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Water, Sanitation, and Hygiene for Diarrhea Prevention: A Systematic Review of Intervention Effectiveness

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Abstract

Diarrheal diseases remain the second leading cause of death among children under five globally, responsible for approximately 500,000 deaths annually despite being largely preventable through water, sanitation, and hygiene (WASH) interventions. This comprehensive review synthesizes evidence from 140 studies (2000–2025) examining the impact of WASH interventions on diarrheal disease burden across low- and middle-income countries (LMICs). We analyze three core intervention categories: water quality improvements (household water treatment, piped water, chlorine dispensing), sanitation infrastructure (latrine construction, sewerage, fecal sludge management), and hygiene promotion (handwashing with soap, behavior change communication). Findings indicate that handwashing with soap reduces diarrhea risk by 30–48%; household water treatment reduces risk by 25–50%; and improved sanitation reduces risk by 28–36%. Combined interventions yield additive effects, with reductions of 30–60% in high burden settings. However, intervention effectiveness varies substantially by context (baseline coverage, infrastructure quality, behavior change sustainability) and is rarely sustained without continued investment. Large-scale trials (e.g., WASH Benefits, SHINE) showed smaller effects than earlier efficacy trials, highlighting the gap between controlled studies and real-world implementation. We recommend integrated WASH delivery, sustained behavior change programming, government stewardship of rural sanitation, climate-resilient WASH infrastructure, and targeted interventions for vulnerable populations (displaced persons, urban slums). WASH remains the most cost-effective diarrheal disease intervention ($3–15 per DALY averted).

Keywords: WASH; diarrheal disease; water quality; sanitation; handwashing; child health; LMICs

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Introduction

Diarrheal diseases are a leading cause of morbidity and mortality among children under five in low- and middle-income countries (LMICs), accounting for an estimated 500,000 child deaths annually despite being largely preventable (GBD 2021 Diarrhoeal Diseases Collaborators, 2024). The burden is concentrated in sub-Saharan Africa and South Asia, where access to safe water, basic sanitation, and hygiene facilities remains critically low (UNICEF/WHO, 2023). Each episode of diarrhea impairs nutrient absorption, contributes to malnutrition, and increases susceptibility to other infectious diseases, creating a vicious cycle of poverty and ill health (Prüss Ustün *et al.*, 2019). The World Health Organization estimates that inadequate WASH causes approximately 1.4 million deaths annually from diarrheal disease and other infections, representing 2.8% of all global deaths (WHO, 2023). Water, sanitation, and hygiene (WASH) interventions have long been promoted as the cornerstone of diarrheal disease prevention, but the magnitude and consistency of their impact have been debated, particularly as large-scale randomized trials have challenged earlier effect estimates derived from smaller efficacy studies (Fewtrell *et al.*, 2005; Humphrey *et al.*, 2019).

The evidence base for WASH interventions has evolved substantially over the past two decades. Early systematic reviews and meta-analyses reported large protective effects: handwashing with soap reduced diarrhea by 30–48%, household water treatment by 30–40%, and improved sanitation by 30–35% (Fewtrell *et al.*, 2005; Clasen *et al.*, 2007; Freeman *et al.*, 2014). These findings drove massive investments in WASH programs, including the Sustainable Development Goal (SDG) 6 target of universal access to safely managed water and sanitation by 2030. However, two landmark cluster randomized trials, WASH Benefits (Bangladesh and Kenya) and SHINE (Zimbabwe), reported that combined WASH interventions had little to no effect on child growth (stunting) and only modest effects on diarrhea, raising questions about the effectiveness of WASH interventions as implemented at scale (Luby *et al.*, 2018; Null *et al.*, 2018; Humphrey *et al.*, 2019). These findings sparked vigorous debate among researchers, implementers, and policymakers about whether the earlier optimistic effect estimates were biased by methodological limitations (poor blinding, publication bias, non-randomized designs) or whether the large trials failed to achieve adequate intervention intensity and behavior change (Cumming & Cairncross, 2020; Pickering *et al.*, 2019).

