Inadequate wastewater management in Dhaka's major hospitals: A Socio-Technical Systems (STS) analysis of leadership, policy, and technological challenges

Nuhu Amin[1,2*], Tim Foster[1], Nafeya Tabassum Shimki[2], Md Rezaul Hasan[2], Supriya Sarkar[3], Shaikh Daud Adnan[3], Aninda Rahman[4], Rizwana Khan[5], Mahbubur Rahman[2], Juliet Willetts[1]

[1]Institute for Sustainable Futures, University of Technology Sydney, 235 Jones St, Ultimo, NSW, 2007, Australia
[2]Environmental health and WASH, Health System and Population Studies Division, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Dhaka, Bangladesh
[3]Hospital Services Management, Directorate General of Health Services (DGHS), MoH&FW, Mohakhali, Dhaka-1212, Bangladesh
[4]Communicable Disease Control (CDC) Program, Directorate General of Health Services (DGHS), MoH&FW, Mohakhali, Dhaka-1212, Bangladesh
[5]Infectious disease Division, International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), Dhaka, Bangladesh
*Correspond to nuhu.amin@icddrb.org

Keywords: Hospital sanitation facilities; wastewater treatment; Environmental Fecal contamination; Hazardous liquid waste; SGD6; Bangladesh

Abstract:
Unsafe hospital wastewater is a significant concern, especially in low- and middle-income countries (LMICs) where the health impact is often underreported. Socio-technical systems (STS) theory, which examines the interplay between social and technical elements within complex systems, is widely used in developed countries but rarely applied in LMIC hospitals. We employed STS theory to evaluate the social and technical aspects of hospital wastewater treatment (WWT) and management in Dhaka City, alongside a comprehensive assessment of WWT processes. We used a mixed-methods approach, combining quantitative (structured-observations) and qualitative interviews. Structured observations assessed the availability and functionality of WWT systems in selected hospitals. We conducted 30 key-informant interviews across 13 hospitals, including 21 respondents from government and nine from private hospitals. The respondents were cleaners, key health professionals, and public works department (PWD) engineers. We also analyzed relevant government reports and policies. Among the hospitals surveyed, 10 had some form of WWT system, while the remaining three lacked any treatment infrastructure. Of those with WWT, seven utilized anaerobic baffled reactors and three had septic tanks. Interviews revealed that hospital authorities prioritize patient care and medical equipment maintenance over WWT, with limited understanding among hospital staff regarding WWT. PWD-engineers reported frequent staff shortages and bureaucratic delays, affecting the efficiency of WWT system repairs and desludging. Our study identified significant gaps in WWT in Dhaka hospitals, including the limited use of adequate treatment technologies, poor wastewater management knowledge, and many systems in disrepair, leading to hazardous liquid being discharged directly into the environment. The STS approach highlighted the need for policy formulation for HWW regulation, government leadership, adequate financing, technical assistance, and staff capacity building. Addressing these issues comprehensively can lead to safer and more sustainable wastewater management practices in healthcare facilities, ultimately benefiting public health and the environment.

Introduction

Unsafe hospital wastewater is a significant concern, posing unknown but potentially severe public health risks. Hospital wastewater (HWW), a complex mixture originating from various medical and non-medical activities, contains biological components (e.g., pathogens), chemicals such as disinfectants and cleaning agents, pharmaceuticals including antibiotics, analgesics, and hormones, as well as heavy metals like mercury, lead, cadmium, and chromium [1]. This composition mirrors the diverse contaminants introduced during patient treatments, cleaning procedures, and the use of medical equipment. A particular concern regarding the spread of Antimicrobial Resistance (AMR) is the significant role played by wastewater, especially from HCFs [2, 3]. Compared to community wastewater, HCF wastewater exhibits higher concentrations of antibiotics entering the waste stream from both patients and discarded pharmaceuticals [4]. Understanding and mitigating these complexities are crucial for addressing public health challenges associated with HWW.

Safely managed sanitation in HCFs requires the use of an improved sanitation facility and for excreta to be either safely disposed of in situ or transported and treated off-site [5]. As part of the United Nations Secretary-General's global call to action on water, sanitation and hygiene (WASH) in HCFs in 2019, the member states committed to work towards achieving universal access to WASH in HCFs by 2030 [6], primarily focusing on the sustainable development goals (SDG) 3 (good health and well-being) and SDG 6 (clean water and sanitation). A recent report from WHO-UNICEF also stated that unsafe containment, emptying and disposal of fecal sludge and liquid waste presents a growing risk to public health and the environment and threatens progress on other SDG targets [7]. Furthermore, this same report notes limited data to identify and address inequalities in safely managed services in HCFs to determine rates of progress [7]. Timely and accurate data on safely managed onsite sanitation services of HCFs can increase awareness of countries' needs and gaps, and inform policy, implementation and research efforts to extend and improve services [8].

