Where is the Evidence? A Global Systematic Review of Sanitation System Resilience

Wallace, J.L.[a]*., Wright, M[a]., Camargo-Valero, M.A[a]., Charles, K.J.[b]., Engebretson, B[c]., Gore, F[c]., Howard, G[d]., Johnston, R[c]., Kohlitz, J[f]., Mills, F[f]., Moon, K[a]., Nijhawan, A[d]., Slaymaker, T[e]., Takane, M[c]., Willetts, J[f]. & Evans, B.E[a].,

[a]School of Civil Engineering, University of Leeds, Leeds, UK, *ll14jlw@leeds.ac.uk

[b]School of Geography and the Environment, University of Oxford, Oxford, UK

[c]Water, Sanitation, Hygiene and Health Unit, Department of Environment, Climate Change and Health, World Health Organization (WHO), Geneva, Switzerland.

[d]University of Bristol, Civil, Aerospace & Design Engineering and Cabot Institute for the Environment, Royal Fort House, Bristol, UK

[e]Division of Data, Analytics, Planning and Monitoring, UNICEF, New York, New York, USA

[f]Institute for Sustainable Futures, University of Technology Sydney, Ultimo, NSW 2007, Australia

Abstract:

Despite sustained efforts over several decades, no region is projected to achieve universal sanitation access by 2030, according to international monitoring frameworks. Climate change is increasingly disrupting human and ecological systems, in turn deepening existing inequalities in access to essential services, including sanitation. Coupled with broader socio-economic and political dynamics, these pressures are expected to further widen the global sanitation service gap.

Strengthening the resilience of sanitation systems to climate-related impacts represents a critical component of addressing this challenge. Building resilience requires an understanding of the attributes of sanitation systems and the adaptation actions across scales that contribute to their capacity to anticipate, withstand and recover from climate hazards. While existing scholarship has primarily examined the impacts of climate hazards on sanitation system performance, less attention has been given to resilience-building processes and practices.

This systematic review is the first to synthesise the evidence on resilience in sanitation systems. It identifies twenty-seven (n=27) attributes and adaptation actions with potential to enhance resilience. However, with only seventeen (n=17) studies meeting the inclusion criteria and limited empirical evidence, substantial knowledge gaps remain. These findings underscore the urgent need for targeted research and the development of measurable indicators of climate resilience to inform international monitoring frameworks and guide effective adaptation strategies.

Keywords: Sanitation; resilience; climate change

Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (1) highlights that human-induced climate change is increasingly disrupting both human and natural systems and doing so in profoundly unequal ways. The report underscores that climate change is driving widespread loss and damage — including loss of life, deteriorating human health, and heightened social vulnerabilities — while further deepening inequalities in access to basic essential services. Sanitation is one such essential service.

The sanitation sector is uniquely vulnerable to climate-related hazards, particularly flooding and drought. This vulnerability stems not only from its intrinsic connection to natural processes such as the water cycle (sewer conveyance) and soil dynamics (infiltration from pit latrines), but also from its heterogeneous service delivery models, which rely on both permanent infrastructure and more fragmented, road-based systems. Flooding can trigger sewage overflows and wash out pits and tanks, while drought reduces water availability for flushing and conveyance. Heavy rainfall and erosion may collapse latrines; rising sea levels threaten coastal infrastructure; and increasing temperatures can disrupt the biological processes essential to treatment. These risks are especially acute in low-income areas with limited adaptive capacity (2) (3) (4) (5) (6).

The WHO/UNICEF Joint Monitoring Programme (JMP) and the UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS), which track progress towards the sanitation-related Sustainable Development Goals (SDGs), report that no region is currently on track to achieve universal access by 2030. Climate change further threatens these efforts, intensifying risks and widening existing disparities in sanitation access worldwide (7) (1).

Adaptation to enhance climate resilience is essential for closing service gaps amid accelerating and intensifying climate change–related hazards (8). Yet the most effective methods and modes of adaptation remain insufficiently defined (9). Existing reviews of sanitation systems in relation to climate and weather resilience have paid limited attention to the specific attributes or adaptation actions that contribute to resilience (3) (10) (11). To date, no rigorous systematic reviews have assessed and synthesised evidence on these attributes and adaptation actions or their influence on sanitation system resilience. This review addresses that gap and aims to benefit a range of stakeholders: researchers, by identifying which domains of resilience are well studied and which require further attention; and practitioners and policymakers, by highlighting programmes, interventions, and approaches that have successfully strengthened sanitation system resilience.

Scope and Conceptual Model

This study forms part of a broader series of reviews designed to strengthen global monitoring efforts by systematically analysing existing evidence to inform the development of climate-resilience indicators for Water Supply, Sanitation and Hygiene (WASH). These indicators are intended to support the integration of climate-resilience considerations into monitoring of SDG targets 6.1 and 6.2 through the WHO/UNICEF Joint Monitoring Programme (JMP), as well as targets 6.a and 6.b through the Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS). This series of reviews contributes to a multi-year initiative led by the JMP and GLAAS teams to identify indicators for monitoring “climate-resilient WASH” at the global level, facilitating the progressive integration of climate-resilience information into both national and international WASH monitoring frameworks.

Using a global systematic review approach, this study examines the existing body of evidence on how resilience is built within sanitation systems. Developing robust and meaningful indicators of climate

resilience requires first, a clear understanding of the key attributes of sanitation systems that determine their capacity to withstand and adapt to climate-related shocks and stresses, as well as the adaptation actions that can be implemented to strengthen that resilience. Mapping and synthesising the evidence base for these attributes and actions not only reveals critical knowledge gaps but also ensures that resulting indicators are scientifically sound, context-appropriate, and capable of informing policy, planning, and investment decisions to enhance the climate resilience of sanitation services worldwide.

For this initiative, a conceptual logical framework was developed to guide the design and methodology of the reviews and to organise potential indicators. The specific sanitation components of this framework are shown in Figure 1. The framework illustrates how 'upstream' adaptation actions (shown on the left-hand side) influence the consequent attributes and outputs for sanitation (progressively shown to the right). At the right-hand side of the framework are the outcome variables, which are shaped by the earlier actions and attributes. These outcome variables capture changes in sanitation service performance and in the experiences of sanitation for users.

Figure 1 - The Resilience of Sanitation Systems & Services - System of Concern for Monitoring: Conceptual Framework. Adapted from (12)

The framework presented in Figure 1 represents an adaptation of the model developed by WHO and UNICEF (12) , refined to focus specifically on sanitation systems. Whereas the original framework encompassed the entire WASH sector, this study tailors it to the unique components, processes, and interlinkages within sanitation. Further details on the original conceptualisation are provided in (12). The adapted framework serves as the analytical basis for this study and is applied and referenced throughout the remainder of this paper.

Terminology and Framing

In this review, we specifically investigate the attributes of sanitation infrastructure and the adaptation actions employed to enhance resilience in the sanitation system against climate hazards. For clarity, we use specific definitions of these and related terms (Table 1). This is a global review with no focus on specific context or country income level.

Table 1 - Table of definitions

Item	Definition
Attribute of Sanitation Infrastructure	A measurable or observable characteristic—such as aspects of its design, infrastructure, or operational features—that reflects its engineering resilience, robustness, protection, and flexibility. (12)
Adaptation Action	Adaptation in sanitation systems is the process of adjusting infrastructure, operations, governance, and financing mechanisms to actual or expected climate conditions to reduce risks, comply with regulations, and enhance resilience and opportunities (13)
Climate Resilient Sanitation Service	One that can anticipate, respond to, cope with, recover from, and adapt to climate-related events, trends, and disturbances. (14)
Sanitation System	The integrated set of technologies, services, and governance structures that manage sanitation products from their point of generation to safe disposal or reuse, encompassing capture, containment, conveyance, treatment, and final disposal or resource recovery (15) (This includes sewered and non-sewered systems.