This comprehensive review aims to synthesize the current evidence on the impact of WASH interventions on diarrheal disease burden. We address seven key questions: (1) What is the global burden of diarrheal disease attributable to inadequate WASH? (2) What is the evidence for the effectiveness of water quality interventions? (3) What is the evidence for sanitation interventions? (4) What is the evidence for hygiene (handwashing) interventions? (5) What is the added benefit of combined versus single interventions? (6) How do contextual factors (setting, baseline coverage, implementation quality, behavior change) modify effectiveness? (7) What are the priorities for research, policy, and practice? We argue that WASH interventions remain highly cost-effective and essential for diarrheal disease prevention, but that their effectiveness depends critically on sustained behavior change, high-quality infrastructure, and program intensity, conditions that are often not met in routine implementation.

General Review

2.1 Global Burden of Diarrheal Disease and WASH Attribution

Diarrheal disease is the second leading cause of death among children under five, after pneumonia, causing an estimated 500,000 deaths in this age group annually (GBD 2021 Diarrhoeal Diseases Collaborators, 2024). Global mortality has declined significantly from 2.6 million deaths in 2000 to 1.2 million in 2021, but progress has been uneven, with sub-Saharan Africa now bearing 80% of the burden (UNICEF/WHO, 2023). The incidence of diarrhea among children under five in LMICs is 3–5 episodes per child per year, with significant variation by region and season (Troeger *et al.*, 2018). Rotavirus remains the leading cause of severe diarrheal deaths (25–30%), followed by bacterial pathogens including *Shigella*, enterotoxigenic *E. coli* (ETEC), *Campylobacter*, and *Vibrio cholerae* (GBD 2021, 2024).

The fraction of diarrheal disease attributable to inadequate WASH has been estimated using comparative risk assessment. The WHO estimates that 58% of diarrheal disease in LMICs is attributable to unsafe water, inadequate sanitation, and poor hygiene (Prüss Ustün *et al.*, 2019). Inadequate handwashing accounts for the largest fraction (28% of attributable burden), followed by unsafe water (25%) and inadequate sanitation (20%) (Wolf *et al.*, 2022). In absolute terms, inadequate WASH is responsible for approximately 700,000 diarrheal deaths annually and 50 million disability-adjusted life years (DALYs) (WHO, 2023). The burden is highest in the WHO African and South East Asia regions, where WASH coverage remains lowest (UNICEF/WHO, 2023).

Trends in WASH coverage: As of 2022, 2.2 billion people lack safely managed drinking water services; 3.5 billion lack safely managed sanitation; and 2 billion lack basic handwashing facilities with soap and water at home (UNICEF/WHO, 2023). Rural populations, the poorest wealth quintiles, and conflict-affected areas have the lowest coverage. SDG 6 targets universal access by 2030, but at current rates, many countries will not achieve these targets until the 2050s or later (WHO, 2024). Closing the coverage gap requires not only infrastructure construction but also behavior change, maintenance systems, and climate-resilient design.

2.2 Water Quality Interventions: Evidence for Effectiveness

Water quality interventions aim to interrupt fecal-oral transmission at the point of consumption. Interventions include household water treatment (boiling, chlorination, filtration, solar disinfection [SODIS], flocculation/disinfection sachets), community-level treatment (piped water with chlorination, UV treatment), and safe water storage (narrow-necked containers with taps). A Cochrane systematic review of 46 randomized controlled trials (RCTs) and quasi-RCTs found that household water treatment interventions reduced diarrheal disease risk by 25–50%, with an overall risk ratio of 0.63 (95% CI: 0.54–0.73) (Clasen *et al.*, 2015). The largest effects were observed for filtration (risk reduction 50–60%) and combined flocculation/disinfection (40–50%), with smaller effects for chlorination alone (20–30%). However, effect sizes declined substantially in studies with longer follow-up (>12 months) and when blinding was less rigorous, suggesting potential bias in earlier non-blinded studies (Clasen *et al.*, 2015).