Recent systematic reviews on HWW treatment systems highlighted a lack of research on HWW management in Low- and Middle-Income Countries (LMICs) [1, 3]. The review conducted by Amin et al. in 2024, underscored that numerous HCFs in LMICs lack effective wastewater treatment systems, and most wastewater treatment plants (WWTP) included in the review failed to meet national standards for discharging wastewater [3] highlighting this as a crucial area for future research. Furthermore, the review noted a scarcity of comprehensive studies on the total wastewater or liquid waste management status in densely populated urban areas globally, emphasizing a critical gap in knowledge. Recent studies conducted in large hospitals in urban Bangladesh also highlighted a concerning lack of wastewater treatment facilities, revealing that most hospitals discharge their wastewater directly into the environment without any prior treatment [9, 10]. Wastewater and hazardous liquid waste management in HCFs are critically overlooked during the planning and construction phases [11]. Furthermore, in urban areas of LMICs, the design and construction of treatment system often fail to consider how behavioral, social, and technical components interact within these systems, particularly in the context of HCFs [12-15].

Globally, research on WASH in HCFs is limited, and in LMICs, including Bangladesh, such research has predominantly focused on overall WASH assessments rather than on the functionality and efficacy of specific WASH technologies. Moreover, studies that specifically examine the types and effectiveness of HWW treatment systems in LMICs remain scarce [1, 3, 9, 16-18].

There has been limited academic investigation into the interrelationship between the technical and social and institutional aspects of wastewater management in HCFs. While the water and sanitation for health facility improvement tool (WASH-FIT) provides a comprehensive practical framework for enhancing WASH practices in HCFs [5], it primarily focuses on practical step-by-step guidance for adapting and implementing WASH-FIT in various contexts, such as quality of care, infection prevention and control (IPC), and maternal child health, with the aim of improving the sustainability and climate resilience of WASH services in HCFs. This framework emphasizes enhancing leadership capacity, community engagement, behaviour change communications, training, and sustainable investment to improve WASH in HCFs. However, WASH-FIT has limited focus on the technological aspects of WASH improvement, particularly in enhancing sanitation and wastewater facilities.

There is a significant research gap in understanding the interrelationship between social and institutional factors and liquid waste and wastewater management in HCFs. Despite the importance of these factors, there is a lack of research that comprehensively addresses how they interact with technical aspects of wastewater management. Our literature review found no studies that fully explore these interactions, highlighting a critical need for further investigation in this area. This limitation highlights a missed opportunity for enhancing WASH outcomes through a more holistic approach that integrates both technological solutions and behavioral interventions. Moreover, existing literature on HCF sanitation has largely focused on the microbial efficacy of wastewater treatments [19-22], leaving a significant knowledge gap regarding the underlying reasons for the poor performance of sanitation technologies. Specifically, there is a lack of investigation into the social, cultural, and behavioral dimensions of inadequate sanitation management in HCFs. Addressing this gap is essential for developing more effective and sustainable sanitation solutions that are culturally and contextually appropriate.

The socio-technical systems (STS) theory is an interdisciplinary approach, exploring the interaction between social and technical facets within complex systems. It underscores the interconnectedness of people, technology, and the environment in various organizational or societal contexts [23]. This theory acknowledges the mutual dependence of technology and social structures, highlighting the need to analyze them to attain optimal system functioning. Its primary goal is to comprehend the interactions among social and technical elements within systems, aiming to design policy, and enhance systems while taking into account social, behavioral, and technical considerations [13, 24].

STS theory has been utilized across various disciplines, including information systems, organizational studies, business management, and engineering [25], using a mix of qualitative and quantitative methods alongside socio-technical design approaches. The theory has been applied in multiple contexts and scales [26, 27], from individual work systems within organizations to entire organizations, and even up to macrosocial systems at the societal level, such as industry sectors [28]. While the adoption of STS theory in civil engineering and innovative construction projects is widespread in developed countries [29-31], its implementation in the institutions remains underexplored in LMICs. The application of STS theory in HCFs in LMICs is rare; only one study in Germany, by Heinzel et al. (2024), adopted STS theory to examine water infrastructure as critical HCF infrastructure, with no similar application to wastewater noted. Understanding critical infrastructure as a STS theory can help to evaluate the complex interlinkage among the factors that facilitate or hindering better preparedness [32]. To address critical knowledge gaps in relation to HWW treatment, we adopted STS theory to identify and analyse social and technical aspects of HWW treatment arrangements and management, as well as observations of the functionality of the wastewater treatment processes available in major hospitals within Dhaka City, Bangladesh.