Climate Hazard	The occurrence of a climate-related physical event or trend that can cause loss of life, injury, health impacts, or damage and disruption to property, infrastructure, livelihoods, services, ecosystems, and environmental resources (13). A full list of climate hazards analysed in this paper can be found in (12)

Review Questions and Objectives

The guiding question for this review is "To what extent do technical, operational and enabling environment attributes and adaptation actions impact user experience and system functioning of sanitation systems during and following climate hazards?" The objectives were to: (a) identify studies that assess or report on sanitation system attributes or adaptation actions contributing to resilience and evaluate the strength of this evidence; (b) identify key climate resilience indicators for inclusion in international monitoring frameworks; and (c) identify gaps in the evidence regarding system attributes or adaptation actions that build resilience in sanitation systems.

Methods

Search Strategy

This study follows the standard systematic review methodology, in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (16). This process was adopted to identify original qualitative or quantitative evidence that a given attribute of a sanitation system provides a resilient outcome, i.e. the service and user experience is continual or minimally interrupted during and following a climate event.

This review was restricted to studies available in English, whether originally written in the language or translated, and did not impose any restrictions on the publication date of the literature considered. Evidence was collected from peer-reviewed journal articles and published conference proceedings. Searches were conducted in grey literature databases.

To search for peer-reviewed literature, a search strategy was developed. This was based on a combination of three primary concepts: climate change, sanitation systems and service continuity. The search terms used can be found in Table 2. A protocol for this review can be found in Supplementary Materials S8. This review protocol was not registered.

Table 2 – Search Terms and Combinations

Ref	*Concept*	*Search terms*	
A *(1 OR 2)*	Climate change	1	(Extreme* OR intense* OR declin* OR prolong* OR increas* OR variab* OR heavy OR decreas* OR rise*) w/3 (rain* OR precipitation OR "dry period" OR snow OR storm OR wind* OR "sea-level" or heat or cold OR temperature OR cyclone* OR typhoon* OR hurricane)
		2	Drought or flood or clima*
B	Sanitation system	3	toilet* OR latrine* OR sanita* OR

(3 OR 4 OR 5 OR 6)			ecosan OR "septic tank"
		4	(feces OR faeces OR fecal OR faecal OR excre* OR waste OR sludge OR wastewater OR "waste water") W/3 (dispos* OR manag* OR service OR treat* OR desludge* OR empt* OR transport* OR pit OR pits OR *pits)
		5	sewage OR sewer* OR sewerage OR wastewater OR "waste water"
		6	open W/1 defecation OR sanitation
C	Continuity of service and user experience	7	(contin* OR maintain* OR increas* OR decreas* OR interrupt* OR consistent OR inclusive OR equal* OR equit* OR reliable OR level) w/3 (access Or provi* OR availab* OR us* OR afford* OR connect* OR allocat*)

[a]This table presents the search strategy used for the Scopus database. The proximity operators have been adapted in compliance with the conventions of the respective database

The search was conducted in July 2024 in databases: Web of Science, CAB Abstracts, Medline, Global Health, and Scopus.

Screening and selection

The systematic search of literature databases yielded almost 4,000 article returns. After uploading the results to the Rayyan QCRI web tool and removing duplicates, 3,461 articles were deemed eligible for title screening. Titles, abstracts, and full texts were then reviewed against exclusion criteria by two independent authors (JW and MW), with a third reviewer (BE) resolving any disagreements. The identification, screening and selection process is described in Figure 2.

Figure 2 -PRISMA flow diagram of screening and selection process

Thirteen (n=13) additional articles were identified through hand-searching the reference lists of reviewed studies. Grey literature searches and expert consultations yielded no studies eligible for inclusion. A total of 495 duplicate records were removed, leaving 3,478 articles. Of these, 57 were selected for full-text screening, but 8 were inaccessible and thus excluded from the final analysis. Six (n=6) of these articles were conference proceedings, and the remaining two (n=2) were published prior to 1990. Following the full-text screening, seventeen (n=17) were included in the final analysis. Most of the excluded articles were omitted based on the exclusion criteria outlined in Supplementary Material S1. There are several articles that may be perceived to have met the inclusion criteria for this study. For example, while (17), (18), and (19) discuss several indicators of resilient sanitation systems, their failure to ground these indicators in real-world case studies supported by empirical or reported data led to their exclusion from this study. Following the article screening, data were extracted by JW characteristics of the data, analysis and discussion are found in the Results and Discussion Section.

Quality Appraisal

This study employs a modified version of the quality appraisal framework originally developed by (20) and later adapted by (3) to assess the quality of the included articles. The framework evaluates

research using ten criteria, each scored on a scale from 0 to 1. These criteria are divided into two categories: Quality of Reporting and Relevance & Generalisability of Evidence.

The Quality of Reporting category comprises seven criteria, which assess the clarity and rigour of the research objectives, contextual details, data collection methods, analysis, author's interpretation of results, discussion of limitations, and conclusions. The Relevance & Generalisability of Evidence category focuses on the strength of the evidence, including the spatial scale and generalisability of the sanitation system attribute or adaptation action, as well as the temporal scale and generalisability in relation to the climate hazard. Further details of these criteria can be found in Supplementary Material S3.

Each included article was scored by the first author (JW), with 10% of the articles independently reviewed by MW for quality control. Criterion scores were aggregated to produce a total score out of ten. Papers with an aggregated score of 7.5 or higher were considered to provide "strong" evidence.

Results and discussion

Literature Characteristics

General characteristics of the literature included in this study can be found in Table 3 and Table 4. These tables present information on aspects such as geographical coverage, focus on sanitation components, consideration of climate hazards, and the types of evidence reported, including both published studies and field-based research. The following sections provide a more detailed analysis of these characteristics.

Field Foci

The articles providing evidence that specific system attributes or adaptation actions influence system performance or user experience during and following a climate hazard fall into two main clusters: sanitation studies from engineering literature (n=6) and those from international development literature (n=11).

The first group predominantly focuses on attributes and adaptation actions relating to sewered systems in high-income contexts, featuring studies which are generally more quantitative in nature. These studies tend to adopt a traditional engineering resilience approach focussing on robustness, redundancy and reparability (21).

The second cluster centres on lower-income contexts, analysing non-sewered sanitation systems and developmental approaches to resilience. While these studies also take an engineering perspective, they adopt more qualitative approaches to explore the relationship between the attribute or action and the resilience outcomes. This approach allows for a deeper understanding of the user experience outcomes, which were missing entirely from the first cluster. This focus on user involvement may arise from the fact that many of the system attributes or adaptation actions in this group are either directly controlled or heavily influenced by the user or household.