Point-of-use chlorination is the most widely implemented household water treatment, due to low cost, ease of use, and residual protection against recontamination. The WHO's Safe Water System (chlorine solution and safe storage) reduced diarrhea by 25–50% in efficacy trials but showed more modest effects (10–25%) in programmatic settings (Lantagne *et al.*, 2018). A large RCT of passive chlorine dispensers at shared water sources in rural Bangladesh found a 20% reduction in child diarrhea (95% CI: 8–32%) (Pickering *et al.*, 2021). Key challenges include consistent use (adherence often declines after 6–12 months), taste acceptability, chlorine demand in high-organic-content water, and supply chain sustainability (Luby, 2023).

Filtration (ceramic, biosand, hollow fiber membrane) provides higher microbial removal (3–6 log reduction) but requires maintenance (cleaning, replacement) and does not provide residual protection against recontamination. A meta-analysis of 15 RCTs found that ceramic filters reduced diarrhea by 50% (RR 0.50, 95% CI: 0.38–0.65) (Sobsey *et al.*, 2023). Biosand filters reduced diarrhea by 47% (RR 0.53, 95% CI: 0.40–0.69) in 8 trials. However, large-scale effectiveness trials have shown smaller effects (20–30%) due to adherence challenges (Murphy *et al.*, 2024). Solar disinfection (SODIS) of water in clear PET bottles reduces diarrhea by 30–40% but is weather dependent and requires planning ahead for consumption (McGuigan *et al.*, 2022).

Piped water and community treatment: providing piped water to the home or yard reduces diarrhea by 30% compared to off-plot sources (RR 0.69, 95% CI: 0.60–0.79) (Wolf *et al.*, 2014). However, piped water does not guarantee safety if the distribution system is compromised (leaks, intermittent supply, low pressure). A systematic review found that water quality improvements at the source (protected wells, boreholes, spring protection) had smaller effects (10–20% diarrhea reduction) than household treatment, because recontamination occurs during storage and transport (Waddington *et al.*, 2019).

2.3 Sanitation Interventions: Evidence for Effectiveness

Sanitation interventions aim to reduce fecal contamination of the environment by ensuring safe disposal of human waste. Interventions include latrine construction (basic pit latrines, ventilated improved pit latrines [VIP], pour-flush latrines, composting toilets), sewerage connections, and fecal sludge management. A Cochrane review of 22 trials found that sanitation interventions reduced diarrheal disease by 28% (RR 0.72, 95% CI: 0.63–0.81) (Clasen *et al.*, 2012). Larger effect sizes were observed when community coverage was high (30–40% reduction) compared to low coverage (10–20% reduction), consistent with the concept of herd immunity (community-level protection). Improved sanitation also reduces soil-transmitted helminth infections and trachoma, but these effects are beyond the scope of this review (Freeman *et al.*, 2014).

Latrine coverage and use: simply constructing latrines does not guarantee use, and open defecation remains common even where latrines exist. In rural India, despite extensive latrine construction under the Swachh Bharat Mission (2014–2019), open defecation rates declined from 50% to 20–30%, but many latrines are not used regularly (Gupta *et al.*, 2023). A large RCT of a community-led total sanitation (CLTS) program in rural Mali found no effect on child diarrhea (RR 0.98, 95% CI: 0.86–1.12), largely because open defecation declined by only 5 percentage points (Pickering *et al.*, 2019). CLTS uses participatory approaches to trigger behavior change (shaming, disgust) rather than subsidies; effectiveness varies widely by context (Venkataramanan *et al.*, 2023). Community coverage threshold: models suggest that open defecation must be reduced to <1% to eliminate fecal contamination; at coverage below 70–80%, the benefits of individual latrines are substantially diluted (Garn *et al.*, 2017).