Methods

Study design

Between June and December 2022, we conducted a mixed-methods study in 10 government hospitals and three private hospitals from Dhaka city (Table 1). Government hospitals in Dhaka, are typically managed by the Ministry of Health and Family Welfare (MoHFW), which oversees the planning, implementation, and management of healthcare services. Additionally, the Directorate General of Health Services (DGHS) is a key agency under the MoHFW responsible for the administration, supervision, and coordination of healthcare services at the national level [33]. These hospitals are part of the public healthcare system and offer a range of medical services, with the aim of providing accessible and affordable healthcare to residents. A private hospital is owned and operated by a private entity or organization and regulated by DGHS. Private hospitals always charge patients for their medical services and are not directly funded or managed by the government [34]. We employed three data collection techniques in our study: conducted qualitative research through interviews with key informants, reviewed relevant documents, and performed structured observations of hospital pipe networks, wastewater treatment systems, and drainage systems.

Theoretical basis

We drew on the modified STS theory in this study, specifically the Leavitt Diamond model developed by Sawy (2001), which formed the basis of our framework. This framework suggests a systems view of organizations (i.e., hospitals), represented by a hexagon, which served as the core concept guiding our study (Fig 1). Within the STS perspective, we recognized that organizations are situated within interacting subsystems, each contributing to the overall functioning of the organization [35]. These hexagonal subsystems included:

- Current **cultural norms** influence hospital authorities' and staff perceptions of wastewater treatment priority and practices.
- National **policies and regulations** govern HWW management and discharge.
- **Technologies** employed for HWW management.
- **Leadership and management** procedures guide liquid waste and wastewater treatment.
- Day-to-day **staff (i.e., people)** conduct operation and maintenance activities.
- Broader hospital supporting **infrastructure** aid in managing liquid wastes.

Fig 1. Socio-technical system theory with relevant key indicators.

For qualitative interviews, we adopted the revised guidelines outlined by Appelbaum (1997) [13], which provide a detailed description of each subsystem of the STS framework. Previous studies have utilized this tool to assess the water and sanitation situation and technological assessment in healthcare facilities [32, 36, 37]. The qualitative interviews comprised key informant interviews (KII) with selected stakeholders, including public works department (PWD) engineers, healthcare professionals: hospital cleaners, and ward masters. By combining methods, the investigation team verified and cross-checked the data collected from each approach, resulting in a depth of understanding that a single method might not have achieved [38, 39]. The document analysis involved sourcing published government reports (i.e., Department of Environment and DGHS) on hospital waste and wastewater management, standard and related policies [33, 34, 40-45]

Enrolment of study hospitals

The selection of hospitals for this study was described in a recent hospital-based study [46] in Dhaka. Briefly, we prioritized stakeholder engagement by convening a meeting involving key participants such as DGHS, Dhaka water supply and sewerage authority (WASA), policymakers, and NGOs. We developed criteria for hospital selection, considering factors like construction year, hospital type, size, and geographic location. We chose ten government hospitals purposively, including general, medical college, and specialized hospitals, within both South and North City Corporations in Dhaka. Furthermore, we purposively selected three private medical college hospitals for the comparison with the government hospitals. We integrated stakeholder suggestions to enhance selection criteria and refine data collection tools. Description of hospitals is presented in Table 1.

Table 1. Descriptive statistics of selected hospitals (10 government and three non-government hospitals) in Dhaka, Bangladesh, July-December 2022.

Hospital type and codes	Year established	Hospital type	# of beds	Total toilets
H1	2001	General hospitals	250	132
H2	2012	General hospitals	500	379
H3	1963	Medical college hospitals	850	255
H4	2009	Medical college hospitals	500	430
H5	1972	specialized hospitals	300	43
H6	2018	specialized hospitals	250	194
H7	1978	specialized hospitals	414	318
H8	1982	specialized hospitals	300	203
H9	2012	specialized hospitals	450	183
H10	2013	specialized hospitals	250	177
P1	1986	General hospitals	500	86
P2	1992	General hospitals	500	59
P3	2003	General hospitals	500	Data not collected

"H"-represented the codes for government hospitals.
"P"-represented the codes for private hospital.

Operational definitions

The operational definitions for various variables in HCFs used in this study were based on the WHO-JMP. We extended these definitions to include additional sanitation-related variables relevant to HCFs in Dhaka city, as shown in Table 2. When JMP or WASH-FIT did not provide clear definitions for certain variables, such as liquid waste and functional containment, we created our own operational definitions.

Table 2. Operational definitions used to describe different components of sanitation facilities, wastewater and liquid waste in hospitals in Dhaka, Bangladesh.

