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Assessing Health Risks of Unsafe WaSH in India: A Systematic Review and Implications for Policy

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Abstract

Water, Sanitation and Hygiene (WaSH) is foundational to human existence and sustainable development. The ramifications of inadequate and unsafe WaSH conditions extend to a broad spectrum of health concerns. The present paper examines the state-of-the-art literature in the domain of WaSH and health outcomes in India employing a Systematic Literature Review approach. Examining 91 relevant articles, the authors delineate crucial research themes, existing gaps and suggest potential research avenues. The five key themes span from various health risks associated with contaminated water, different chemicals causing contamination of drinking water, the efficiency of household water treatment devices, and geographic classifications, to emerging research areas such as end-user practices outweighing water supply quality and disinfection by-products. Findings highlight the significant health hazards such as dental fluorosis, diarrheal infections, chronic kidney diseases, typhoid and cryptosporidium. Moreover, the presence of chemicals like fluoride and arsenic further exacerbates health risks, necessitating urgent attention and mitigation measures. Additionally, the importance of evaluating the efficiency of household water treatment devices and understanding end-user practices to address quality challenges is equally pertinent. Further, a pooled prevalence of 20.99% was observed in the context of health risks associated with unsafe drinking water demonstrating significant variability across different studies analysed for the review. The findings offer valuable guidance for researchers and practitioners, elucidating extant practices in public health safety and laying the groundwork for evidence-based interventions.

Keywords

Contamination, Drinking Water, Health, India Sanitation and Hygiene (WaSH), Sustainable Development Goals, Systematic Literature Review

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Introduction

Water is pivotal in sustaining life on earth and bolstering socio-economic resilience. Access to clean drinking water is a basic entitlement of every human being. It epitomises safety, security, dignity, and existence (Popkin and Rosenberg, 2010). Further, sanitation and hygiene (having access to facilities for the safe removal of human waste both, faeces and urine, as well as upholding hygienic conditions, through services such as garbage collection, industrial waste management, and wastewater processing and disposal) are also essential to health, environment, and well-being and cannot be seen in isolation to water (World Bank, 2023). Only about 57% of the population had access to safely managed sanitation services in 2022 (WHO, 2024). Further, open defecation (OD) is still practised by 419 million individuals. OD can be profoundly detrimental as it perpetuates a vicious cycle of disease and deprivation. Poor sanitation intensifies the transmission of antimicrobial infections often resulting in malnutrition, stunting, and morbidity. Both gender and wealth inequalities are exacerbated adding fuel to poverty and destitution. These conditions not only prohibit opportunities for work and education but also hinder human development and economic well-being.

Together, inadequate and unsafe Water, Sanitation and Hygiene (WaSH) is responsible for the death of 1.4 million people annually (Gordon et al., 2023). Of this total, 5,64,000 deaths are attributable to poor sanitary facilities. In 2022, merely 33% of the global population possessed private sanitation facilities linked with connected sewers for treating wastewater (WHO, 2022). Regrettably, WaSH remains a globally significant challenge due to multifaceted reasons such as rapid population growth, urbanisation, climate change, conflict, underinvestment, poor waste management, and excessive consumption (Taing, 2022; Dickin and Gabrielsson, 2023).

Over time, WaSH has emerged as one of the significant threats to human existence. Adequate and safe WaSH facilities are the primary means of mitigating numerous diseases (Prüss-Ustün et al., 2017; Meki et al., 2022). Water contamination (natural or anthropogenic), OD and poor hygienic practices can have far-reaching health consequences encompassing waterborne diseases (diarrheal diseases, dysentery, hepatitis A, and cryptosporidiosis), vector-borne diseases (malaria, dengue, and chikungunya), respiratory infections, skin ailments, malnutrition, and neglected tropical diseases (NTDs) (Ross et al., 2023).

These health hazards impact vulnerable populations such as children, women, and the elderly disproportionately (Kumar et al., 2021; Soliman et al., 2021; Wani et al., 2022; and Singh & Chakrabarty, 2023). Poor WaSH practices often result in escalated healthcare costs, decreased productivity, and a strain on healthcare systems (UN-Habitat and WHO, 2021). Lack of safe WaSH perpetuates a cycle of poverty, as communities spend time and resources dealing with preventable illnesses rather than investing in education and economic development. It leads to restrictions in the movement of individuals and is an added burden on females due to the lack of provision for special needs during menstruation. Therefore, improving WaSH conditions is not just about preventing diseases—it is also about promoting human dignity, improving quality of life, facilitating hunger elimination, women's empowerment, food security, education and peace (Parikh et al., 2021).

United Nations' Sustainable Development Goal 6.1 aims to guarantee equitable and affordable access to safe WaSH and eradicate OD practices. Subsequently, from 2015 to 2022, the proportion of individuals consuming safely managed drinking water improved from 69% to 73%, safely managed sanitation rose from 49% to 57%, and basic hygiene services increased from 67% to 75% (UN, 2023). In India, too, the situation has improved. However, around 25% of individuals continue to be without safe water and 48% lack safe hygienic conditions (Water.org, 2023). Further, approximately 21% of communicable diseases are linked to water, impacting around 37.5 million people annually (UN, 2023). Diarrhoea, primarily resulting from poor WaSH, is the foremost cause of death among children, claiming 1.5 million lives annually. Furthermore, a staggering 66 million Indians are exposed to excessive fluoride and 10 million to excessive arsenic in drinking water. The astounding annual economic toll of USD 600 million and the loss of 73 million labour days due to waterborne illnesses indicates the high incidence of health risks in India attributed to inadequate WaSH provisions (WHO, 2023).