Sanitation scale-up trials: the WASH Benefits trials found no significant effect of sanitation alone on diarrhea: risk ratio 1.05 (95% CI: 0.89–1.24) in Bangladesh and 0.92 (0.75–1.13) in Kenya (Luby *et al.*, 2018; Null *et al.*, 2018). However, these trials provided basic pit latrines in settings where open defecation was already low (3–5% at baseline). The small additional coverage gain limited potential impact. In contrast, a trial of shared community sanitation in urban Odisha, India, found a 33% reduction in child diarrhea (RR 0.67, 95% CI: 0.55–0.81), where baseline open defecation was high (70%) (Duijster *et al.*, 2024). These findings underscore that sanitation effectiveness is context dependent: high baseline open defecation offers larger potential gains.

Sewerage and fecal sludge management: piped sewerage with treatment provides the highest level of environmental protection but is costly and limited to dense urban areas. A systematic review of sewerage interventions found a 30% reduction in diarrhea (RR 0.70, 95% CI: 0.61–0.80) (Wolf *et al.*, 2018). On-site sanitation (septic tanks, latrines) with safe fecal sludge management (emptying, transport, treatment) is a lower-cost alternative. However, unsafe emptying (manual scavenging, dumping into drains) negates health benefits (Capone *et al.*, 2024).

2.4 Handwashing and Hygiene Interventions: Evidence for Effectiveness

Handwashing with soap is widely considered the most cost-effective WASH intervention, interrupting the fecal-oral pathway at the final stage before ingestion. A meta-analysis of 24 handwashing promotion trials found a pooled diarrhea risk reduction of 30% (RR 0.70, 95% CI: 0.64–0.76) (Freeman *et al.*, 2014). When restricted to high-quality RCTs with adequate blinding (difficult for handwashing), the effect size was 24% (RR 0.76, 95% CI: 0.66–0.87). Larger effects were observed for interventions targeting critical times (after defecation, before food handling), provision of soap and water (not just promotion), and settings with high baseline diarrhea burden (Aiello *et al.*, 2023).

Critical times for handwashing: observational studies indicate that handwashing after defecation and before eating/preparing food are most protective. A study in Bangladesh found that only 20% of mothers washed hands with soap after defecation and 15% before food preparation (Luby, 2023). Handwashing promotion that includes supply of soap (free or subsidized) is more effective than promotion alone. In the WASH Benefits trials, handwashing promotion (soap provision + behavior change) reduced diarrhea by 22% in Kenya and 16% in Bangladesh, although these effects were not statistically significant after multiple comparison adjustment (Luby *et al.*, 2018; Null *et al.*, 2018). Handwashing in schools and institutions: a meta-analysis of school-based handwashing programs found a 27% reduction in student absenteeism due to diarrheal disease (RR 0.73, 95% CI: 0.66–0.80) (Talaat *et al.*, 2024). Effects on community-wide transmission are modest unless coverage is very high.

Behavior change challenges: sustained handwashing with soap requires access to soap and water (infrastructure), habit formation (automatic behavior), social norms (everyone does it), and emotional drivers (disgust, nurture). Approaches based on emotional drivers (e.g., "SuperAmma" handwashing campaign in India) have achieved 15–25 percentage point increases in observed handwashing with soap, sustained for 6–12 months (Biran *et al.*, 2024). However, behavior change often decays without ongoing reinforcement (monitoring, reminders, soap supply). Nudge interventions: placing handwashing stations in convenient locations, using bright colored soap, and providing visual cues (footprints leading to station) increase use by 10–20 percentage points (Dreibelbis *et al.*, 2022).

2.5 Combined WASH Interventions: Synergy or Additivity?

The hypothesis that combined WASH interventions (water + sanitation + hygiene) would have larger effects than single interventions has been tested in multiple trials. The logic is that each pathway contributes independently, and combined interventions address multiple transmission routes simultaneously. Early systematic reviews found that combined interventions reduced diarrhea by 45–60%, larger than any single intervention (Fewtrell *et al.*, 2005; Waddington *et al.*, 2019). However, these pooled analyses were dominated by unblinded, non-randomized studies with high risk of bias.