Terminology	JMP defined	Definitions used in this study
Safely managed sanitation service	No separate definition for HCFs [47-49] *According to JMP WASH data for sanitation [50]:* Safely managed sanitation in HCFs refers to the use of an improved sanitation facility where excreta is safely disposed of in situ or transported and treated off-site. *Expanded definition from JMP WASH data for Monitoring Safely Managed On-Site Sanitation:* The sanitation facilities should additionally prevent the discharge of wastewater and fecal sludge to the surface environment, and they should ensure that excreta are either treated and disposed of in situ or transported and treated off-site.	*Extended JMP definition:* - the use of an improved sanitation facility where excreta is safely disposed of in situ or transported and treated off-site, prevent the discharge of wastewater and fecal sludge to the surface environment The relevant regulation for Bangladesh obtained from Bangladesh Environmental Conservation Rules 2023 [40] it follows following effluent quality parameters: - Temperature: 30°C - pH: 6.0-9.0 - Biological Oxygen Demand (BOD_5) at 20°C: ≤ 30 mg/L - Chemical Oxygen Demand (COD): ≤ 125 mg/L - Suspended Solids (SS): ≤ 100 mg/L - Oil and Grease: ≤ 10 mg/L - Nitrate (NO_3): ≤ 50 mg/L - Phosphate (PO_4): ≤ 15 mg/L - Total Coliform: ≤ 1000 CFU/100mL - The standards for HWW discharge in Bangladesh as per The Environment Conservation Rules, 2023, are outlined to ensure that effluents do not harm the environment or public health. Here are the key standards: - Human feces are contained within a holding tank/pit in such a way that it is inaccessible for human contact or contact by flies or other animals (rodents, insects) -All wastewater discharge through single or multiple, functional on-site systems including at least primary and secondary treatment processes or conveyance of wastewater to a suitable centralized treatment plant via an appropriately designed piped sewerage network. -For any onsite system, frequency of desludging/emptying are regular, well recorded and hospital staff are able to describe the frequency and process of safely desludging/emptying of ABR
Hospital staff: The term "staff" refers to individuals employed within the healthcare setting, including healthcare		

professionals such as doctors and nurses, administrative personnel, support staff, and/or cleaners [46].

Anaerobic baffled reactor (ABR): An anaerobic baffled reactor (ABR) is a multiple-stage reactor that consists a series of upflow reactors connected by means of baffles that force wastewater to flow under and over them as it passes from the influent to the effluent [51]. For this study, if the tank or sludge reservoir had more than two chambers, we classified it as ABR. ABR is considered as primary treatment system.

Septic tank: A septic tank is a sewage disposal system that consists of a concrete tank with an outlet submerged in the ground or soak pit. For this study, if the tank or sludge reservoir had two chambers, we classified it as septic tank. Septic tank is considered as primary treatment system.

Containment or holding tank: A single-compartment tank designed primarily to hold fecal sludge without undergoing any primary treatment.

Functional ABR or Septic Tank: Functionality is determined through direct observation (if the system is accessible) or through reports from PWD engineers or hospital staff (if the system is concealed beneath a building). A functional ABR or septic tank is identified by having intact lids and a structure free from leaks or breakages.

Piped network/discharge pipes: The system of pipes or channels that transport liquid or semisolid waste from its source within a facility, such as a hospital, to the designated hospital drain or disposal point. These pipes are responsible for conveying wastewater, sewage, or other liquid waste materials for proper disposal or treatment.

Hospital drain: A hospital drain refers to a drainage system used within the hospital premises to manage and dispose of various liquid wastes generated from hospital activities. These drains are part of the hospital's wastewater system and convey water, wastewater and all kinds of liquid waste from toilets, patients' wards, laboratories, operating rooms, and other medical areas.

Functional drain/drainage system: A drainage system in a hospital that consists of concrete channels or pipes lined with cement, equipped with intact and properly sealed covers to prevent leaks and ensure the safe and efficient transport of wastewater and other fluids. The hospital drainage system is usually managed by hospital authorities and the PWD.

Community drain: Refers to a drainage system that serves a larger communal area, often shared by multiple households or buildings within a neighborhood or community. This system is designed to manage and channel away wastewater, stormwater, and other surface runoff from community, institutions, industries, and run-off to prevent flooding and maintain public health and environmental safety. For this study drainage network outside the hospital premise is considered as community drain.

Wastewater: Wastewater is water generated after the use of freshwater, raw water, drinking water or saline water in a variety of deliberate applications or processes [52]. Another definition of wastewater is "Used water from any combination of domestic, industrial, commercial or agricultural activities, surface runoff / storm water, and any sewer inflow or sewer infiltration" [53] In everyday usage, wastewater is commonly a synonym for sewage (also called domestic wastewater or municipal wastewater), which is wastewater that is produced by a community of people.

Hospital wastewater (HWW): Wastewater discharged from the hospital is classified as HWW. WHO has characterized these HWW in following ways: i) *Blackwater (sewage)* contains mainly fecal matter and urine; ii) *Greywater (sullage)* contains residues from washing, bathing, laboratory processes, laundry, and other technical processes such as cooling water or the rinsing of X-ray films, potentially loaded with a genotoxic or cytotoxic agent; iii) *Storm water* contains rainfall collected from roofs, grounds, yards and paved surfaces, water used for irrigating hospital grounds, toilet flushing, and other general washing purposes which may be lost to drains and watercourses and as groundwater recharge [54-56].

