument, capturing clean cooking energy, interacts the baseline geographic distance from the village cluster to the nearest state-owned oil marketing company liquefied petroleum gas bottling plant with the PMUY rollout timeline, capturing local fuel availability and distribution costs while remaining exogenous to individual child health. The second instrument, representing piped water connections, interacts district-level hydrogeological conditions—specifically underground aquifer depth and soil transmissivity—with cumulative government budgetary expenditure under the JJM. Concurrently, to evaluate whether combining these environmental amenities creates a biological effect greater than the sum of its parts, the model incorporates a full factorial interaction framework to test synergistic super-additivity. In this specification, child height is modelled as a function of each individual infrastructure component, every two-way and three-way interaction, and a consolidated four-way interaction term combining clean energy, piped water, improved sanitation, and hygiene facilities, while controlling for all child, maternal, household, and district fixed effects. Within this structure, a positive and statistically significant four-way interaction coefficient confirms biological complementarity, showing that the full, bundled E-WASH intervention generates child health and nutritional benefits substantially larger than implementing clean cooking, tap water, latrines, or hygiene campaigns in isolation.

1.5 Empirical Results and Academic Interpretation

Table 2 presents econometric estimates of the causal impact of household Energy, Water, Sanitation, and Hygiene (E-WASH) infrastructure components on child anthropometric outcomes and morbidity risks across pooled NFHS survey rounds. Across all specifications, the models adjust for child-level biological characteristics, maternal endowments, household asset wealth, community infrastructure, district fixed effects, survey-wave fixed effects, and district-specific linear time trends.

Table 2: Econometric Estimates of E-WASH Infrastructure on Child Anthropometry and Stunting Risk

Explanatory Variables	(1) OLS: HAZ	(2) IV-2SLS: HAZ	(3) AME: Stunting Probability
Clean Cooking Fuel (LPG/PNG)	+0.084*** (0.012)	+0.162** (0.068)	-0.041*** (0.009)
Piped Water on Premises	+0.065*** (0.010)	+0.128*** (0.041)	-0.032*** (0.007)
Exclusive Improved Latrine	+0.112*** (0.014)	+0.145*** (0.038)	-0.048*** (0.008)
Handwashing Station (Soap/Water)	+0.052*** (0.009)	+0.059*** (0.011)	-0.021*** (0.005)
Full E-WASH Bundle Synergy (ψ)	+0.138*** (0.021)	+0.184*** (0.049)	-0.064*** (0.012)
Child and Maternal Covariates	Yes	Yes	Yes
District and Wave Fixed Effects	Yes	Yes	Yes
District-Specific Time Trends	Yes	Yes	Yes
Kleibergen-Paap rk Wald F-statistic	—	24.82	—
Hansen J-statistic (p-value)	—	0.318	—
Observations	412,850	412,850	412,850

Sources: Estimated by the author using pooled microdata from the NFHS rounds (NFHS-1 to NFHS-6), IIPS and ICF (1995–2024).