193 *Table 3 - Literature included in analysis*

Study	Study Location	Sewer/non-sewered	Position along sanitation value chain	Study country classification by Income[b]	Climate hazard studied
(22)	Malawi	Non-sewered	Capture	Low	Drought
(23)	Algeria	Mixed	Treatment	Upper-middle	Drought/Extreme heat
(24)	Malawi	Non-sewered	Capture	Low	Increasing rainfall/Flooding
(25)	Bangladesh	Non-sewered	Capture	Lower-middle	Increasing rainfall/Flooding
(26)	India	Non-sewered	Capture	Lower-middle	Increasing rainfall/Flooding
(27)	Zimbabwe	Non-sewered	Capture	Low	Increasing rainfall/Flooding Drought Severe wind
(28)	Australia	Sewered	Conveyance	High	Drought Increasing rainfall/Flooding
(29)	USA	Sewered	Treatment	High	Increasing rainfall/Flooding Severe wind
(30)	United Kingdom	Sewered	Conveyance	High	Increasing rainfall/Flooding
(31)	Bangladesh	Non -Sewered	Capture Containment	Lower-middle	Increasing rainfall/Flooding
(32)	Bangladesh	Non-sewered	Capture Containment	Lower-middle	Increasing rainfall/Flooding Severe wind
(33)	USA	Sewered	Treatment	High	Increasing rainfall/Flooding
(34)	Bangladesh	Non-sewered	Capture Containment	Lower-middle	Increasing rainfall/Flooding Sever wind
(35)	Japan	Mixed	Conveyance	High	Increasing rainfall/Flooding
(36)	Botswana	Non-sewered	Capture	Upper-middle	Increasing rainfall/Flooding
(37)	Philippines	Non-sewered	Capture	Lower-middle	Increasing rainfall/Flooding Severe wind
(38)	Bangladesh	Non-sewered	Capture Containment	Lower-middle	Increasing rainfall/Flooding

194 [b]According to World Bank classification for the 2025 fiscal year (39)

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Table 4 - Literature characteristics

Characteristics	**No. of documents**		
Literature type			
Journal-published study	16		
Conference Proceedings	1		
Type of evidence	**Quantitative**	**Qualitative**	
Empirical	4	-	
Reported	-	13	
Field Foci			
Primarily engineering	6		
International development	11		
Climate hazard studied[a]			
Drought/ Extreme heat	5		
Flooding/increasing rainfall	15		
Severe wind	3		
Saltwater intrusion	1		
Study classification by income[b]	**Sewered**	**Non-sewered**	**Mixed[c]**
High	4		1
Upper-Middle		1	1
Lower-Middle		7	
Low		3	

[a]The sum of climate hazards studied is greater than number of documents as several documents study multiple climate hazards. [b]According to World Bank classification for the 2025 fiscal year (39) [c]Mixed refers to studies on treatment works where it is unclear if they are part of a sewered or non-sewered system.

Type or element of the sanitation system

Sixteen of the seventeen (n=16/17) articles focussed on a single element of the sanitation service chain. One case study (32) presented an enabling environment attribute which took a 'system-wide' perspective. Other literature which presented operational or enabling environment adaptation actions reported outcomes which were specific to a particular sanitation system component.

From the sixteen (n=16) remaining articles, nine (n=9) of those presented evidence relating to latrines (including their containment) and their ability to capture, flush and contain. Four (n=4) articles analyse sewers and their ability to convey faecal sludge (FS), wastewater (WW) and supernatant (SN). Three (n=3) articles give attributes or adaptive actions for treatment works. There were no (n=0) studies that capture resilience-building efforts relating to the road-based conveyance of FS, WW, and SN.

Climate hazards

The most prominent climate hazard studied was the changing frequency and intensity of rainfall, often resulting in pluvial or fluvial flooding (n=15), one of these studies included saltwater intrusion due to coastal flooding. Sea level rise (SLR) as a slow-onset climate hazard was not represented in the

included literature. However, other longer-term hazards such as drought (n=4) and extreme heat (n=1) were covered. Four (n=4) studies considered several climate hazards.

Global coverage

One third of the literature was based on case studies in High-Income countries, distributed evenly across North America, Europe, East Asia and Oceania. All of these studies related to sewered systems (n=4) or treatment facilities (n=1). Eight studies were conducted in low-income countries, all of which addressed adaptation actions of attributes relating to latrines or toilets, with five of these studies carried out in Bangladesh. Four studies were focussed in UMICs (n=2) or LMICs (n=2). One study contained case studies from four discrete countries, relating to several income classification levels, but evidence was only presented for one of these case studies.

Quality appraisal

The quality of the evidence is moderately varied (Standard Deviation: 1.63) when evaluated against the quality appraisal criteria in Supplementary Material S3. **Error! Reference source not found.** presents the aggregated quality scores of the included studies, categorised by their field foci. Overall, eight articles achieved a score of at least 7.5/10, classifying them as strong evidence. 82% of the studies scored at least 5/10. No significant relationship was observed between the total aggregated scores and field foci, as both fields attained an average score of 6.5. All but one of the included studies were journal articles. Study 12, a conference paper, had a low aggregated quality score. However, the sample size is too small to draw any meaningful conclusions from this finding.

Figure 3 - Quality Appraisal scores of the included literature by field foci

Attributes and adaptation actions along the sanitation service chain

Across the seventeen (n=17) included articles, thirty-three distinct attributes or adaptation actions were initially identified. As many of these articles reported similar or overlapping attributes or actions, they were consolidated into a final set of twenty-seven (n=27) summarised in Table 5. These twenty-seven attributes or adaptation actions are listed in Tables 6 and 7. Each attribute or action is mapped to the specific climate hazard it aims to address for resilience-building, as well as to the service continuity outcome it supports. Additionally, each attribute is categorised as an attribute of infrastructure, operational, or an action by National or Subnational Governments, and aligned with the Conceptual Framework components illustrated in Figure 1 and Table 5.

Table 5 - Summary of attributes and adaptation actions extracted from literature

Conceptual Framework Component		**Count**
Attributes of Sanitation Systems	User-defined Attributes	6
	Service provider defined Attributes	12
Actions by users		2
Actions by service providers		4
Actions by national and sub-national governments		3

Continuity in capture, flush, and containment of faecal sludge, supernatant and wastewater

The outcome variables 'capture and flushing of wastewater' and 'containment of FS, WW, and SN have been combined, as many attributes and adaptation actions aiming to satisfy one outcome have a strong influence on the other. The actions relating to droughts tended to focus on the flushing of excreta in the absence of water, but other studies did not distinguish between actions which impacted containment, capture and flushing.

Most attributes and adaptation actions related to these outcomes were derived from studies conducted in low-income settings, except for a study in Botswana (36).These studies primarily focused on pit latrines or on their adoption as an alternative when primary flush toilets were unusable due to climate events. These studies can be split into three groups focused variously on building resilience to droughts, severe winds and increasing rainfall leading to flooding.

During droughts or extended dry periods, the primary challenge was reported to be ensuring sufficient water for flushing excreta for flush toilets. This was typically addressed by building redundancy through diversifying the sanitation options within the system, referred to as 'infrastructure stacking,' which included access to multiple water sources for manual flushing (22) and the use of non-flush or low-flush latrines during water-scarce periods (22, 36). We will see 'infrastructure stacking' as a common theme for building resilience, particularly in lower-income settings. In these studies, the actions involved users implementing adaptation measures to enhance resilience, with evidence indicating that, in almost all cases, these were autonomous household responses to climate hazards.

For severe winds, resilience building was focussed on increasing the robustness of the superstructure (32), construction of temporary facilities when primary options were interrupted (38), and the availability of multiple sources of water for flushing when the water supply is cut off during a storm (37). One study (32) cites the allocation of above-average funding to projects significantly increasing their climate resilience. This not only enabled the use of more durable construction materials but also ensured dedicated financing for operations and maintenance, allowing facilities to be promptly repaired after adverse events.

To build resilience to increasing rainfall or flooding, the evidence base was largely centred around increasing the robustness of the latrine pit and its superstructure. For instance, designs incorporated higher cement content to improve structural integrity, and trenches or earthen walls were constructed to redirect water flow and prevent latrine pits from filling (27). Achieving this requires an enabling environment that can equip service providers—and, in this case, users—with the technical knowledge needed to build resilient structures as demonstrated in (24). Additionally, the necessary materials for robust construction must be accessible and affordable (24). Related to this was evidence showing that a quality assurance process, however informal, leads to a more resilient construction (24-27).

Other attributes or adaptation actions building resilience to increasing rainfall or flooding focused on siting and technology choice, and availability. Constructing latrines on higher ground and raising the latrine base increased resilience by reducing the likelihood of latrine pits becoming inundated with surface flood water, as shown by (27) and (38). Finally, (31) and (34) show that carrying out an assessment of the most appropriate latrine technology, in terms of climate resilience but also user appropriateness and accessibility, can give more resilient outcomes.