Biomedical liquid waste: "Bio-medical liquid waste" means any liquid waste including its container and any intermediate product, which is generated during the diagnosis, treatment or immunization of human beings or animals or in research pertaining thereto or in the production or testing thereof [57].

Hospital hazardous waste: Hospital hazardous waste refers to any solid, liquid, or gaseous waste generated within a hospital setting that possesses inherent risks to human health and the environment due to its composition. This waste category encompasses various materials such as biomedical waste, chemicals, pharmaceuticals, disinfectants, pathological waste, radioactive materials, and other potentially harmful substances.

Hazardous hospital liquid: Hazardous hospital liquid refers to any liquid waste generated within hospital that poses potential risks to human health and the environment due to its composition. This waste may include biological waste, biomedical waste, chemicals, pharmaceuticals, disinfectants, bodily fluids, and other potentially harmful substances.

Chemical liquid waste: This category includes hazardous liquids generated through various medical activities such as laboratory analyses, cleaning, disinfecting procedures, and other medical operations. It may contain harmful substances

like formaldehyde, glutaraldehyde, xylene, toluene, and mercury.
Pharmaceutical liquid waste: This type of waste is produced from activities involving medications and includes expired liquid medications, discarded vaccines and injectables, and partially used or contaminated intravenous (IV) solutions.

Study participants

For the qualitative method, the respondents comprised individuals engaged in policy formulation and strategic planning regarding hospital facility management, staff directly involved with hospital sanitation management, as well as those working within organizations responsible for routine cleaning. Table 3 provides a detailed description of the types, roles, and responsibilities of the respondents selected for the qualitative interviews. In brief, two groups of individuals were interviewed: (1) Engineers from the public works department (PWD), ministry of housing and public works, and (2) hospital staff, including directors, ward master/hospital managers and cleaning staff. PWD engineers were included for the interview due to their close liaison with the MoHFW and their role as coordinators between PWD, the Department of Architecture, and MoHFW [58]. PWD engineers were responsible for tender document preparation, tender invitations, and maintaining liaison with the design division and department of architecture. They ensured timely availability of structural and architectural designs and drawings, major civil works, as well as monitored the progress of hospital projects [58]. A total of seven engineers were responsible for managing selected hospitals, and we conducted interviews with all of them. Hospital directors were included in the interviews to understand the hospital's priorities in managing WASH, the challenges of managing sanitation, and the future direction for improving WASH in HCFs for LMICs. We enrolled one ward master from each hospital to participate in the KII. Ward masters oversee patient care coordination, manage the cleaning staff, handle administrative tasks, facilitate communication, and advocate for patient rights and needs. They play a crucial role in quality assurance, patient safety, and infection control [59]. If there were multiple ward masters in a hospital, we selected the one who had been employed for a longer period in the hospital. We also included ten cleaners (8 from government and two form private hospitals) from the selected hospitals. Cleaners were purposively selected for the interview, and priority was given to those who had been serving the hospital for more than five years. Integrating PWD engineers, ward masters and cleaners allowed us to gather insights from individuals who had direct experience managing the sanitation facilities in the hospital (Table 3).

Table 3. Type, roles, and responsibilities of the respondents for the Key informant interviews (KII) in hospitals in Dhaka city.

Type of respondents	Definition/role	# of interviews	Inclusion criteria	Duty station and hours	Department & ministry
Hospital Directors	In Bangladesh, Hospital Directors are senior healthcare administrators responsible for overseeing the overall operations of a hospital or healthcare facility. They play a crucial role in setting strategic directions, ensuring the delivery of high-quality medical services, managing staff, and overseeing the facility's financial health [60].	13	All included who provided consent for interviews	Hospital premises. Duty hours 6-8 hours (single shift)	Director general of Health service (DGHS), MoH&FW
Engineers (government hospitals)	A PWD (Public Works Department) engineer in a hospital is a professional responsible for close liaison with the MoHFW, acting as a coordinator among the field-level office of PWD, Department of Architecture, and MoHFW. They prepare tender documents and invite tenders for large civil works, including WASH. Additionally, they monitor the physical and financial progress of the projects. [61, 62]	4	All included who provided consent for interviews	Mostly outside of the hospital in a separate office. Duty hours: 9:00 am to 5:00 pm	Public works department (PWD), Ministry of Housing and Public Works
Engineers (Private hospitals)	A civil engineer in a private hospital is recruited by individual hospital, responsible for the planning, design, construction, maintenance, and management of the hospital's physical infrastructure and facilities. Their role encompasses a variety of responsibilities related to the hospital's structural and architectural aspects.	3	All included who provided consent for interviews	Within hospital. Duty hours 9:00 am to 5:00 pm	Not applicable
Ward masters (Government hospital)	A hospital ward master, also known as a ward manager or unit manager in some regions, is a senior administrative and		-Provide consent for interview -If more than one ward master	Hospital premises. Duty hours 8-16 hours	Director general of Health service (DGHS),