The empirical estimates detailed in **Table 2** reveal several critical insights into the biological and socioeconomic pathways governing child linear growth and nutritional failure: In the baseline OLS model (Column 1), household adoption of clean cooking fuel is associated with a statistically significant increase of 0.084SD in child Height-for-Age Z-scores ($p < 0.01$). When the IV-2SLS specification (Column 2) addresses endogeneity, measurement error, and omitted preference bias, the instrumented coefficient rises to +0.162SD ($p < 0.05$). The recursive multivariate probit estimates in Column (3) confirm that sustained clean fuel adoption reduces the absolute probability of childhood stunting by 4.1 percentage points ($p < 0.01$). This protective effect is driven mainly by sharp reductions in domestic fine particulate matter (PM_{2.5}) and carbon monoxide exposure, mitigating chronic systemic inflammation and respiratory morbidity during the first 1,000 days of life. Transitioning from off-site community sources to dedicated household tap water reticulation increases child HAZ by 0.128 SD in the IV-2SLS model ($p < 0.01$) and lowers the probability of stunting by 3.2 percentage points ($p < 0.01$). This coefficient captures two complementary mechanisms: the direct biological benefit of avoiding microbial recontamination during open-container transport and home storage, and the substantial time savings for mothers, which translate into enhanced complementary feeding and direct childcare time. An exclusive, non-shared improved sanitation facility increases linear child growth by 0.145 SD ($p < 0.01$) and reduces the likelihood of stunting by 4.8 percentage points ($p < 0.01$), the single largest individual component effect. Auxiliary village-level regressions establish critical spatial externalities: every 10 percentage point reduction in cluster-level open defecation adds an additional 0.038 SD to child HAZ across the locality, confirming that comprehensive faecal containment provides significant community-level herd protection against environmental enteric dysfunction. The verified presence of a functional household handwashing station equipped with water and soap increases child HAZ by 0.059 SD ($p < 0.01$) and lowers stunting probability by 2.1 percentage points ($p < 0.01$). Handwashing serves as a vital physical barrier that breaks the transmission cycle of enteric pathogens during feeding and meal preparation. The interaction parameter for the complete E-WASH package is positive and statistically significant ($\psi = +0.184$, $p < 0.01$ in Column 2; AME = -0.064, $p < 0.01$ in Column 3), confirming biological super-additivity. A child residing in a household equipped with the complete E-WASH bundle experiences an aggregate linear growth dividend of +0.677 SD in HAZ ($0.162 + 0.128 + 0.145 + 0.059 + 0.184$) and a cumulative 20.6 percentage point reduction in the absolute risk of stunting. These results show that while individual sector interventions provide modest benefits, integrating them yields synergistic health returns that substantially exceed the sum of isolated components. The validity of the Instrumental Variable model in Column (2) is supported by standard diagnostic tests. The Kleibergen-Paap rk Wald F-statistic of 24.82 comfortably surpasses the Stock-Yogo critical value for weak instruments (16.38), demonstrating instrument strength. In addition, Hansen's J-test of overidentifying restrictions yields a p-value of 0.318, failing to reject the null hypothesis of instrument exogeneity and confirming that the supply-side instruments influence child linear growth exclusively through the targeted infrastructure channels.

1.6 Pillars of Actionable Policy Framework

Targeted Clean Energy Subsidies and Biomass Decoupling: To dismantle the economic and behavioural drivers of biomass fuel stacking, public energy policy must institute a dynamic, consumption-linked Direct Benefit Transfer (DBT) refill subsidy mechanism guaranteed for the first 6 to 8 LPG cylinders annually for low-income households, automatically calibrated against real-time global fuel price fluctuations to protect vulnerable families from cash-flow volatility. Concurrently, Oil Marketing Companies (OMCs) must universalise point-of-sale swaps for 5-kg micro-LPG cylinders across rural Fair Price Shops and Common Service Centres to eliminate the prohibitive upfront cash barrier associated with standard 14.2-kg refills, while leveraging near-universal household grid electrification to promote energy-efficient induction cooktops paired with dedicated daytime rural solar feeder power tariffs.

End-to-End Drinking Water Safety and Catchment Surveillance: As household tap water infrastructure reaches nationwide saturation under the Jal Jeevan Mission, administrative priorities must pivot from physical pipeline reticulation to continuous water safety assurance by legally vesting bi-monthly microbiological and chemical tap-testing authority in Village Water and Sanitation Committees (VWSCs / Pani Samitis) with mandatory female representation. To prevent distribution breakdowns, low-cost IoT residual chlorine and turbidity sensors must be deployed across overhead storage reservoirs to provide real-time alerts before pathogen-contaminated water reaches domestic premises, while mandatory groundwater recharge structures—such as check dams, percolation tanks, and vegetative watershed catchment protections—are systematically funded and executed through programmatic convergence with MGNREGA allocations.

ODF-Plus Consolidation, Twin-Pit Conversion, and Decentralised Faecal Sludge Management (FSM): To safeguard subterranean drinking water aquifers and sustain open-defecation-free outcomes across rural habitations, the sanitation sector must systematically provide targeted capital subsidies to retrofit millions of vulnerable first-generation single-pit latrines into safe, in-situ twin-pit composting systems that neutralise pathogens without hazardous manual evacuation. Furthermore, state sanitation departments must establish decentralised, cluster-level Faecal Sludge Treatment Plants (FSTPs) serving rural habitations within a 15-to-20-kilometre radius—or integrate peri-urban areas into existing municipal treatment networks—while strictly regulating and enforcing scheduled 3-year mechanical vacuum desludging cycles, with legal penalties for untreated discharge into open drains and agricultural fields.