Continuity in emptying and conveyance faecal sludge, supernatant and wastewater

This section focuses on attributes and adaptation actions related to the conveyance of FS, SN, and WW through sewered systems. The evidence presented here largely pertains to the attributes of the sewers themselves, along with adaptation actions that service providers can take to enhance system resilience.

Several of the included studies dealt with the construction material of the sewer pipes. For example, research by (29) indicates that sewers made from brittle materials, such as vitrified clay, are more prone to fractures from increased dynamic pressure within the sewer, compared to those made of polyvinyl chloride (PVC) or reinforced concrete, when used under similar environmental conditions.

Additionally, blockage rates in sewer systems vary with the material of the sewers, especially under drought conditions. Analysis in (28) suggests that concrete and vitrified clay sewers have higher blockage rates during droughts than PVC or polyethene sewers. This difference is attributed to older pipes often lacking rubber gaskets, which decreases their flexibility at joints and increases susceptibility to root intrusion and water infiltration. Evidence in (28) also demonstrates that sewers in highly variable or shrinkable soils need to be designed to incorporate greater changes in soil density as areas experience more intense, heavy rain followed by longer dry spells.

Sewer diameter also plays a role in system resilience, with smaller diameter sewers more prone to blockages, particularly in drought conditions (28). Possible explanations for this include the shallower placement of smaller-diameter sewers, which makes them more vulnerable to root intrusion and increases the likelihood of being affected by surcharge loading on the ground surface. Additionally, smaller sewers require less debris to become blocked, resulting in a higher frequency of obstructions.

Material selection is critical for other sewer components as well, such as manhole covers. Research in (29) record iron manhole covers corroding upon contact with saline water during storm events, further demonstrating the importance of material choice in maintaining system durability and resilience.

In terms of operational adaptation actions by service providers or utilities, pipe maintenance and replacement were identified as key measures for reducing blockages (28). Maintenance and rehabilitation programmes can prevent debris accumulation and address potential vulnerabilities in the system, while timely pipe replacement mitigates the risks associated with ageing infrastructure. Finally, (30) examines the impact of using drag-reducing polymers to enhance flow velocity, demonstrating that these polymers can increase flow rates by 60-70% under constant conditions through reducing friction energy loss through drag reduction.

Continuity of volume, proportion, and level of treatment of faecal sludge, supernatant and wastewater

For treatment of FS, SN and WW, attributes and adaptation actions can be grouped around two main climate-related challenges: more intense, prolonged precipitation, including storms, and rising ambient temperatures. Resilience-building measures to address heavy rainfall or flooding, as outlined in (33), focus on both technical and operational actions by service providers to prevent service disruptions. Proactive measures, such as constructing flood defences around treatment facilities, are intended to protect these sites from inundation.

Other measures include increasing the overall treatment capacity to accommodate higher volumes of surface water and introducing backup treatment processes for times when the facility becomes

completely overwhelmed, such as chlorination for untreated effluent that bypasses the system (33). The article also provides evidence showing the importance of early warning systems, which trigger a series of preparatory actions for facility staff, ensuring that these measures are implemented effectively when needed.

The selection of an appropriate treatment technique (23) was evidenced for effective service continuity under rising temperatures and drought. Activated sludge (AS) treatment was the most effective for pollutant removal, outperforming both constructed wetlands (PB) and aerated lagoons (AL). Specifically, AS achieved the highest removal rates of BOD5, COD, and SS, while AL consistently had the lowest. Statistical analysis showed a significant performance gap between AS and AL, but no significant difference between AS and PB, suggesting that PB was similarly effective yet less stable with seasonal changes.

The final adaptation action in this section is presented in (35). This study evaluated a high-speed fibre filter for removing suspended solids from wastewater, achieving 65% efficiency for primary treatment on rainy days and 75% for secondary treatment on fine days. The filter resisted clogging but showed variable efficiency for biochemical oxygen demand and chemical oxygen demand.

Table 6 - Literature mapping – Attributes and adaptation actions by climate change event and outcome variables

Climate Change Effect	Potential climate hazard	Continuity in capture (and flush) of FS	Continuity in containment of FS SN and WW	Continuity in emptying FS SN and WW	Continuity in conveyance of FS SN and WW	Continuity of volume, proportion, and level of treatment of FS SN and WW

More intense and prolonged precipitation/ more frequent or intense storms or cyclones	Increased flooding/High -intensity rainfall	(i) Latrine sited at risk-based distance from water body (27, 38)			(ii) Infrastructure in high volume change potential soil is designed to tolerate expected movement (29)	(iii) Back up treatment process for untreated effluent that bypasses the system (33)
		(iv) Latrine soffit raised above expected flood level (38)				(v) Increased volume capacity at treatment facility (33)
		(vi) Sanitation technology selected based on climate risk (31, 34)			(vii) Material selection considers flexibility requirements to accommodate variations in pressure (29)	(viii) Flood protection around treatment facility (33)
		(ix) Erosion protection installed around latrine soffit (27)				
		(x) Compliance with established design standards (27)			(xi) Selection non-corrosive materials (29)	(xii) Plan to facilitate increased flow (33)
		(xiii) Technical knowledge of robust construction (24)				
		(ixv) Local availability of materials required for robust construction (24)				
		(xv) Access to multiple sanitation technologies (38)			(xvi) Filtration system added to limit CSO spill and increase suspended solid removal efficiency (35)	
		(xvii) Quality assurance process implemented (24-27)			(xviii) Polymer dosing of WW to maintain/increase flow rates (30)	
	More extreme winds	(ixx) Multiple water sources for manual flushing if water has been cut off (37)				
		(xx) Construction of temporary toilets during wet or stormy weather (38)				
		(xxi) Dedicated CR investments allow for robust construction & rapid response and repair following climate hazard (32)				

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364 *Table 7 - Literature mapping – Attributes and Adaptation actions by climate change event and outcome variables*
365 *(continued..)*

Climate Change Effect	Potential climate hazard	Continuity in capture (and flush) of FS	Continuity in containment of FS SN and WW	Continuity in emptying FS SN and WW	Continuity in conveyance of FS SN and WW	Continuity of volume, proportion, and level of treatment of FS SN and WW
More variable or declining rainfall or run-off	More extended dry periods, increased frequency of occurrence of drought (seasonal and longer term	(xxii) Availability of multiple sanitation technologies during drought season (22, 36)			(xxiii) Sewer diameter-larger diameter pipes give fewer blockages (28)	
					(xxiv) Sewer material - Concrete and VC pipes have high blockage rate than PVC or PE (28)	
		(xxv) Multiple water sources for manual flushing during dry periods (22)			(xxi) Sewer maintenance and rehabilitation programmes (29)	
Sea level rise	Rising groundwater in coastal/low/lying areas					
	Saline intrusion in coastal/low-lying zones					
	High water levels (potentially flooding, erosion, landslides)					
More variable or increasing temperatures	Higher ambient air temperatures					(xxvii) Select appropriate treatment technique for changing ambient temperature (23)
	Hot and cold extremes					

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User defined attribute		Adaptation action by users		Attributes of sanitation infrastructure	
Service provider defined attribute.		Adaptation actions by service providers		Adaptation actions by national and subnational governments	
Policy		Financing		Regulation	
Institutions					

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Analysis by climate hazard and position along the sanitation service chain

Overall, evidence on how specific attributes or adaptation actions influence the resilience of sanitation systems to climate hazards is limited. The literature search identified only seventeen articles, offering twenty-seven distinct attributes or adaptation actions with evidence of their influence on the sanitation system's performance during and following a climate hazard.

Tables 6 and 7 show the attributes and adaptation actions extracted from the literature mapped against the climate hazard they address and the system continuity outcome they satisfy. This approach enables a comprehensive analysis of the distribution of existing evidence and helps identify gaps in current knowledge.