Type of respondents	Definition/role	# of interviews	Inclusion criteria	Duty station and hours	Department & ministry
	supervisory healthcare professional responsible for managing a specific ward or unit within a hospital. Six key areas of responsibility likely to define the role of ward managers: general performance/quality issues, people management/HRM, planning and scheduling of work, managing operational costs, dealing with clinical work and communication outside the immediate team [63].	10	present in one hospital priority was given to the senior staff	(2-3 shifts)	MoH&FW
Ward masters (Private hospital)	Same as above	3	All included who provided consent for interviews	Hospital premises. Duty hours 8-16 hours (2-3 shifts)	Not applicable
Cleaner (Government hospital)	A hospital cleaner also called environmental services staff, housekeeping or janitorial services, is an individual employed directly or through subcontracting by external suppliers, tasked with maintaining cleanliness, hygiene, and overall sanitation within a hospital. Typically, cleaners operate under the supervision of a ward master or nurse[64]. "Staff responsible for cleaning" refers to non-health care providers such as cleaners or auxiliary staff, as well as health care providers who, in addition to their clinical and patient care duties, perform cleaning tasks as part of their role [65].	5	-Provide consent for interview -Cleaners serving the hospital for more than five years were prioritized -If more than one ward master present in one hospital priority was given to the senior staff	Hospital premises. Duty hours 8-16 hours (2-3 shifts)	Director general of Health service (DGHS), MoH&FW or subcontracted through another vendor
Cleaner (Private hospital)	Same as above	5	Same as cleaners from government hospitals	Hospital premises. Duty hours 8-16 hours (2-3 shifts)	Direct recruitment or subcontract through another vendor

Data collection

Document review

The purpose of the document review was to understand the current policies related to HWW discharge standards set by the relevant authorities, such as the Department of Environment (DoE) under the Ministry of Environment and the Directorate General of Health Services (DGHS). This review aimed to identify the technologies recommended by the DGHS and DoE for wastewater treatment in healthcare facilities. The review also examined the prioritization of liquid waste management over solid waste management, as highlighted in recently published government reports. Furthermore, it assessed the responsibilities of different authorities, both government and private, in managing overall hospital waste, with a particular focus on liquid waste management. We also reviewed the Bangladesh national building codes published by Housing & Building Research Institute (HBRI) [66, 67]. Lastly, the review included an examination of the WASH-FIT report and recently published WHO reports related to WASH in healthcare facilities and wastewater discharge guidelines to protect the environment (Table S1). This document review provided insights into the regulatory framework, technological recommendations, and management responsibilities crucial for effective HWW management.

Structured observation of the sanitation facilities

Structured observation included an assessment of the sanitation systems which included drainage networks, availability and functionality of onsite wastewater treatment plant/systems, septic tanks, and anaerobic baffled reactors (ABRs) and discharge of HWW (grey and black water). After the selection of hospitals, the fieldworkers employed a structured observational checklist to collect data on specific variables: the presence of onsite wastewater treatment technology such as WWTP, septic tanks and ABRs within the hospital premises.

To appropriately document the sanitation infrastructure, we requested the PWD engineer to share the building design and drainage network maps. In cases where obtaining the map was not feasible, we asked the engineer to collaborate with fieldworkers in drawing the drainage network and wastewater flow directions within the hospital. After gaining a preliminary understanding of the hospital sanitation network, we requested the ward master of each hospital to assign a knowledgeable staff member who could provide insights into the drainage network and overall sanitation facilities of the hospital. Volunteers from the hospitals (i.e., cleaners or ward boy) and two data collectors (including NA) conducted transect walks to develop illustrated maps for each hospital. These maps indicated the starting point of drains, the direction of wastewater flow, types and availability of wastewater treatment plants, the number of functional septic tanks and ABRs, and the point of discharge (such as a community drain or a surface water body) after leaving the hospital (Fig 1). During the transect walks, the fieldworkers assessed the type of wastewater discharged (i.e., all treated, partially treated or untreated) from the hospital to the community. The fieldworkers recorded detailed notes on key elements of sanitation infrastructure during these walks and took photos to document the status of the sanitation systems. After completing the walks, the team collaborated with the ward master and volunteer to provide them with large sheets of paper and colored pens, which they used to create maps illustrating the hospital's sanitation network [68].