In recent years, there has been a substantial rise in interest amongst researchers and practitioners across the globe in WaSH and health. Researchers are delving into various facets surrounding WaSH such as investigating quality, availability, governance, water-related diseases, contaminants, and the interplay of water with urban environment and sustainable development, broadening the scope of publications in the field. However, there remains a gap in understanding as to which interests dominate WaSH research, especially related to health. Further, there has been scant research output in the context of emerging economies such as India where the prevalence of disease is significantly higher (Kanungo et al., 2021; Biswas et al., 2022). Past review studies are limited and have examined specific topics on drinking water and sanitation (Basu and Dasgupta, 2020; Maraddi and Ho, 2022). Their research is restricted to either only a particular source of water such as groundwater (Gyanendra et al., 2022) or for narrow periods. Recent research has also emerged to evaluate studies on SDG 6 (Sarka and Bharat, 2021; Biswas et al., 2022). However, a comprehensive analysis of research on WaSH and health, elucidating evolving themes over time, is yet to be undertaken. Thus, this study aims to bridge the gap by assessing research trends on WaSH and health in India from 2004 to the present, emphasising advancements in narrowing research disparities over time. Employing a systematic literature review (SLR) methodology allows for the synthesis and analysis of existing literature to construct a research framework guiding scholars and practitioners (Tranfield et al., 2003). Further, a pooled prevalence approach is crucial to quantitatively synthesize results from various studies. This will enable authors to estimate overall health hazards and prevalence rates linked with unsafe WaSH practices in India. This study adopts an SLR approach and addresses the following three key research questions (RQs):

RQ1: What is the research profile of relevant prior literature on WaSH and health in India?

RQ2: What are the prevalent research themes addressing emerging concerns in the literature on WaSH and health in India?

RQ3: What is the overall pooled prevalence rate of health risks attributable to unsafe Drinking Water in India?

The paper is structured as follows: After a brief introduction in Section 1, Section 2 discusses the research methodology employed. Research profiling of the relevant prior literature is put forward in Section 3. Section 4 discusses the emerging themes delving out of the review and pooled prevalence rate. Finally, Section 5 concludes from a broad policy perspective.

Research Methodology

We adhere to the procedure outlined by Denyer and Tranfield (2009), which comprises five sequential steps: question formulation; study identification; study selection and evaluation; data analysis and synthesis; and finally, result reporting to draw definitive conclusions. Additionally, we incorporate the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) checklist to accurately document the number of studies reviewed (Page et al., 2021). The search based on Web of Science was initiated during April 2024 for which the upper time limit was fixed in March 2024. Web of Science is an extensive database covering multidisciplinary subjects, high-impact journals and provides substantial coverage for the specific area. The approach was strategically formulated to explore titles, abstracts, author-provided keywords, and 'keywords-plus' in pursuit of publications dating back to 2004 till 2024, published in English, and clearly creating a nexus between WaSH and health perspectives in India. Our study navigated through three distinct groups of keywords, as shown in Table 1: Group A focused on drinking water (encompassing potable or residential water), sanitation, and hygiene; Group B centred on health and disease; and Group C pertained specifically to India.

These keywords, honed through iterative searches and expert consultations, were interconnected using Boolean operators to ensure selection of relevant publications. Our search yielded 349 results from the Web of Science, which were filtered to 172 articles based on stringent inclusion criteria, prioritising high-quality peer-reviewed scientific articles in English journals excluding conference proceedings and book chapters. Further refinement through title screening and content analysis led to a final selection of 91 papers that met the requisite standards of methodological rigour and thematic relevance (refer Figure 1).

The study further employed a pooled prevalence approach on 50 research papers to evaluate aggregated prevalence and risk estimates associated with unsafe drinking water across several studies. A random-effects model was employed to address heterogeneity among studies, with pooled prevalence estimates computed for a thorough evaluation. This accounted for the significant heterogeneity observed across studies. Random-Effects model not only accounts for differences in methodology but also population characteristics. The pooled prevalence was examined using a weighted average method, with each study weighted according to the inverse of its variance. This ensures that studies with larger sample sizes and lower variability exert a stronger influence on the overall pooled value. Confidence Intervals (CIs) were calculated using the normal approximation approach, with 95% CIs were generated for each study to measure the uncertainty related to the prevalence estimates (Uman, 2011).

Table 1 Research protocol for database search

Search string: TITLE-ABS-KEY (“Drinking Water” or “Domestic Water” or “Potable Water” or “Household Water” or” Water Access” or “Water Source” or “Water Management” or “Water Availability” or “Water Quality” or “Water Supply” or “Groundwater” or “Freshwater” or “Surface water” or “Sanitation” or “Hygiene” or “Toilet” or “Latrine” or “Wastewater” or “Sewer” or “Handwashing”) AND (“Health” or “Disease” or “Waterborne” or “Illness” or “Cholera” or “Diarrhoea” or “Hepatitis” or “Typhoid” or “Polio” or “Malaria” or “Dengue” or “Hypertension” or “Down Syndrome” or “Cryptosporidiosis” or “Chikungunya” or “Respiratory Infections” or “Skin Infection” or “Neglected Tropical Disease” or “Dysentry” or “Malnutrition”) AND (“India” or “Andhra Pradesh” or “Arunachal Pradesh” or “Assam” or “Bihar” or “Chhattisgarh” or “Goa”, or “Gujarat” or “Haryana” or “Himachal Pradesh” or “Jharkhand” or “Karnataka” or “Kerala” or “Madhya Pradesh” or “Maharashtra” or “Manipur” or “Meghalaya” or “Mizoram” or “Nagaland” or “Odisha” or “Punjab” or “Rajasthan” or “Sikkim” or “Tamil Nadu” or “Telangana” or “Tripura” or “Uttar Pradesh” or “West Bengal”)
Publication type: Journal articles in English
Database: Web of Science
Period: Till 31st March, 2024