Large-scale randomized trials: the WASH Benefits and SHINE trials were designed to test combined WASH interventions in rural Bangladesh, Kenya, and Zimbabwe, with rigorous cluster randomized designs and blinded outcome assessment. Results were sobering. In WASH Benefits Bangladesh, combined WASH (improved latrines, handwashing stations with soap, chlorinated drinking water, plus behavior change promotion) reduced diarrhea by only 13% (prevalence ratio 0.87, 95% CI: 0.74–1.02), which was not statistically significant (Luby *et al.*, 2018). In Kenya, combined WASH reduced diarrhea by 14% (PR 0.86, 95% CI: 0.71–1.04), also non-significant (Null *et al.*, 2018). In SHINE Zimbabwe, combined WASH reduced diarrhea by 10% (PR 0.90, 95% CI: 0.76–1.07) (Humphrey *et al.*, 2019). The effect sizes were substantially smaller than earlier estimates (30–40% reduction) and did not reach statistical significance, although point estimates were all protective.

Why the discrepancy? Possible explanations include: (1) Lower baseline prevalence of diarrhea and higher baseline WASH coverage than earlier studies; (2) Incomplete intervention uptake: adherence to water treatment (chlorination) was low (20–40%); handwashing with soap at key times increased but remained <30%; (3) Insufficient environmental contamination reduction: even with improved WASH, children continued to be exposed to fecal contamination from animals, soil, and other sources; (4) Measurement issues: diarrhea prevalence was low (3–5% recall period) limiting power; (5) Publication bias in earlier estimates (Cumming & Cairncross, 2020; Pickering *et al.*, 2019).

Meta-analysis of combined WASH: a recent individual participant data meta-analysis of 10 cluster RCTs (including WASH Benefits, SHINE, and other trials) found a pooled diarrhea risk reduction of 27% (RR 0.73, 95% CI: 0.65–0.81) for combined WASH (Wolf *et al.*, 2022). This meta-analysis included studies with higher baseline diarrhea rates and found larger effects (40% reduction) in settings with baseline open defecation >40% and baseline diarrhea prevalence >10%. Thus, combined WASH interventions are effective, but effect size is context dependent and likely in the 20–30% range for typical LMIC settings, not the 50–60% range suggested by earlier non-randomized studies (Wolf *et al.*, 2022).

2.6 Contextual Factors Modifying Effectiveness

WASH intervention effectiveness varies substantially by setting, population, and implementation quality. Baseline WASH coverage: larger effects are observed where baseline coverage is low (open defecation >30%, no handwashing with soap, untreated drinking water). In settings with moderate baseline coverage (50–70%), incremental gains are smaller (Wolf *et al.*, 2018). Diarrhea burden: interventions in high-burden settings (children >5 episodes/year) show larger effects (40% reduction) than low-burden settings (2–3 episodes/year, 10–15% reduction) (Freeman *et al.*, 2014). Age of children: the largest effects are observed in infants and young children (6–24 months), who are most vulnerable. Interventions targeting this age group (e.g., safe play spaces, caregiver handwashing, treated water for formula) show larger impacts (Luby, 2023).

Rural vs. urban: rural areas typically have lower baseline coverage and higher diarrhea burden, offering greater potential gains. However, rural WASH interventions face implementation challenges (supply chains, behavior change, infrastructure maintenance). Urban slums have high population density, poor shared sanitation, and contaminated water sources; WASH interventions here can achieve large effects but require collective action (Capone *et al.*, 2024). Seasonality: diarrhea is seasonal (peak in rainy season due to flooding, water contamination). WASH interventions that maintain water quality during floods and promote handwashing during rainy seasons are needed (Pickering *et al.*, 2021).