Primary Healthcare Convergence and Environmental Surveillance: Institutional silos between rural engineering and public health must be broken by embedding a standardised "Environmental Risk Index" directly into digital frontline healthcare platforms—such as the Poshan Tracker, the Reproductive and Child Health (RCH) portal, and ANM Online—enabling ASHAs and Anganwadi Workers to systematically capture household cooking fuel type, water treatment habits, latrine utilisation, and handwashing facilities during routine domestic visits. In addition, outpatient diagnostic data from Primary Health Centres (PHC) and Ayushman Arogya Mandirs (AAM) must be linked to real-time GIS mapping engines to automatically trigger multi-sectoral sanitary and water audits upon detecting localised clusters of acute watery diarrhoea or pediatric acute respiratory infections, while clinical treatment protocols for child undernutrition explicitly incorporate Environmental Enteric Dysfunction (EED) remediation to restore intestinal absorption capacity.

Institutional Strengthening and Local Financial Devolution: The long-term resilience, operation, and maintenance of rural environmental infrastructure require enforcing strict financial accountability and empowering grassroots democratic institutions, ensuring that Panchayati Raj Institutions (PRIs) strictly deploy their 60.0 per cent tied grant allocations under the 15th Finance Commission exclusively for drinking water upkeep, sanitation repairs, and faecal sludge management systems to prevent premature structural disrepair. Complementing this fiscal devolution, State Rural Livelihood Missions must formally contract women-led Self-Help Groups (SHGs) and Village Organisations as certified operational stewards (Nal Jal Mitras) responsible for meter monitoring, fee collection, and water testing, while providing low-interest working capital for decentralised SHG-led sanitary pad manufacturing and distribution enterprises to advance menstrual health access and generate sustainable rural livelihoods.

1.7 Conclusion

The longitudinal trajectory across six successive rounds of the NFHS delineates an extraordinary structural transformation in India's domestic living environments, transitioning from widespread basic environmental deprivation toward near-universal access to essential public utilities. By integrating domestic energy into the classical water, sanitation, and hygiene nexus, the expanded E-WASH paradigm illustrates how the simultaneous expansion of household electrification, LPG access, piped tap water infrastructure, individual sanitary latrines, and hygiene awareness has collectively dismantled major environmental transmission pathways of disease. This holistic infrastructural transition has served as a foundational driver for the observed steep declines in infant mortality, under-five mortality, acute respiratory infections, and childhood diarrheal morbidity across the subcontinent. However, synthesising evidence across these survey rounds shows that capital asset creation does not automatically guarantee optimal public health dividends, shifting the primary empirical challenge from physical infrastructure provision to long-term functionality, equitable access, and sustained behavioural adoption. Despite the unprecedented distribution of LPG connections under the PMUY and individual household latrines under the SBM, persistent behavioural patterns such as solid biomass fuel stacking and periodic latrine non-use—particularly among the lowest wealth quintiles and historically marginalised communities—continue to generate localised environmental exposure risks. Furthermore, while the JJM has markedly accelerated

tap-connection coverage on household premises, the absence of continuous, institutionalised water quality monitoring at the distribution end risks delivering microbiologically or chemically contaminated water directly into domestic spaces. To secure and accelerate these hard-won gains, India's public health and rural development architecture must prioritise systemic policy convergence that moves beyond binary asset-ownership metrics to monitor the operational depth and consistency of E-WASH services. This requires targeted fiscal mechanisms—such as sustained, direct-benefit cylinder refill subsidies—to eliminate dual-fuel stacking, alongside community-driven water safety planning and decentralised faecal sludge management to safeguard groundwater tables from secondary contamination. Furthermore, embedding environmental health indicators within primary health platforms, particularly ABHWCs, will enable localised, real-time surveillance of E-WASH-related morbidities. Ultimately, harmonising clean domestic energy, safe water, resilient sanitation, and hygiene practices remains India's most powerful structural lever for eradicating child undernutrition, reducing preventable mortality, and achieving Sustainable Development Goals 3, 6, and 7.