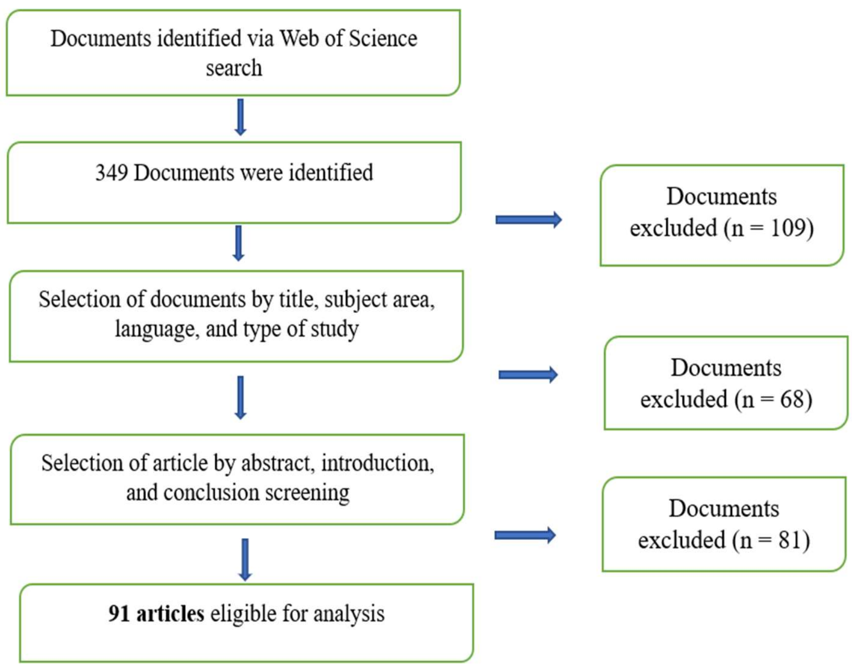

Figure 1 Literature Review Process

Descriptive Analysis

The present section addresses RQ1 by highlighting the research landscape of the pertinent prior literature on WaSH and health in India covering several aspects such as publication timelines, major affiliations and key journals. Each of these are discussed hereby.

Publication Timelines: The analysis of publication output illustrates the evolving landscape of research dedicated to our objective. Figure 2 shows that since 2004, a total of 91 pertinent publications concerning WaSH and health in India have been identified. Notably, there has been a marked surge in publications post-2011, however, the trajectory of publication history has been characterised by fluctuations rather than a consistent upward trend.

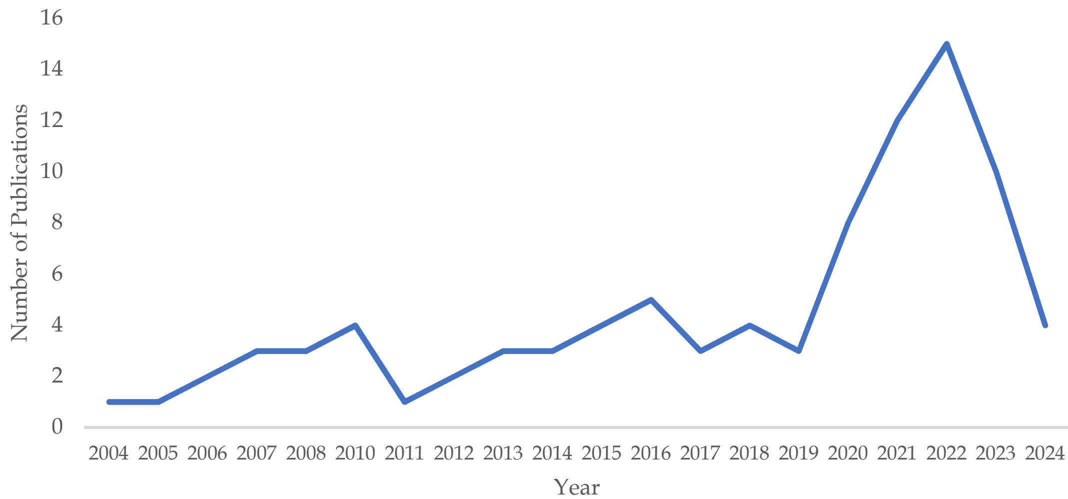

Figure 2 Distribution of studies on WaSH and Health in India (2004-2024)

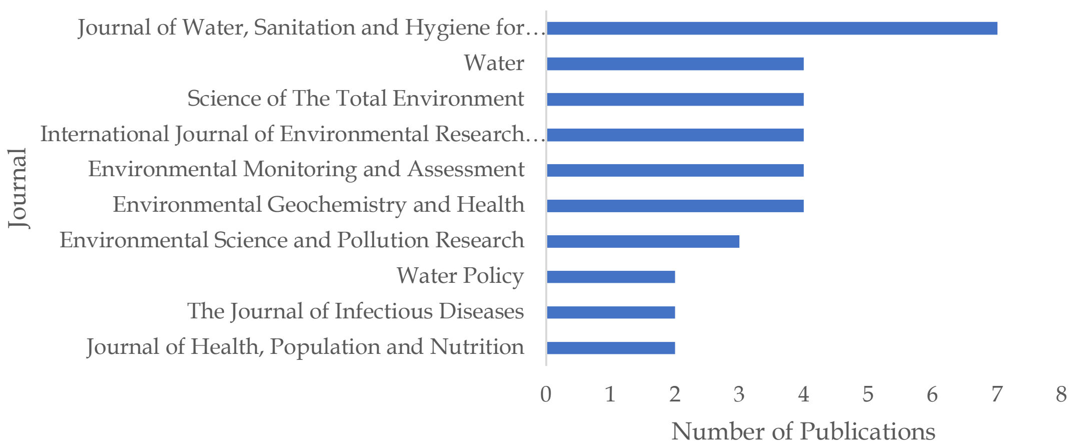

Figure 3 Publications from top ten journals on WASH and Health in India (2004-2024)

Key Institutions and Journals: Since 1993, authors affiliated with the Council of Scientific and Industrial Research have contributed the highest number of publications (23 publications). Following closely behind, are authors affiliated with the Indian Council of Medical Research, with 17 publications. The Christian Medical College and Hospital, Vellore, has produced 10 publications, while the Indian Institute of Technology System has contributed 7 publications during this period.