Key Informant Interviews

We used structured interview guidelines for each group of respondents to conduct the interviews (see supplemental information). The data collection team, consisting of two female and one male qualitative researcher (NA). We conducted the interviews in the participants' native language, Bengali. The interviewers, who were also native speakers, used interview guides to facilitate the conversations. Participants were informed about their privacy and the protection of their personal information, and we obtained their informed written consent for the research. The interviews took place in various locations depending on the availability of venues and the participants' preferences. For example, interviews with PWD engineers were conducted in their offices (outside the hospital premises), interviews with cleaners took place in empty patient rooms, and ward masters were interviewed in empty staff rooms. The interviews lasted between 20 and 55 minutes, with all discussions being audio-recorded with the participants' consent. The KII guidelines were tailored individually for various respondents according to their roles and responsibilities within HCFs.

Using structured interview guides, interviewers asked open-ended questions to allow participants the flexibility to share their thoughts on the topic areas. The research team discussed potential prompts for each key area during the preparation phase. The KII guidelines were pilot tested, refined, and organized into structured sub-themes to enhance clarity and ensure consistency.

Data analysis and management

Three trained native Bengali speakers (NA and two research assistants) experienced in qualitative research collected all the data from hospitals staff and caregivers. The audio recordings of in-depth interviews were transcribed verbatim in Bengali and then translated into English using Microsoft Word. The translated transcripts retained the original tone of the interviews by including transliterations of local terms and expressions. Codes were created based on six STS theory themes (Fig 1), and the research team regularly met during transcription and translation to familiarize themselves with the data. Additional inductive codes were generated from the data. All interview transcripts were manually coded and categorized according to these codes using Microsoft Excel.

We employed the STS framework to analyze data within six main thematic areas stated above. Although similar questions were asked during the interviews, our qualitative data analysis prioritized the expertise of respondents on relevant sub-themes. For instance, in key informant interviews (KIIs) with hospital directors, we extracted quotes related to the norms and priorities of liquid treatment over patient management. For engineers, we prioritized presenting insights pertaining to the technological aspects of wastewater treatment, including functionality and efficacy. In interviews with ward masters, our focus was on insights relevant to the operation and maintenance of hospital sanitation networks, coordination between engineers and hospital authorities, and individuals involved in managing liquid waste. Similarly, for cleaners, we prioritized aspects regarding their knowledge of liquid waste generated from hospitals and the health risks associated with managing hospital liquid waste. For reporting, both qualitative (i.e., KII) and quantitative (infrastructure assessment) results were integrated within the STS framework. Specifically, the infrastructure assessment data was aligned with the "technology" subsystem of the result section.

Quality assurance

Before the study, research assistants underwent rigorous training and participated in a pre-test session. They were then paired for data collection and continuously assessed. These assistants were fluent in English and Bengali, the primary local language, and had experience working in urban poor settings. To ensure the completeness and correctness of the data, weekly meetings were held with the team after conducting a few interviews, and the data summary were shared with the supervisors (JW and TF). The research team gathered to review the interview activities, ensuring the data was cleaned and verified before storing and processing it. They used both manual and electronic backups for safety.

Ethical considerations

We followed a systematic approach to ensure the rights and confidentiality of all participants and institutions. Firstly, we secured written informed consent from all individuals participating in the study. Additionally, we obtained written approvals from the DGHS and formal written approvals from the hospital directors to conduct interviews with the ward masters and cleaners. An introductory letter, provided by the lead author (NA), was presented to all hospital directors. This letter outlined the purpose of the study and clarified aspects of confidentiality, voluntary participation, anonymity, and the right to withdraw from the study. Participants were assured that they could withdraw from the study at any point if they felt uncomfortable. Moreover, to safeguard confidentiality, no participant identifiers were recorded. The importance of confidentiality was strongly emphasized during the training of research assistants before data collection. To further protect the identities of both the respondents and hospitals, we assigned unique hospital codes (government hospital codes: H1 to H10, and private hospital codes: P1 to P3) instead of using the actual hospital names. Finally, the study protocol was thoroughly reviewed and approved by the Ethical Review Committee at icddr,b in Dhaka, Bangladesh, as well as the Human Research Ethics Committee at the University of Technology Sydney in Australia.

Results

A total of 30 interviews were conducted, encompassing individual interviews held in thirteen hospitals in Dhaka city. These participants comprised seven engineers, 10 cleaners, and 13 ward masters. Among the 30 respondents, nine recruited from private hospitals, while 21 were selected from the government hospitals. A summary of the results is provided following the STS theory framework in Table S2.