Continuity in capture, flush, and containment of faecal sludge, supernatant and wastewater

A significant proportion of the evidence for attributes or actions influencing resilience of sanitation systems (8/27) pertains to user adaptations in latrine design, siting, and construction. This underscores the current state of sanitation systems in many low-middle income settings, where users are integral to the system, bearing responsibility for the construction and maintenance of latrine structures—and by extension, their resilience. However, this review identifies several challenges associated with this delegation of responsibility to users. Specifically, the knowledge, skills, and materials needed to construct durable, robust structures are not always accessible, leading to increased vulnerabilities and even maladaptation.

None of the screened articles, including those ultimately included, focused on the user interface (toilet) in sanitation systems in high-income countries. This is likely because in high-income settings, domestic toilets or latrines are typically housed indoors, shielding them from climate impacts and reducing the need for user-interface-related adaptation actions.

None of the included articles provided evidence on FS or WW containments (pits and tanks) of any kind. The vulnerabilities of septic tanks to flooding and backflows and highlighted in (2), but no studies providing evidence were found as part of this review. This presents a significant research gap regarding the resilience of containment tank technologies, both in terms of their structural integrity and their operation.

Continuity in emptying and conveyance of faecal sludge, supernatant and wastewater

There is a lack of studies addressing faecal sludge management (FSM), particularly in relation to emptying and road-based conveyance. A similar research gap was identified in (3) relating to the connection between faecal sludge management and climate change. This article (3) highlights the potential to adapt knowledge in the transport sector to enhance resilience in FSM. However, a significant research gap remains when we consider the resilience of the FSM worker – an integral part of the emptying process. In low-income, peri-urban settings, manual or semi-mechanised pit emptiers, often working informally, typically come from marginalised backgrounds (Grisaffi et al., 2022). These frontline workers already face substantial mental and physical health risks due to the hazardous nature of their work, risks that are likely to be exacerbated by the increasing impacts of climate hazards in the areas they operate.

There was a lower-than-expected return on the number of articles presenting evidence relating to sewered conveyance. Many of these were rejected during the screening process for adopting computational modelling as an analysis method. These studies test simulated future climate scenarios to analyse the impact on the sewer system, or how systems could be adapted to enhance resilience to future events, but there is limited empirical work in this area.

Continuity of volume, proportion, and level of treatment of faecal sludge, supernatant and wastewater

There were relatively few articles included in this study that addressed attributes and adaptation actions related to wastewater treatment works. During the screening process, many studies were excluded as they were conducted under laboratory conditions rather than in real-world settings.

All but one of the articles in this category (24) provided evidence relating to rapid onset events. The most frequent were increased rainfall, causing pluvial and fluvial flooding, and decreasing rainfall, resulting in long-term droughts. Severe winds or storms were often discussed in papers that focussed on increasing rainfall quantity and intensity. However, there was a notable lack of literature examining long-term trends such as sea-level rise (SLR) and changing ambient temperatures. Considering the vulnerability of wastewater treatment works (WWTWs) to SLR due to their typical coastal locations, there is a need for further research on adaptation measures to address these challenges.

Cross-cutting themes

The literature shows a significant bias towards rapid-onset events, with twenty (n=20) out of twenty-seven attributes or adaptation actions focused on addressing storms, heavy rainfall, and increased flooding. This is a common observation in climate and climate resilience research, attributed to the fact that rainfall and flooding, with their immediate impacts, are relatively easier to study within the time and resource constraints of research projects. In contrast, longer-term impacts, such as sea-level rise (SLR) or droughts, pose greater challenges for analysis due to their complexity, gradual onset, and less visible effects (40, 41).

Table 6 and Table 7 Highlights a significant lack of evidence connecting policy, institutional, regulatory, or financial (PIRF) attributes and adaptation actions implemented by national or subnational governments with the outcome variables. While (32) gives evidence of NGO actions, and (24) shows that the presence of such attributes or skills enhances resilience, but neither offered evidence of government-led initiatives or tools designed to foster such outcomes. The Conceptual Framework (Figure 1) illustrates how government and non-government actions theoretically influence system attributes, service providers, supply chains, users, and service functioning. However, the evidence focuses largely on outcomes at the user experience level, while government actions occur much earlier in the process. This disconnect makes it difficult to trace the impact of PIRF attributes or actions, as their effects often manifest indirectly—enabling further actions by users or service providers, which are then attributed to improved resilience.

Emerging perspectives

In addition to the clear gaps in the evidence base highlighted in the previous section, this review also uncovered emerging perspectives that are worth exploring further in this section.

Climate resilience or just good practice?

Resilience as a concept in the sanitation sector has been questioned for its additive nature compared to simply *good sanitation.* To analyse this, where possible, we mapped each of the indicators to the part of the sector-wide definition for climate-resilient WASH:

> "-*Climate-Resilient Water, Sanitation and Hygiene (WASH)* ***services anticipate, respond to, cope with, recover from, adapt to or transform*** *based on climate-related events, trends and disturbances…"* (Sanitation and Water for all, 2024)

In Table 5, we show the attributes and actions identified in this review, mapped against the elements of the SWA definition above. Where an attribute or action could not be mapped to one of the elements of the definition, they were categorised as *"Good Sanitation"*.

Table 8 shows that most of the identified attributes and actions map well to ' *responding to*' and to '*cope with*' or can be said to fall in the category of *"Good Sanitation".* It is also worth noting that many of the attributes and actions that map to "*anticipate*" can also be considered "*Good Sanitation*," especially those related to infrastructure design, as, regardless of climate factors, all risks and hazards should be incorporated into any design. This reflects a broader tendency in the literature to focus on infrastructure attributes (n = 18/27) or actions related to infrastructure design, thereby emphasising the engineering principles of resilience (42).

The severity of climate change hazards is projected to increase, rendering it unsustainable to rely solely on enhancing the robustness of infrastructure without rethinking the underlying approaches to system design, service delivery, and disaster response—particularly in low- and middle-income countries, where financial constraints, spatial limitations, and weak governance continue to hinder infrastructure development (43). A critical aspect of resilience is acknowledging a reduction in system performance or outright system failure and responding to it. However, adaptation actions that focus on system recovery and long-term adaptation are notably absent from the evidence base. Efforts to address this gap are evident through sector initiatives such as Systems Strengthening (44) and Citywide Inclusive Sanitation (CWIS) (45), which aim to reinforce the systems within which sanitation infrastructure operates. While existing climate resilience frameworks in the WASH sector cite indicators (5, 46) related to recovery and adaptation, there remains a lack of supporting evidence in the literature.

Perspectives from engineering resilience often refer to restoring a system to its functional state (47) or returning to a perceived "normal." However, as argued in (48), the notion of "normal" in this context is problematic, as it reflects a state in which the system previously failed. The final stage of the SWA definition, "transformation," goes beyond restoration, emphasising the importance of learning from past experiences to establish a new, more resilient equilibrium. This perspective is underrepresented in the evidence base, but capturing it objectively remains a challenge. This issue can be particularly contentious in settings where limited technical expertise, economic constraints, and governance challenges create a perception that simply restoring infrastructure to its pre-disaster state is a significant achievement, not to mention the general subjectivity and relativity of resilience terminology (49). This highlights the need to consider the socio-ecological context of the system in question.