Various journals ranging in the domains of environment, diseases, health, water and sanitation have published the concerned research articles. However, 'Journal of Water, Sanitation, and Hygiene for Development' produced the highest number of relevant publications (7), followed by 'Water', 'Science of the Total Environment', 'Environmental Monitoring and Assessment' and 'International Journal of Environmental Research and Public Health' producing 4 articles each (refer Figure 3).

Findings and Discussion

Thematic Analysis

The present section aims to address RQ2 by examining research themes related to the pressing issues highlighted in the literature concerning WaSH and health in India (refer Table 2). Following a comprehensive review, the authors have broadly categorized the emerging themes into five key areas: health risks associated with unsafe WaSH; various chemicals causing contamination; the effectiveness of household water treatment devices; geographic locations for conducting studies; and end-user practices impacting water supply quality along with rising disinfection by-products. Each of these are discussed herein.

Health risks attributable to unsafe WaSH facilities

Several health risks associated with contaminated water have been documented by researchers. Studies reveal a range of severe health issues resulting from unsafe WaSH, particularly in rural areas (Misra and Paunikar, 2023; Sheel et al., 2024). Dental fluorosis, diarrhoea, typhoid fever, hepatitis A, chronic kidney diseases, cryptosporidium infections, hypertension, and low Intelligence Quotient (IQ) levels are among the reported hazards. For instance, in the Jhajjar district of Haryana, Gupta and Misra (2018) found that approximately 15% of surveyed individuals experienced water-related health issues, with 6% reporting frequent *stomach infections* and 9% diagnosed with *dental fluorosis*. Ayoob and Gupta (2006), Adimalla, Venkatayogi & Das (2019) and Dugal and Sharma (2022) also emphasised the impact of groundwater quality on dental health due to natural fluoride, which can result in *dental fluorosis*. The adverse effects of fluoride on human health extend to bone structure and density, potentially leading to *skeletal fluorosis*. Moreover, groundwater contamination can lead to significant monthly medical expenses for villagers.

In a study by Sarkar et al. (2013), involving 176 children in a semiurban slum, *cryptosporidium infections* persisted despite the provision of bottled drinking water, suggesting alternate transmission pathways within the community. Anbazhagi et al. (2007) detected *cryptosporidium oocysts* in Chennai City's drinking water supply, highlighting the need for routine water quality surveillance. Further, a study conducted by Kaur et al. (2022) aimed to investigate the impact of varying fluoride levels in drinking water on the *Intelligence Quotient* (IQ) of rural school children, comparing areas in Jaipur, Rajasthan with differing fluoride concentrations. Findings aligned with previous research showing higher urine fluoride levels and lower IQ scores in areas with elevated fluoride in drinking water.

Arsenic-contaminated water resulted in severe health effects, including skin conditions, in West Bengal (Mondal et al., 2010, Maity et al., 2012). In Kerala, Usha et al. (2014) found a correlation between *hepatitis A* incidence and contamination of dug wells, emphasizing the risk associated with faecal pollution. Meanwhile, Reddy and Gunasekar (2013) and Mohanty et al. (2020) identified drinking water and inorganic chemicals in groundwater as potential risk factors for *chronic kidney diseases*. In West Bengal, Biswas et al. (2023) observed severe health issues due to excessive arsenic and fluoride concentrations in groundwater, including *black foot disease, skin cancer,* and *cardiac problems.* Furthermore, Uthappa et al. (2015) investigated a *cholera outbreak* in Medipally village, Andhra Pradesh, highlighting sewage stagnation and faecal pollution as the underlying factors. Muzembo et al. (2022) also identified contaminated water sources, OD, and poor sanitation as major drivers of cholera outbreaks in India. Water quality assessment in Sumari village, Uttarakhand, revealed elevated coliform contamination resulting in waterborne diseases such as 38% of surveyed individuals experiencing *dysentery*, 23% suffering *diarrhoea*, and 17% afflicted by *typhoid* (Chauhan et al., 2020).

Childhood diarrhoea is one of the primary public health problems in rural West Bengal. Rotavirus is the main pathogen behind the illness, and factors such as water source and breastfeeding practices influence the likelihood of diarrhoea prevalence (Panda et al., 2014). Prolonged exposure to arsenic through drinking water has been associated with a heightened risk of hypertension, but the association between arsenic intake from food and hypertension risks is unclear based on a study in Bihar involving 150 participants (Xu et al., 2021). Thus, unsafe WaSH imposes serious health hazards and a substantial economic burden on individuals and healthcare systems, exacerbating poverty and straining resources.

Chemicals causing contamination of WaSH facilities

Chemical contamination in drinking water can be life-threatening and poses a significant challenge in India. Research has identified several chemicals, such as fluoride, arsenic, and bacterial pathogens, causing concerns in ensuring safe WaSH. *Fluoride contamination* has been a persistent issue especially in rural areas of northern Rajasthan (Suthar, 2011) so much that 95% of sites report elevated levels. Duggal and Sharma (2022) unveiled similar levels spanning seven districts in Punjab. Furthermore, this chemical depicted a positive relationship with total dissolved solids (TDS) and electrical conductivity (EC), indicating its widespread mobility within groundwater. The study also highlighted substantial non-carcinogenic risks, particularly impacting children and teenagers.