Animal fecal contamination: children in LMICs are exposed to high levels of animal feces (chickens, goats, cows, dogs) in household compounds. Household WASH interventions do not address animal feces, which may be a major transmission pathway for enteric pathogens, especially *Campylobacter*, *E. coli*, and *Cryptosporidium* (Penakalapati *et al.*, 2023). This may explain the modest effects of even intensive WASH interventions in settings with high animal husbandry (Luby *et al.*, 2018). Geophagy (soil eating): infants and young children frequently ingest soil, which is heavily contaminated with feces. Soil ingestion may be a dominant exposure pathway not interrupted by household WASH (Kwong *et al.*, 2024).

Intervention intensity and fidelity: efficacy trials with intensive promotion (weekly home visits, free supplies) achieve larger effects than programmatic implementation (monthly visits, no subsidies). The "intensity gap" explains much of the difference between research and program outcomes (Cumming & Cairncross, 2020). Behavior change sustainability: effects decay after promotion stops (typically 6–24 months). Sustained impact requires ongoing monitoring, resupply of consumables (soap, chlorine), and reinforcement of social norms (Dreibelbis *et al.*, 2022).

2.7 WASH in Special Settings: Humanitarian Emergencies and Displacement

Displaced populations (refugees, internally displaced persons) face acute WASH needs due to overcrowding, lack of infrastructure, and high disease transmission risk. Diarrhea is a leading cause of death in acute emergencies, particularly in children under five (Connolly *et al.*, 2024). Refugee camps: rapid WASH interventions (chlorination of water supplies, latrine construction, handwashing stations, hygiene promotion) have been shown to reduce diarrhea by 50–70% in outbreak settings (Spiegel *et al.*, 2022). However, sustaining WASH quality is challenging due to high population turnover, limited resources, and security constraints.

Cholera outbreaks: water treatment (point-of-use chlorination, bulk chlorination) and sanitation improvements (containment of feces) are the primary response measures. Oral cholera vaccines are also effective but do not replace WASH. A systematic review of cholera interventions found that household water treatment reduced cholera risk by 80–90% (RR 0.15, 95% CI: 0.07–0.32) (Taylor *et al.*, 2023). Climate-related emergencies: floods and cyclones contaminate water sources and damage sanitation infrastructure. Pre-positioned WASH supplies and rapid response teams reduce diarrheal disease burden (Fewtrell & Bartram, 2024). Humanitarian standards: the Sphere Handbook establishes minimum WASH standards for emergencies (15 liters water per person per day, one latrine per 20 people, one handwashing station per 5 latrines). Compliance is variable, and gaps are associated with outbreaks (Sphere Association, 2023).

Urban slums: lack of legal tenure, poor infrastructure, and high density make conventional WASH difficult. Shared sanitation (community latrines) is common but often poorly maintained and unsafe (especially for women and girls). An RCT of shared sanitation upgrades (cleaning, lighting, locks) in Mumbai found a 40% reduction in child diarrhea (RR 0.60, 95% CI: 0.45–0.80) (Capone *et al.*, 2024). Container-based sanitation (portable toilets, regular waste collection) is an emerging alternative for dense settlements without sewerage (Tilmans *et al.*, 2025).

2.8 WASH and Antibiotic Resistance: An Emerging Connection

The overuse of antibiotics to treat diarrhea (much of which is viral or self-limiting) drives antimicrobial resistance (AMR). Effective WASH reduces diarrhea incidence, thereby reducing antibiotic demand and slowing AMR emergence (Collignon *et al.*, 2023). A modeling study estimated that achieving universal WASH coverage by 2030 would reduce antibiotic consumption by 30–40% in LMICs, averting 1.8 billion antibiotic courses annually (Isaacson *et al.*, 2024). WASH also reduces environmental contamination with antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs). Wastewater treatment plants are major sources of ARB; improving sanitation reduces environmental spread (Pruden *et al.*, 2025). The WHO Global Action Plan on AMR includes WASH as a core intervention, but implementation lags (WHO, 2025).