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493 *Table 8 – Mapping of attributes and adaptation actions to SWA Definition of Climate Resilient WASH*

	Attribute or Adaptation Action (Article ref)		**Relevant to which part of SWA explanation**	**Risk hazard/Contextual Vulnerability/ SES**
(i)	Latrine sited at risk-based distance from water body (27, 38)	*..respond to..*	*"..reducing exposure through better planning and design.."*	Risk hazard
(ii)	Infrastructure in high volume change potential soil is designed to tolerate expected movement (29)	-	Good Sanitation	Risk hazard
(iii)	Back up treatment process for untreated effluent that bypasses the system (33)	*..cope with..*	*"..short-term survival and stability.."*	Risk hazard
(iv)	Latrine soffit raised above expected flood level (38)	*..respond to..*	*"..reducing exposure through better planning and design.."*	Risk hazard
(v)	Increased volume capacity at treatment facility (33)	*..respond to..*	*"..preparedness and response plans.."*	Risk hazard
(vi)	Sanitation technology selected based on climate risk (31, 34)	*..respond to..*	*"..risk management decision-making.."*	Risk hazard
(vii)	Material selection considers flexibility requirements to accommodate variations in pressure (29)	-	Good Sanitation	Risk hazard
(viii)	Flood protection around treatment facility (33)	*..respond to..*	*"..reducing exposure through better planning and design.."*	Risk hazard
(ix)	Erosion protection installed around latrine soffit (27)	-	Good Sanitation	Risk hazard
(x)	Compliance with established design standards (27)	-	Good Sanitation	Risk hazard
(xi)	Selection non-corrosive materials (29)	-	Good Sanitation	Risk hazard
(xii)	Plan to facilitate increased flow at treatment facility (33)	*..respond to..*	*"..preparedness and response plans.."*	Risk hazard
(xiii)	Technical knowledge of robust construction (24)	-	Good Sanitation	Risk hazard
(ixv)	Local availability of materials required for robust construction (24)	-	Good Sanitation	Risk hazard
(xv)	Access to multiple sanitation technologies (38)	*..respond to..* *..cope with..*	*"..short-term reliance on backup systems.."* *"..short-term survival and stability.."*	SES
(xvi)	Filtration system added to limit CSO spill and increase suspended solid removal efficiency (35)	-	Good Sanitation	Risk hazard
(xvii)	Quality assurance process implemented (24-27)	-	Good Sanitation	Risk hazard
(xviii)	Polymer dosing of WW to maintain/increase flow rates (30)	*..respond to..*	*"..reducing exposure through better planning and design.."*	Risk hazard
(ixx)	Multiple water sources for manual flushing if water has been cut off (37)	*..respond to..*	*"..short-term reliance on backup systems.."*	SES
(xx)	Construction of temporary toilets during wet or stormy weather (38)	*..cope with..*	*"..short-term survival and stability.."*	Risk hazard
(xxi)	Dedicated CR investments allow for robust construction & rapid response and repair following climate hazard (32)	*..respond to..*	*"..robust against recurring climate stresses.."* *"..rebuilding infrastructure.."*	Contextual Vulnerability
(xxii)	Availability of multiple sanitation technologies during drought season (22, 36)	*..respond to..*	*"..short-term reliance on backup systems.."*	SES

		..cope with..	*"..short-term survival and stability.."*	
(xxiii)	Sewer diameter-larger diameter pipes give fewer blockages (28)	-	Good Sanitation	Risk Hazard
(xxiv)	Sewer material - Concrete and VC pipes have high blockage rate than PVC or PE (28)	-	Good Sanitation	Risk Hazard
(xxv)	Multiple water sources for manual flushing during dry periods (22)	*..cope with..*	*"..short-term survival and stability.."*	SES
(xxvi)	Sewer maintenance and rehabilitation programmes (29)	-	Good Sanitation	Risk Hazard
(xxvii)	Select appropriate treatment technique for changing ambient temperature (23)	*..respond to..*	*"..risk management decision-making.."*	Risk Hazard

The necessity of an enabling environment

Table 5 highlights the dominance of risk-hazard thinking in the literature, which primarily focuses on outcome vulnerability and response strategies. Socio-ecological systems (SES) thinking is reflected through community pooling and user diversification of sanitation options during and after climate hazards. One adaptation action has been classified as contextual vulnerability, as it involves allocating a specialised climate resilience investment plan for vulnerable populations.

It is highlighted in (50) addressing contextual vulnerability requires reducing inequalities, empowering people to cope with external stresses, and alleviating poverty. To build effective resilience, governance structures and processes must be strengthened to provide the enabling environment for service providers and users to build effective resilience and enact *transformational change*. In many low-income areas, government policy solutions are obscured by the active marginalisation of these communities, fed by unfavourable perceptions of residents. This necessitates recognition by both local and national governments of existing inequalities, along with the development of an inclusive strategy to address them.

In low- and middle-income contexts, the literature is largely shaped by user-defined attributes and actions. The prevailing focus remains on response and coping strategies, which are often autonomous adaptations arising spontaneously due to a lack of formal services, political will, and institutional support. While these adaptations demonstrate ingenuity in creating workable living environments despite limited resources (51, 52), these adaptations are limited by the user's own adaptive capacity, resources and technical knowledge. Such strategies can be valuable for immediate coping (53), infrastructure investments alone are insufficient without engagement with broader local and national governance structures. Without this integration, adaptation remains limited and even risks leading to maladaptation (51).

Similarly, for service providers, resilience-building actions are only as strong as the weakest adjacent sector. We know that sanitation as a system touches on so many adjacent sectors and services. Effective adaptation depends on cross-institutional thinking, data sharing, and collaboration to prevent strategies from operating in isolation. A proactive government plays a crucial role in breaking down these silos, ensuring alignment with broader adaptation planning and fostering cohesive, integrated resilience efforts.

National and subnational governments must provide an enabling environment through legislative frameworks, funding, and institutional support, ensuring local capacities can effectively respond to climate change while fostering cross-sector collaboration and integrated resilience efforts.

Limitations

There are several limitations to this study. While we reviewed close to four thousand (n=3,956) articles, the evidence gathered could never be conclusive. Firstly, this review only included articles written in or translated into English. As a result, valuable research published in other languages may have been excluded, potentially leading to a geographic or cultural bias in the findings. Expanding the language scope in future reviews could enhance the inclusivity and representativeness of the research.

Although the authors included maladaptation and commented on its potential, there may have been a bias during the screening process to include articles that included positive resiliency outcomes. This may have influenced the overall emphasis of the article on successful strategies rather than challenges, barriers, or negative outcomes.

Articles focussing solely on stormwater systems were not included; in hindsight, this could have provided valuable insights into the resilience of piped systems and their capacity to handle extreme weather events. Additionally, these findings could have contributed to a more comprehensive discussion on the coordination between stormwater and sanitation systems.

This article defines the scope of this study using the IPCC climatic drivers as the framework for identifying climate hazards. Other types of natural hazards, such as earthquakes and tsunamis, were excluded as they were not covered under the IPCC's extreme weather definition.

Conclusion

This study is the first to systematically summarise and analyse the evidence base of resilience-building efforts within sanitation systems in response to climate change hazards. The systematic review highlights significant gaps in the available evidence on the resilience of sanitation systems to climate hazards, with only seventeen (n=17) articles meeting the inclusion criteria. Despite identifying twenty-seven (n=27) distinct attributes or adaptation actions that may enhance resilience, the overall evidence linking these actions to improved sanitation system performance during and after climate extremes remains limited. Notably, only four (n=4) of the seventeen (n=17) included articles provided empirical evidence, underscoring the need for more robust research to better understand the specific drivers of resilience in sanitation systems.

Our findings indicate that resilience-building attributes and actions identified in the literature primarily focus on infrastructure-related system attributes. There is inadequate evidence addressing operational adaptations or enabling environment strategies implemented by service providers or government actors. This reflects a prevailing approach to climate resilience in sanitation systems that is largely confined to modifications in infrastructure design, often addressing only isolated components of the sanitation chain. Further evidence-based research is required to understand the role of operational and enabling environment adaptations in effective sanitation adaptation planning.

For international monitoring frameworks such as JMP and GLAAS, these findings highlight a critical gap in the evidence base needed to track and assess climate resilience in the WASH system. As countries work towards meeting climate adaptation targets, there is an urgent need for targeted research and the development of measurable, actionable, and evidence-based indicators to guide policy and implementation.