Table 2 Emerging Research Themes from the Systematic Literature Review

Theme	Descriptions	References
Contaminant Exposure and Health Risks	Studies exploring severe health risks caused by fluoride and arsenic contamination, including dental and skeletal fluorosis, chronic kidney diseases, and IQ reduction.	Sheel et al. (2024); Misra and Paunikar (2023); Biswas et al. (2023); Duggal and Sharma (2022); Kaur et al. (2022); Muzembo et al. (2022); Xu et al., (2021); Adimalla et al. (2019); Gupta and Misra (2018); Panda et al. (2014); Sarkar et al. (2013); Mondal et al. (2010); Maity et al. (2012); Ayoob and Gupta (2006).
Waterborne Illnesses and Pathogen Transmission	Research investigating disease/pathogen transmission via contaminated water and poor sanitation, open defecation and sewage stagnation.	Marghade et al. (2023); Majumder et al. (2023); Nath et al. (2021); Singh et al. (2021); Chauhan et al. (2020); Das et al. (2020); Uthappa et al. (2015); Lakshmi Reddi et al. (2016); Malhotra et al. (2015); Panda et al. (2014); Sarkar et al. (2013); Palit et al. (2012); Suthar et al. (2008); Ghosh et al. (2006)

Efficiency of Household Water Treatment Devices	Studies assessing the efficacy of household water treatment devices in reducing diarrhoea and pathogen removal.	Malan et al. (2023); Arora et al. (2022); Wolf et al. (2022); Bailey et al. (2020); Rosa and Clasen (2017); Saxena et al., (2015); Bhathena et al. (2013); MacDonald et al. (2015); Poulos et al. (2012); Clasen and Menon (2007)
Geographic Classification of Studies	Research highlighting WaSH disparities between rural and urban areas, with urban slums facing higher disease risks and rural areas suffering from groundwater contamination.	Kanyagui et al. (2023); Sinha et al. (2022); Dadhich et al. (2022); Giri et al. (2021); Falkenberg et al. (2018); Bivins et al. (2020); Ray et al. (2016); Kattula et al. (2015); Paul et al. (2012); Khurana and Sen (2008).
End-user practices over water supply quality	Studies emphasizing the superior role of proper hygiene behaviours such as handwashing and safe water storage in disease prevention.	Vellingiri et al. (2023); Wolf et al. (2022); Abu Bhashar and Soundappan (2022); Bindra et al. (2020); Karande et al. (2021); Ravindra et al., (2019); Falconi et al. (2017); Mondal et al. (2014); Palit et al. (2012); Gopal et al. (2007).
Theme	Descriptions	References
Contaminant Exposure and Health Risks	Studies exploring severe health risks caused by fluoride and arsenic contamination, including dental and skeletal fluorosis, chronic kidney diseases, and IQ reduction.	Sheel et al. (2024); Misra and Paunikar (2023); Biswas et al. (2023); Duggal and Sharma (2022); Kaur et al. (2022); Muzembo et al. (2022); Xu et al., (2021); Adimalla et al. (2019); Gupta and Misra (2018); Panda et al. (2014); Sarkar et al. (2013); Mondal et al. (2010); Maity et al. (2012); Ayoob and Gupta (2006).
Waterborne Illnesses and Pathogen Transmission	Research investigating disease/pathogen transmission via contaminated water and poor sanitation, open defecation and sewage stagnation.	Marghade et al. (2023); Majumder et al. (2023); Nath et al. (2021); Singh et al. (2021); Chauhan et al. (2020); Das et al. (2020); Uthappa et al. (2015); Lakshmi Reddi et al. (2016); Malhotra et al. (2015); Panda et al. (2014); Sarkar et al. (2013); Palit et al. (2012); Suthar et al. (2008); Ghosh et al. (2006)

Similarly, *arsenic contamination* in drinking water has been found in places such as North 24 Parganas, Nadia, and Jalangi districts of West Bengal as investigated by Rahman et al. (2005), Ghosh et al. (2006), Mazumder et al. (2010), and Das et al. (2020). Subclinical effects of arsenic led to higher levels of arsenic retention in the nails and hair of the impacted even without visible skin lesions. While attempts have been made to provide arsenic-safe drinking water, challenges remain in addressing non-dermatological symptoms (Paul et al., 2012). Majumder et al. (2023) examined arsenic exposure risks across different age groups in two villages in West Bengal, focusing on ingestion from drinking water, rice grain, and vegetables finding significant associations through Spearman correlation analysis. Marghade et al. (2023) discovered that implementation of community water purification systems and rainwater collection initiatives can effectively mitigating arsenic levels. Further, Nath et al. (2021) analysed the interrelated concerns of arsenic biomagnification, land salinity, and agrochemical pollution in the Sundarbans delta resulting in widespread migration. The arsenic contamination has not only posed significant health hazards but also imposed a financial burden on affected communities (Thakur and Gupta, 2016).

Moreover, *bacterial contamination*, particularly from the family Enterobacteriaceae (coliforms), has been considered as major problem in rural areas of northern Rajasthan (Suthar et al., 2008). Microbiological assessment of drinking water quality is essential for safety and human survival. Singh et al. (2021) investigated indicator organisms, such as thermotolerant coliforms, and their association with diarrheal diseases in Solan District. A water quality assessment was conducted by Chauhan et al. (2020), in Sumari village, Uttarakhand, evaluating various physicochemical parameters such as pH, TDS, dissolved oxygen (DO), temperature, alkalinity etc. Though physicochemical parameters remained within limits, coliform counts exceeded permissible levels at all sites. Noroviruses (NoV), often transmitted through contaminated water, were detected with 20% positivity in Chennai with real-time PCR depicting reliable detection capabilities for routine monitoring of contamination (Anbazhagi and Kamatchiammal, 2010). George et al. (2015) used Quantitative Microbial Risk Assessment (QMRA) to explore disease intensity in drinking water in Mysore Urban City, India. The findings showed alarming risks due to infected water. Such water quality assessments have also been conducted in various regions, including Lucknow (Pathak et al., 1993), New Delhi (Singh et al., 2000), Jaipur (Chandra et al., 2016; Bivins et al., 2020), Maharashtra (Tambe et al., 2008), and Himachal Pradesh (Sharma et al., 2023). The studies have concluded widespread contamination, particularly in piped water supplies and submersible pumps (Saxena et al., 2015; Malhotra et al., 2015; Lakshmi Reddi et al., 2016).