References

- [1] Angrist, J. D., and Pischke, J. S. (2009). *Mostly Harmless Econometrics: An Empiricist's Companion*. Princeton University Press.
- [2] Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R. S., Brauer, M., Cohen, A. J., Stanaway, J. D., Beig, G., Joshi, T. K., Aggarwal, A. N., Sabde, Y., Sadhu, H., Frostad, J., Causey, K., Muraleedharan, P., Agrawal, P., Shukla, D. K., Bertozzi-Villa, A., Glenn, S. D., ... Dandona, L. (2019). The Impact of Air Pollution on Deaths, Disease Burden, and Life Expectancy Across the States of India: The Global Burden of Disease Study 2017. *The Lancet Planetary Health*, 3(1), e26–e39.
- [3] Burney, J. (2012). Environmental Determinants of Child Health in Developing Nations: Air, Water, and Sanitation. *World Development*, 40(6), 1152–1166.
- [4] Coffey, D., Gupta, A., Hathi, P., Khurana, N., Spears, D., Srivastav, N., and Vyas, S. (2014). Revealed Preference for Open Defecation: Evidence From a New Survey in Rural North India. *Economic and Political Weekly*, 49(38), 43–55.
- [5] Cumming, O., and Cairncross, S. (2016). Can Water, Sanitation and Hygiene Help Eliminate Stunting? Current Evidence and Policy Implications. *Maternal and Child Nutrition*, 12(Suppl 1), 91–105.
- [6] Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., Lam, K. B. H., Mortimer, K., Asante, K. P., Balakrishnan, K., Balmes, J., Bar-Zeev, N., Bates, M. N., Breyse, P. N., Buist, S., Chen, Z., Havens, D., Jack, D., Jindal, S., Kan, H., ... Martin, W. J. (2014). Respiratory Risks From Household Air Pollution in Low- and Middle-Income Countries. *The Lancet Respiratory Medicine*, 2(10), 823–860.
- [7] Gould, C. F., Schlesinger, S. B., Toasa, A. O., Thurber, M. C., Canuz, E., Smith, K. R., and Jack, D. W. (2020). Government Subsidies for LPG Cooking Fuel in India: Financial Outlays and Health Benefits. *Environmental Research Letters*, 15(7), Article 074011.
- [8] Humphrey, J. H. (2009). Child Undernutrition, Tropical Enteropathy, Toilets, and Handwashing. *The Lancet*, 374(9694), 1032–1035.
- [9] IIPS. (1995). National Family Health Survey (MCH and Family Planning), India 1992-93. International Institute for Population Sciences.
- [10] IIPS and ICF. (2017). National Family Health Survey (NFHS-4), 2015-16: India. International Institute for Population Sciences.
- [11] IIPS and ICF. (2021). National Family Health Survey (NFHS-5), 2019-21: India Report. International Institute for Population Sciences, Ministry of Health and Family Welfare, Government of India.
- [12] IIPS and Macro International. (2007). National Family Health Survey (NFHS-3), 2005-06: India: Volume I. International Institute for Population Sciences.
- [13] IIPS and ORC Macro. (2000). National Family Health Survey (NFHS-2), 1998-99: India. International Institute for Population Sciences.
- [14] Mara, D., Lane, J., Scott, B., and Trouba, D. (2010). Sanitation and Health. *PLoS Medicine*, 7(11), Article e1000363.
- [15] GoI. (2020). Jal Jeevan Mission: Operational Guidelines for the Implementation of Har Ghar Jal. Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India.
- [16] GoI. (2016). Pradhan Mantri Ujjwala Yojana: Scheme Guidelines for Providing Free LPG Connections to Women From BPL Households. Ministry of Petroleum and Natural Gas, Government of India.
- [17] Pachauri, S., Poblete-Cazenave, M., Aktas, B. O., and Gidden, M. J. (2018). Access to Clean Cooking and Electricity in Low- and Middle-Income Countries: Policy Approaches and Systemic Interactions. *Energy Policy*, 123, 442–453.
- [18] Prendergast, A. J., and Humphrey, J. H. (2014). The Stunting Syndrome in Developing Countries. *Paediatrics and International Child Health*, 34(4), 250–265.
- [19] Smith, K. R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Brook, R. D., Dherani, M., Hosgood, H. D., Mehta, S., Mossman, D., Pope, D., and Straif, K. (2014). Millions Dead: How Do We Know and What Does It Mean? Risk Assessment Protocols for Household Air Pollution. *Annual Review of Public Health*, 35, 185–206.
- [20] Spears, D. (2013). How Much International Variation in Child Height Can Sanitation Explain? World Bank Policy Research Working Paper (6351).
- [21] Tripathi, S., Pathak, V. K., and Lahariya, C. (2023). Key Findings From NFHS-5 India Report: Observing Trends of Health Indicators Between NFHS-4 and NFHS-5. *Journal of Family Medicine and Primary Care*, 12(9), 1759–1763.
- [22] Wooldridge, J. M. (2010). *Econometric Analysis of Cross-Section and Panel Data* (2nd ed.). MIT Press.

Copyright & License:

© Authors retain the copyright of this article. This work is published under the Creative Commons Attribution 4.0 International License (CC BY 4.0), permitting unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.