Supporting Information

S1- Inclusion Criteria

S2- Search Strategy

S3-Quality Appraisal Framework

S4-Quality Appraisal

S5-Details of Included Literature

S6-PRISMA Flow Diagram

S7-PRISMA Checklist

S8-Review Protocol

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Author Contributions

Conceptualisation: James L. Wallace, Kelly Moon, Betsy Engebretson, Barbara E. Evans, Fiona Gore, Guy Howard, Jeremy Kohlitz, Anisha Nijhawan, Rick Johnston, Katrina Charles, Freya Mills, Tom Slaymaker, Marina Takane, Juliet Willetts.

Data curation: James L. Wallace.

Formal analysis: James L. Wallace, Madison Wright, Barbara Evans

Funding acquisition: Betsy Engebretson, Barbara E. Evans, Fiona Gore, Rick Johnston, Tom Slaymaker, Marina Takane.

Investigation: James L. Wallace, Madison Wright, Barbara E. Evans,

Methodology: James L. Wallace, Madison Wright.

Project administration: Betsy Engebretson, Barbara E. Evans, Fiona Gore, Rick Johnston, Tom Slaymaker, Marina Takane.

Resources: Betsy Engebretson, Barbara E. Evans, Fiona Gore, Rick Johnston, Tom Slaymaker, Marina Takane.

Supervision: Miller A. Camargo-Valero, Katrina Charles, Betsy Engebretson, Barbara E. Evans, Fiona Gore, Guy Howard, Rick Johnston, Jeremy Kohlitz, Freya Mills, Anisha Nijhawan, Tom Slaymaker, Marina Takane, Juliet Willetts.

Visualisation: James L. Wallace, Jeremy Kohlitz, Freya Mills, Juliet Willetts.

Writing – original draft: James L. Wallace.

Writing – review & editing: James L. Wallace, Barbara Evans.

Notes

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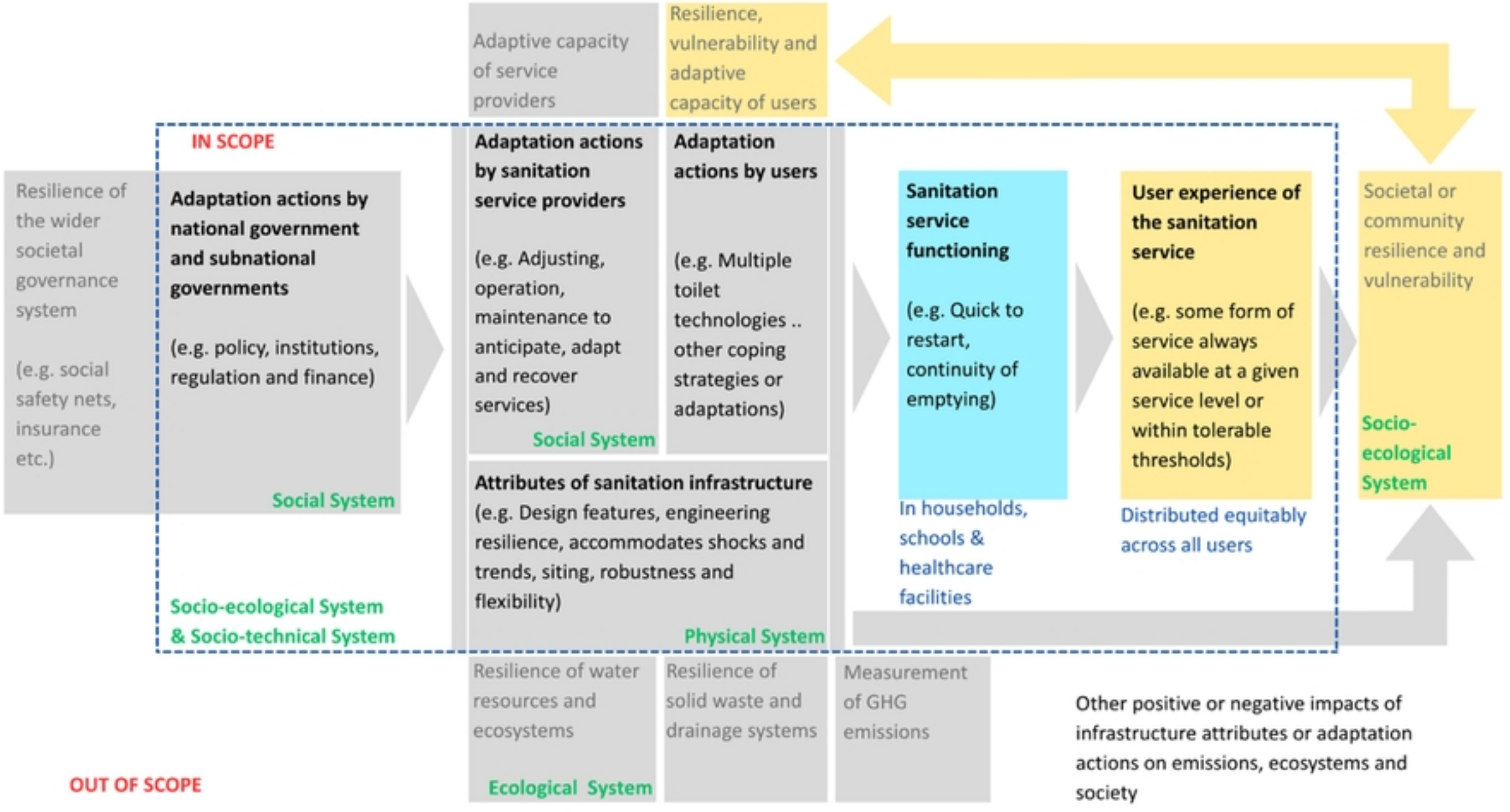

Adaptive capacity of service providers
Resilience, vulnerability and adaptive capacity of users
IN SCOPE
Resilience of the wider societal governance system
(e.g. social safety nets, insurance etc.)
Adaptation actions by national government and subnational governments
(e.g. policy, institutions, regulation and finance)
Social System
Socio-ecological System & Socio-technical System
Adaptation actions by sanitation service providers
(e.g. Adjusting, operation, maintenance to anticipate, adapt and recover services)
Social System
Adaptation actions by users
(e.g. Multiple toilet technologies .. other coping strategies or adaptations)
Attributes of sanitation infrastructure
(e.g. Design features, engineering resilience, accommodates shocks and trends, siting, robustness and flexibility)
Physical System
Sanitation service functioning
(e.g. Quick to restart, continuity of emptying)
In households, schools & healthcare facilities
User experience of the sanitation service
(e.g. some form of service always available at a given service level or within tolerable thresholds)
Distributed equitably across all users
Societal or community resilience and vulnerability
Socio-ecological System
OUT OF SCOPE
Resilience of water resources and ecosystems
Ecological System
Resilience of solid waste and drainage systems
Measurement of GHG emissions
Other positive or negative impacts of infrastructure attributes or adaptation actions on emissions, ecosystems and society