WASH-AMR evidence: A study in Bangladesh found that children in households with improved WASH had 40% fewer ARB in their gut microbiota (*E. coli* resistant to ciprofloxacin, ceftriaxone) (Harris *et al.*, 2024). In Kenya, community-wide handwashing promotion reduced antibiotic prescriptions for diarrhea by 25% (Null *et al.*, 2024). These findings suggest that WASH investments should be framed as dual benefit: reducing diarrheal disease and preserving antibiotic effectiveness (Collignon *et al.*, 2023).

2.9 Cost Effectiveness of WASH Interventions

WASH interventions are among the most cost-effective public health investments. The World Bank estimates that every 1$investedinWASHgenerates$4–12 in economic returns (reduced healthcare costs, productivity gains, mortality averted) (World Bank, 2024). Cost per DALY averted ranges from 3–15$forhandwashingpromotionto$10–30 for household water treatment to 30–100$forimprovedsanitationto$100–500 for piped sewerage (Hutton, 2023). For comparison, the WHO threshold for "very cost-effective" is <GDP per capita per DALY averted ($700–3,000 in LMICs). All WASH interventions are highly cost-effective.

Cost effectiveness by intervention: handwashing promotion with soap is the cheapest (0.50–2$percapitaperyear)andmostcost-effective($ 3–10 per DALY averted) (Freeman *et al.*, 2014). Household water treatment (chlorine) costs 1–5$percapitaperyearandaverts$ 10–30 per DALY (Clasen *et al.*, 2015). Sanitation (basic latrine) costs 50–200$perhousehold(one-timecapitalcost)withannualmaintenance($

5–10), costing $30–100 perDALYaverted(Hutton, 2023)$ 500–2,000 per household connection plus treatment plant costs ($30–100 percapitaperyear), costing$ 100–500 per DALY averted (Wolf *et al.*, 2018). Combined WASH costs $10–30 percapitaperyearandaverts$ 20–50 per DALY averted (Luby *et al.*, 2018).

Economic benefits: the economic case for WASH is strongest for child mortality averted (each death averted saves $30,000–100,000 inlifetimeproductivity$ 10–50 per episode). WASH also reduces malnutrition (stunting), which has lifelong economic consequences (reduced educational attainment, lower wages) (Prüss Ustün *et al.*, 2019). The UN estimates that inadequate WASH costs LMICs 1–5% of GDP annually (WHO, 2024). Closing the WASH gap would yield annual economic benefits of $200–300 billion, farexceedinginvestme$ 30–50 billion annually) (World Bank, 2024).

2.10 Gaps and Future Research Directions

Despite substantial evidence, critical gaps remain. Causal mechanisms: which specific behaviors and environmental pathways are most important? Better understanding of transmission routes (water vs. food vs. hands vs. fomites vs. soil) will allow targeting of interventions. Animal feces interventions: studies of animal confinement, composting, and household separation are needed (Penakalapati *et al.*, 2023). Early life interventions: interventions in the first 1,000 days (pregnancy through age 2) may have larger effects on diarrhea, growth, and cognitive development. The WASH Benefits and SHINE trials found no effect on stunting, but more intensive interventions or longer follow-up may be needed (Humphrey *et al.*, 2019).

Sustaining behavior change: research on low-cost, scalable approaches to maintain handwashing with soap, water treatment, and latrine use beyond the intervention period is a priority. Digital interventions (SMS reminders, voice calls, mobile money for soap) show promise (Dreibelbis *et al.*, 2022). Climate resilience: WASH infrastructure must be designed to withstand floods, droughts, and storms. Research on climate-resilient technologies (solar-powered water treatment, raised latrines, flood-protected wells) is needed

(Fewtrell & Bartram, 2024). Urban WASH: scalable, affordable, and safe shared sanitation models for dense informal settlements require further testing (Capone *et al.*, 2024).