Efficiency of household-scale water treatment (HWT) devices

Efficiency of HWT devices remains a concern in ensuring safe drinking water among Indian households (Saxena et al., 2015; Bailey et al., 2020). In a study by Wolf et al. (2022), water treatment facilities such as filtration, chlorination, and solar treatment reduced the risk of suffering from diarrhoea by 50%, 37%, and 34% respectively at the point of use. Rosa and Clasen (2017) reported high consistency in the performance of HWT devices across urban (100%) and rural (93.3%) areas, though actual water quality improvement was minimal (13.7% and 25.8% respectively). Bhathena et al. (2013) evaluated three gravity-driven HWT devices in India, concluding its inefficiency in meeting minimum performance recommendations set by international standards. The impact of rainfall and seasonal variability on Point-of-use (PoU) water treatment interventions was undertaken by MacDonald et al. (2015) in Chennai, India. Fortunately, results indicated the efficacy of PoU treatment in minimizing bacterial contaminants.

Clasen and Menon (2007) studied the microbiological quality of three prevalent types of HWT devices in India, namely, ceramic candle gravity filters, iodine resin gravity filters, and iodine resin faucet-mounted filters. Although these devices were successful in reducing bacterial contamination, their efficacy in mitigating viruses and protozoa was restrained. Malan et al. (2023) assessed WaSH practices in rural households of the Kurukshetra district and examined water availability and health conditions in nine ODF villages. Results indicated that a majority relied on government borewell water and about 43% treated their water, mainly through boiling or chlorination. Correspondingly, there was an improvement in sanitation infrastructure. Logistic regression analysis revealed that the proximity of waste to the residence amplified the likelihood of disease incidences. Further, the type of product, pathogen removal efficacy, retail outlet, and treatment time were significant factors influencing consumer choices for HWT devices as explored by Poulos et al. (2012) in Andhra Pradesh. Additionally, filters were preferred over chemical additives and copper-based potable water storage device was found to be much better than plastic containers (Arora et al., 2022).

Geographic classification of studies

Numerous studies have examined WaSH practices in India's rural and urban areas, often suggesting policy interventions to address existing issues (Khurana and Sen, 2008). For instance, Dadhich et al. (2022) utilised spatial analysis to assess WaSH facilities, revealing that only six out of 32 panchayats in Phagi tehsil, Rajasthan, had eliminated OD practices. Kattula et al. (2015) investigated environmental predictors of diarrheal infection in both rural and urban communities of south India identifying modifiable environmental factors responsible for intestinal infections. They also found higher rates of diarrheal incidence in urban slums compared to rural areas, with infants under one year old being the most vulnerable group.

Kanyagui et al. (2023) assessed water scarcity, security, and sustainability in Nagla Chandi village, Uttar Pradesh. The study compared groundwater with bore wells that had reverse osmosis (RO) plant-treated water. While the RO plant provided potable water, frequent breakdowns compelled villagers to use untreated water, leading to health issues. Giri et al. (2021) conducted a case-control study on the household and environmental transmission of typhoid fever in Vellore, Tamil Nadu, revealing that consuming street food increased the risk of typhoid. Falkenberg et al. (2018) conducted a cohort study on wastewater irrigation's impact on in-household water contamination in urban farming households in Ahmedabad, India. Over a year, they collected drinking water samples from 204 households, conducted surveys, and installed observational spot-checks, finding significant disparities in water quality, with only 6% accessing safe drinking water during peak contamination periods. Paul et al. (2012) reported on arsenic-induced toxicity and carcinogenicity in West Bengal, India. They observed a decrease in arsenic-related health issues with lower arsenic exposure. Furthermore, Sinha et al. (2022) evaluated changes in water quality parameters in Uttarakhand over time, identifying potential health risks due to contamination from sources such as plant debris, erosion, and agricultural activities. Enhanced methods such as Dead-end Ultrafiltration (DEUF) and Droplet Digital PCR (ddPCR) enabled the detection of pathogen evidence in drinking water supplies. These methodologies complement traditional culture-based approaches, enhancing the precision of pathogen-specific risk assessment and management, as demonstrated in Jaipur in 2017 (Bivins et al., 2020). In another study, the quality of Indian packaged drinking water in Kolkata was analysed, revealing that most samples were acidic and had low mineral concentrations (Ray et al., 2016).

End-user practices outweigh quality of water supply

Multiple studies have highlighted the significant impact of end-user practices on the risk of diarrheal diseases, which can be more influential than the microbiological purity of the water being supplied. Sanitation services such as basic sewer connection and encouragement of handwashing practices led to a substantial decline in diarrheal risk of individuals by 24% and 30% respectively (Wolf et al., 2022). Mondal et al. (2014) emphasized that despite extensive measures to supply pathogen-free drinking water by drilling millions of tube wells in the Bengal Delta, the presence of arsenic in groundwater continues to pose a substantial health hazard. The occurrence of severe watery diarrhoea in Nakhrauli village, Haryana, was caused by a significant number of infections resulting from the presence of faecal matter in water sources and inadequate sanitation practices (Abu Bhashar and Soundappan, 2022). The situation was worsened by factors such as the lack of water filtration technologies, inadequate storage of drinking water, and unsatisfactory sanitation and hygiene standards. As a result, the number of cases during the outbreak increased rapidly. In their study, Bindra et al. (2020) assessed the commonly used sanitation methods in rural Fatehgarh Sahib. They discovered that groundwater pollution was extensive, since more than 50% of the samples tested positive for E. coli, which is an indicator of fecal contamination. In addition, a lack of proper hygiene practices was noted, as only 30% of participants reported purifying water prior to its usage. Karande et al. (2021) revealed a significant association between personal hygiene practices and the occurrence of waterborne infections in Solapur district, Maharashtra, highlighting the crucial role of initiatives such as the Swachh Bharat Abhiyaan. Brick et al. (2004) evaluated water pollution in Vellore, Tamil Nadu, and emphasized that despite attempts to ensure clean drinking water, contamination continued to exist.