Figure 1

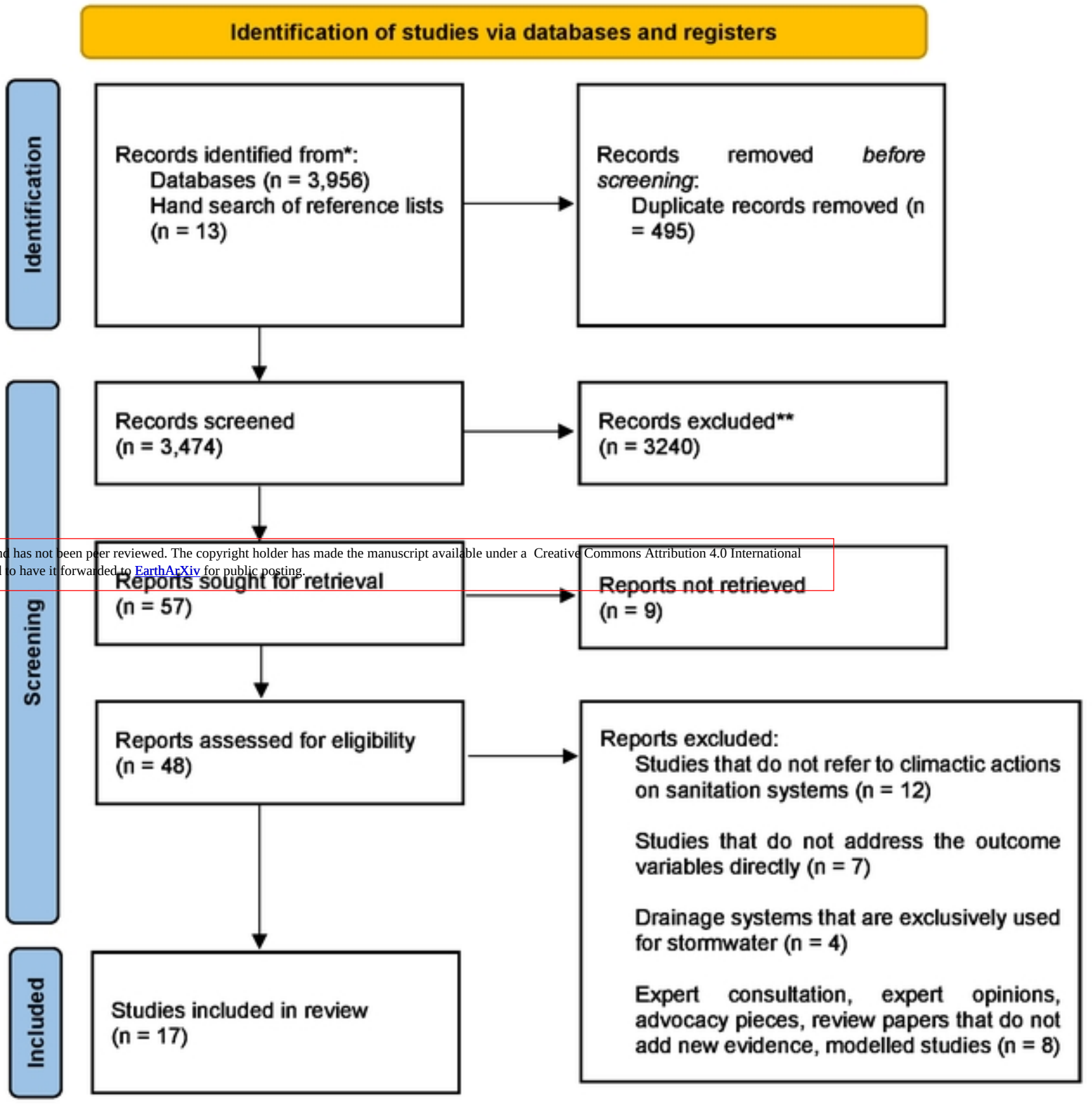
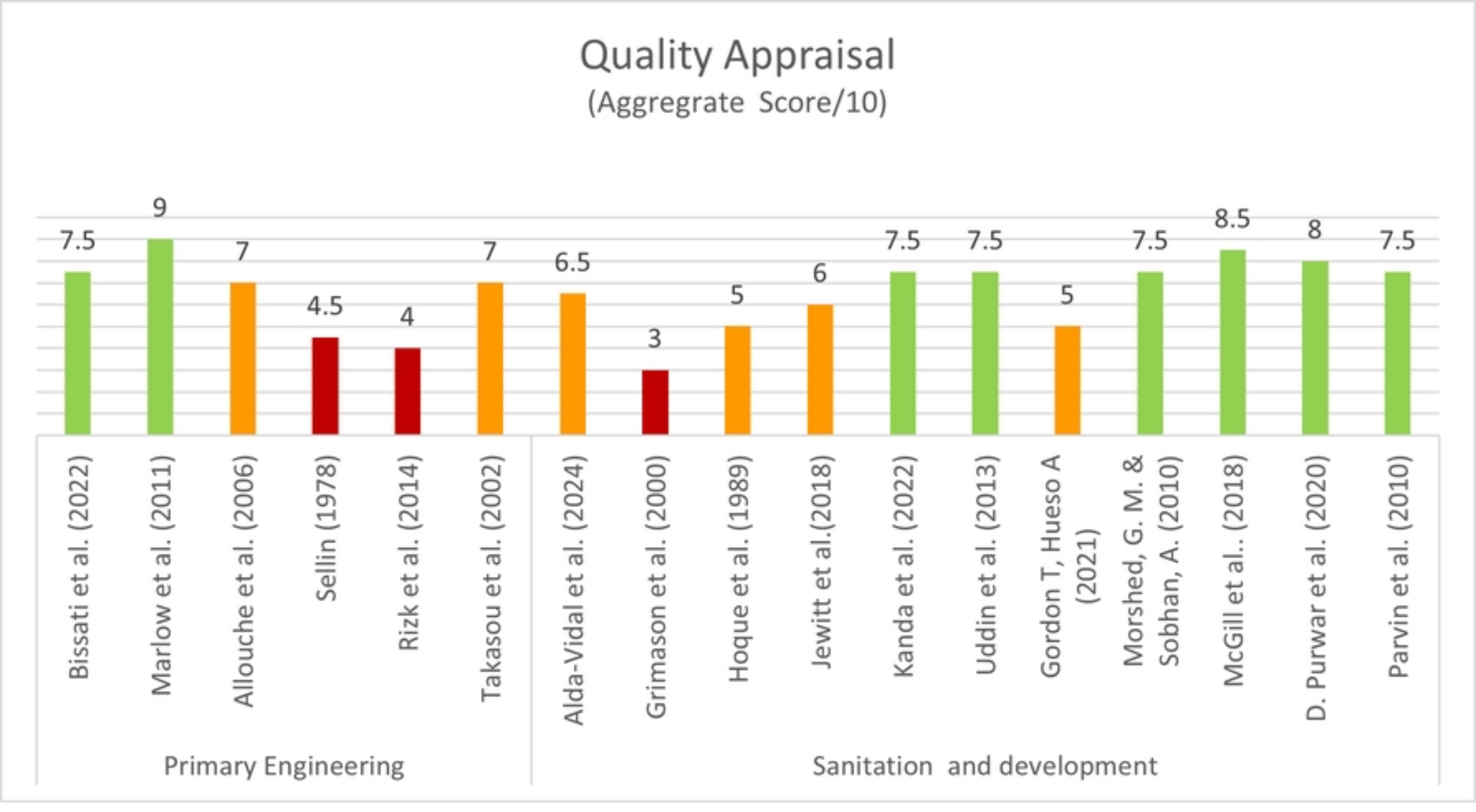


Figure 1 -PRISMA flow diagram of screening and selection process

Figure 2 - PRISMA Diagram


Quality Appraisal
(Aggregrate Score/10)
7.5
9
7
4.5
4
7
6.5
3
5
6
7.5
7.5
5
7.5
8.5
8
7.5
Bissati et al. (2022)
Marlow et al. (2011)
Allouche et al. (2006)
Sellin (1978)
Rizk et al. (2014)
Takasou et al. (2002)
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Grimason et al. (2000)
Hoque et al. (1989)
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Kanda et al. (2022)
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Gordon T, Hueso A (2021)
Morshed, G. M. & Sobhan, A. (2010)
McGill et al.. (2018)
D. Purwar et al. (2020)
Parvin et al. (2010)
Primary Engineering
Sanitation and development

Figure 3