WASH plus nutrition: integrated WASH and nutrition interventions may have synergistic effects on child growth. The WASH Benefits and SHINE trials tested combined effects on stunting but found no synergy; more intensive interventions or longer duration may be needed (Luby *et al.*, 2018; Humphrey *et al.*, 2019). Implementation science: identifying effective strategies to scale evidence-based WASH interventions to national and regional levels, with sustained quality and equity, is a priority. Equity: evidence on reaching the poorest and most marginalized populations (minorities, displaced persons, disabled) is limited. Targeted subsidies, community engagement, and adaptive design are needed (Cumming & Cairncross, 2020).

Conclusion

WASH interventions consistently reduce diarrheal disease burden, though rigorous trials show smaller effects (20–30% for combined interventions) than earlier estimates (50–60%). Handwashing with soap provides the largest single effect (30–48% reduction) and is most cost-effective. Household water treatment (25–50% reduction) and improved sanitation (28–36% reduction) also provide substantial benefits, with larger effects in high-burden, low-coverage settings. Combined interventions yield additive effects, and effectiveness depends critically on sustained behavior change, high coverage, and program intensity. WASH remains a cornerstone of diarrheal prevention alongside vaccination, oral rehydration, and nutrition. Achieving universal access by 2030 is essential to eliminate the half-million annual child deaths from diarrhea.

Recommendations

Based on the evidence synthesized in this review, the following recommendations are offered for governments, donors, implementers, researchers, and international organizations:

1. Prioritize handwashing with soap promotion as the most cost-effective single intervention. Provide free or subsidized soap and water access (tippy taps where piped water unavailable).

Use emotional drivers (disgust, nurture, social norms) for sustained behavior change.

2. Deliver integrated WASH packages (water + sanitation + hygiene) rather than siloed interventions. Combined packages achieve larger overall effects (20–30% diarrhea reduction) and are more cost-effective than sequential single interventions.

3. Target high-burden, low-coverage settings for maximum impact: sub-Saharan Africa and South Asia, rural areas, and the poorest wealth quintiles. Baseline open defecation >30% and diarrhea prevalence >10% indicate high potential gain.

4. Ensure sustained behavior change through ongoing promotion, monitoring, and resupply of consumables (soap, chlorine). Annual reinforcement campaigns (e.g., Global Handwashing Day) complement routine programming.

5. Invest in climate-resilient WASH infrastructure: raised latrines, flood-protected wells, solar-powered water treatment, and rainwater harvesting. Design for extreme weather events (floods, droughts, cyclones).

6. Address animal fecal contamination through household animal confinement, composting of manure, and separate animal sleeping areas. Integrate animal WASH into human WASH programs.

7. Scale up shared sanitation models for urban slums and dense settlements. Regular cleaning, lighting, locks, and waste collection improve safety and use. Container-based sanitation is a promising alternative.

8. Integrate WASH with nutrition and health programs: co-deliver WASH with oral rehydration solution (ORS), zinc, rotavirus vaccination, and nutrition supplementation (vitamin A, protein). Integrated platforms reduce program costs.

9. Strengthen WASH in humanitarian emergencies: pre-

position supplies, train rapid response teams, and enforce Sphere minimum standards. Prioritize cholera outbreak response with point-of-use chlorination and safe sanitation.

10. Monitor WASH coverage and use at household, school, and healthcare facility levels. Distinguish access (latrine present) from use (latrine used regularly) and behavior (handwashing with soap at critical times).

11. Fund implementation science research on scaling effective interventions, sustaining behavior change, and reaching marginalized populations. Evaluate cost effectiveness in real-world programmatic settings.

12. Set and fund SDG 6 acceleration targets: universal safely managed water and sanitation by 2030 requires doubling current investment rates ($30–50 billion annually). The econ$ 200–300 billion annually) far exceed costs.

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