Municipal water sources in India are often contaminated, which worsens the problem when the water is stored in households. Falconi et al. (2017) tackled the problem of measuring the decline in water quality by suggesting a way to link water sources to stored water in households. They studied the effects of geographical assumptions in semi-urban Vellore slums. Researchers combined household and tap samples collected at the same time using three spatial techniques. The findings indicated that, on average, 60% of households displayed elevated levels of faecal coliforms in their stored water in comparison to the water from the original source taps. Palit et al. (2012) investigated the water sources responsible for the transmission of diarrheal diseases in urban slums in Kolkata concluding that stored water had a greater prevalence of faecal coliform and physico-chemical characteristics compared to tap and tubewell water.

Moreover, chlorination has been a fundamental and essential component of water treatment for more than a century. Nevertheless, the detection of disinfection by-products (DBPs) resulting from the process of chlorination has generated apprehension regarding potential health hazards. A major issue with DBPs is their ability to cause negative health effects, specifically cancer. Toxicodynamics is a useful method for studying chlorination techniques and the resulting disinfection byproducts (DBPs). It provides vital information about the potential health impacts of these DBPs and helps in developing measures to reduce their harmful effects (Gopal et al., 2007). Although several countries frequently monitor and examine the toxicity and trends of DBPs, research on DBPs in India is still in its early stages (Vellingiri et al., 2023). Overall, these findings highlight the essential importance of end-user practices, sanitation, and hygiene in reducing the likelihood of waterborne infections (Ravindra et al., 2019).

Thus, the five crucial themes spanning from health risks associated with contamination to the end-user practices impacting water supply quality along with rising disinfection by-products, signal the pertinence of safe and adequate WaSH facilities in mitigating a wide spectrum of health hazards and ensuring increased productivity, low financial burden and improved health outcomes.

Pooled Prevalence Analysis of Health Risk posed by Unsafe Drinking Water in India

The present section aims to address RQ3 to evaluate the overall pooled prevalence rate of health risks attributable to unsafe Drinking Water in India. The analysis, which synthesized data from various studies, demonstrated a combined prevalence rate of 20.99% as shown in the forest plot below. This aggregated estimate reflects the comprehensive impact of drinking water-related health outcomes among various demographics in India.

The forest plot (refer Figure 3) depicts the prevalence estimates and confidence ranges for each study. The weight of each study is represented by the size of the squares, with larger squares indicating a stronger impact on the overall estimate (Uman, 2011). Each square denotes a distinct study, with its size according to the study's weight in the analysis. The diamond at the base of the plot signifies the pooled prevalence, with the width denoting the 95% confidence interval. The vertical blue line indicates the pooled prevalence, considering the substantial variation among research. The study had also assessed the publication bias using funnel plots.

The overall prevalence of 20.99% indicates that among the populations studied, there is a likelihood of one in five individuals suffering from unsafe drinking water-related health issues. Inverse-variance weighting increased the relative weights of studies with large sample sizes in the total estimate thereby improving the validity of the pooled prevalence. There was considerable heterogeneity with prevalence estimates from 12% to 95%. The inconsistency is likely linked to differences in study purpose, population, and site. Future studies should aim at assessing these sources of variability to improve understanding of the factors associated with the changes in the rates of prevalence in certain populations through subgroup analysis or meta-regression.

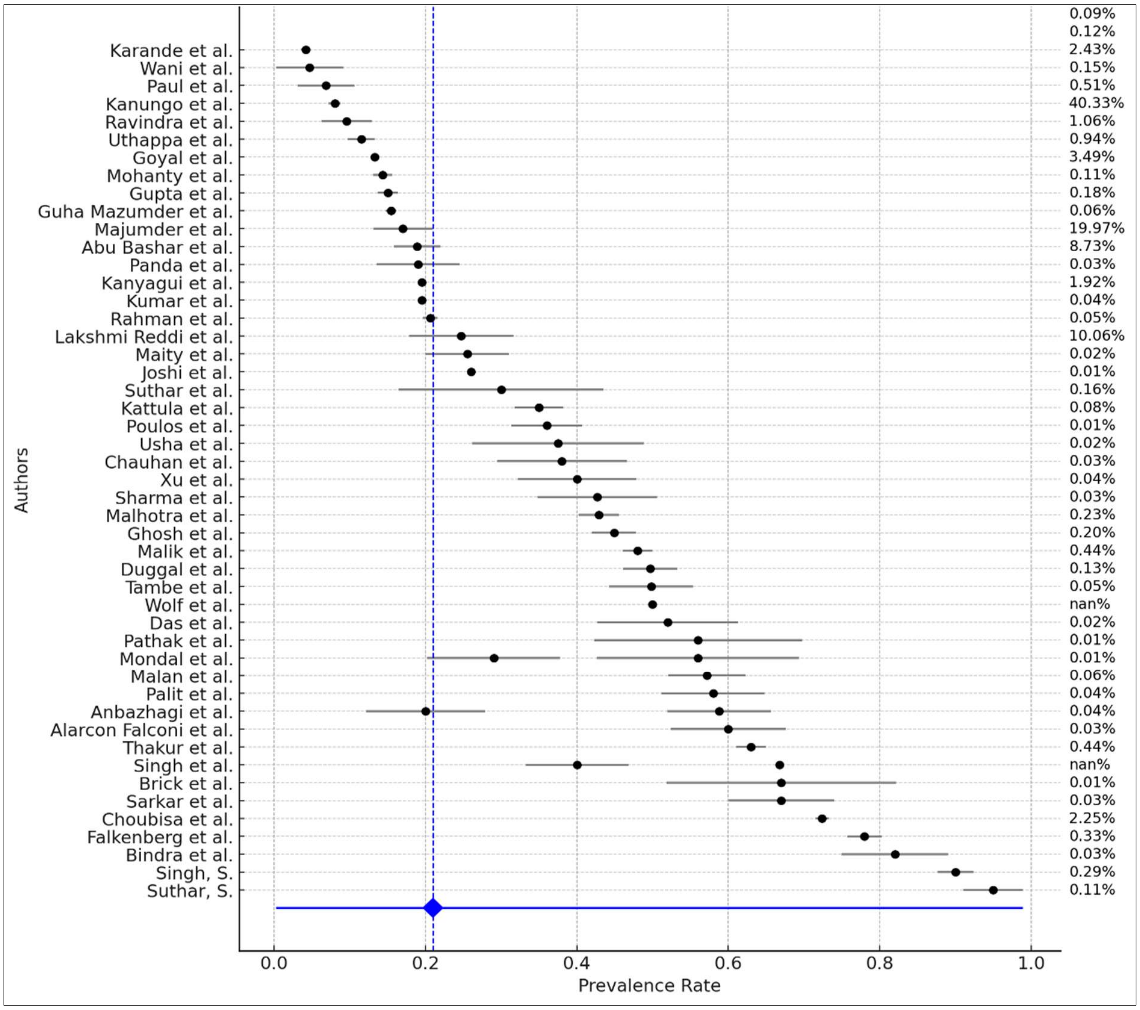

Figure 3 Forest Plot with an overall pooled prevalence of health risks associated with unsafe drinking water.

Conclusion and Policy Implications

Access to safe WaSH is essential for promoting good health, equity, and sustainable development. Urgent global action is imperative to combat waterborne diseases and bridge disparities, particularly in nations such as India where millions still lack essential services (Misra and Paunikar, 2023). The present study has provided valuable insights on critical research priorities in the domain of WaSH and health in India. Through the SLR approach, the study has identified key emerging themes encompassing various health risks associated with contaminated water. Key implications for policy which emerge from the present study are delineated herewith:

Addressing Health Hazards from Unsafe WaSH Sources: WaSH contamination is highly prevalent across several households in India, especially in rural regions. Regrettably, only a minority of households scientifically treat drinking water and utilize safely managed sanitation services. Thus, there is an urgent need to supply clean reliable water along with effective sanitation, with a focus on disadvantaged sections of society as this could lead to potential benefits including poverty alleviation, environmental conservation, and sustainable economic growth (Biswas and Mandal, 2010; Altenburger et al., 2019). Policymakers should take measures that enhance water quality surveillance, implement effective water treatment strategies, and provide equal access to safe drinking water to prevent outbreaks of waterborne diseases such as diarrhoea, cholera, typhoid, hepatitis A, and cryptosporidiosis (Bailey et al., 2020; Lopes et al., 2022). Additionally, policies should aim at reducing the economic burden imposed by waterborne illnesses by improving the existing WaSH infrastructure and building additional capacities including healthcare facilities (Malik et al., 2012; Yang Chan et al., 2021). Ferreira et al., 2021 found that on an average, for every R$100 million (Brazilian Real) investment in WaSH facilities led to a reduction of 1,57,000 hospitalizations in Brazil due to water-attributable diseases, highlighting its profound influence on the health hazards posed by contaminated water.

Regulating Chemical Contaminants and Enhancing Efficiency of Household Water Treatment Devices: To effectively target the contamination of drinking water by various chemicals, including fluoride and arsenic, stricter regulations should be implemented to ensure compliance with international standards for drinking water quality, particularly in rural areas where groundwater contamination is prevalent (Choubisa et al., 2023). Regulatory, legislative entities and development agencies can play a vital role in increasing awareness and addressing this concerning issue by implementing cooperative measures to safeguard our environment and public health, and ensure access to safe drinking water for everyone (Bhat et al., 2024). Further, prioritizing the efficiency of HWT treatment devices to ensure access to safe drinking water for all populations is imperative. This could be achieved through encouraging technological innovation and providing support for research and development (Shayo et al., 2024).

Targeting effective WaSH Practices and Balancing Disinfection By-Products (DBPs): Targeted interventions are required to address water quality, sanitation, and hygiene challenges in both rural and urban settings in India. Improving WaSH practices such as handwashing before meals and after defecation, proper waste management, regular cleaning of sewage, and exclusive use of washrooms can result in substantial reduction of disease incidences (Goyal and Dharwal, 2021). Jatav et al. (2021) emphasized the need of following these practices in coping with health crises such as COVID-19 pandemic. Further, encouraging achievement of higher levels of education, promoting behaviour change through awareness campaigns, enhancing access to sanitation infrastructure, and focusing on reducing disparities in WaSH access between different geographic groups (Weis et al., 2018; Zajacova and Lawrence, 2018) can improve public health outcomes. The reviewed studies cover a broad representation of different geographies however, still these studies mostly focus on States such as Rajasthan, West Bengal and Tamil Nadu. For a balanced approach, future studies need to focus on states from Central India and North-Eastern states. Further, policy measures should aim at striking a balance between the advantages accrued by disinfection practices and the potential health risks caused by disinfection by-products (DBPs).

This study's pooled prevalence analysis highlights the widespread health hazards linked to inadequate WaSH practices in

India, with an overall pooled prevalence of 20.99%. The results highlight the pressing necessity for governmental initiatives to enhance WaSH infrastructure, especially in areas with the highest prevalence rates. Moreover, researchers must investigate the financial strain caused by waterborne diseases and analyze the effects of climate change on WaSH infrastructure. It is crucial to combine WaSH initiatives with public health programs and investigate new methods for monitoring water quality in real-time in order to enhance the well-being of households. Future research should overcome the limitations of the present study by broadening the scope of their investigation and including other databases as well as emerging concerns. The present study's findings offer valuable guidance for researchers and practitioners, elucidating extant practices in public health safety and laying the groundwork for evidence-based interventions. WaSH lies at the core of sustainable development and improving WaSH outcomes will inherently propel public health and safety.

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