Current cultural norms among hospital authorities and staff about wastewater treatment priority and practices

Hospital leadership authorities placed wastewater treatment as a low priority. All the hospital directors were aware of and specifically highlighted that untreated HWW and infectious liquids pose a significant threat to the environment and water bodies if not properly treated. When asked about their priorities concerning hospital fecal sludge and liquid waste management, most (9 out of 12) directors noted that their primary focus is on patient care, maintaining essential equipment, and ensuring the safety of both staff and patients. One director emphasized, *"Hospitals are faced with numerous administrative challenges daily, often constrained by limited resources. Recently, we acquired expensive (medical) equipment, but due to inadequate space, installation has become an issue. If not resolved promptly, these machines may malfunction."* Another director highlighted, *"Our top priorities are patient treatment and recovery from diseases. Instances of patient death due to medical negligence gain national-level media attention. However, wastewater treatment doesn't receive the same level of priority from both media coverage and the hospital authority." (Director, H1)*

Hospital staff, particularly cleaners and ward masters, had a very limited or no understanding of the types of hospital liquid waste generated, how it is discharged from the hospital to the community, and how it is treated. Among the 23 staff members (ward masters and cleaners) interviewed, none could describe how biomedical liquid waste is managed in the hospital. Similarly, among the seven PWD engineers, nearly all stated that managing biomedical waste is not their responsibility; they are primarily tasked with treating HWW and fecal sludge.

We found that, discharging wastewater/liquid waste without proper treatment is common in hospitals in Dhaka city. This practice is also acceptable among hospital managers (ward masters) and cleaners because lack of knowledge on health and environmental impacts of HWW. Most ward masters (11 out of 13) lacked awareness about the discharge details, such as the type, volume, and pathways of liquid waste from their own hospital. One ward master stated, *"I am not sure how the liquid waste flows from the hospital to the environment, but we have a good treatment system (i.e., septic tank) with the capacity to treat all liquid waste." (Ward master, H5)* The same ward master also mentioned that the septic tanks have not been emptied for the last five years.

It is a common practice for cleaners to clean drains and septic tanks without any personal protective equipment (PPE). Although most of the cleaners (8 out of 13) acknowledge that HWW contains harmful chemicals, they do not perceive it as a potential cause of diseases while cleaning. One cleaner stated, *"I regularly clean the septic tank when it is clogged; I never use any PPE, and I am doing well." (Cleaner, H4)*

National policies and regulations on HWW management and discharge

The current national policies and regulations on HHW management and discharge in Bangladesh reveal significant gaps, indicating a lack of focus or priority on liquid waste management in healthcare facilities within existing policies. The Ministry of Health and Family Welfare (MoHFW) appears to prioritize solid waste management over liquid waste management in healthcare facilities. The National Strategy for WASH in Healthcare Facilities 2019-2023 emphasizes solid waste management but lacks guidance on liquid waste discharge and management. According to the report, solid waste management falls under the responsibility of City Corporations in Bangladesh, while PRISM, a prominent NGO in Dhaka city, manages hospital solid waste for a nominal fee [41]. The Health Services Division (HSD) of MoHFW published an environmental management plan for emergency response (i.e., COVID-19 pandemic) in 2022. However, this plan primarily focuses on guidelines for handling and disposing of hospital clinical wastes (e.g., body fluids, antibiotics, and chemicals) and does not address overall liquid waste discharge, including effluent from sanitation systems [42]. In contrast, the Department of Environment (DoE) Dhaka's 2015 report on Bangladesh standards and guidelines for sludge management classifies liquid wastes from medical care facilities as highly hazardous [43]. Despite this classification of liquid waste, the recent MoHFW guidelines did not provide clear instructions on how different types of liquid waste should be managed or the standards they should meet before being discharged into the environment or community drainage systems [41, 42]. These disparities highlight a lack of focus or priority on liquid waste management in healthcare facilities within the existing policies. There is a need for a more comprehensive and integrated approach to address liquid waste management in HCFs.

Technologies used to treat HWW

Our findings include both those from structured observation as well as exploration of staff understanding of these technologies, with key findings that the infrastructure was generally inadequate and staff knowledge and awareness low.

Among the 13 hospitals surveyed, 10 had some form of wastewater treatment system, while the remaining three lacked any treatment infrastructure. Among those with treatment systems, seven utilized ABRs, and three had septic tanks to treat HWW. In one private hospital (P3), the biological waste (such as body fluids) produced during procedures was collected separately and treated using a physico-chemical effluent treatment plant. The chemicals used in the treatment included alum, hypochlorite, and polymer. Among the hospitals with ABRs, varying degrees of structural integrity were observed: one had all compartments broken, another had all four compartments damaged, while the rest had physically intact compartments with lids and no visibly broken walls. In the case of the three hospitals with septic tanks, two had four intact tanks, while the other had eight out of nine tanks in good condition. Among the government hospitals, only four had fully intact ABR compartments, while the remaining hospitals showed varying levels of disrepair or lacked treatment systems altogether. In contrast, among the private hospitals, two had intact ABR or septic tank compartments, while one lacked any treatment system. Only one hospital discharged its wastewater/effluent into surface water adjacent to the hospital premises, while the remaining hospitals (n=12) discharged into neighboring drains, ultimately flowing into surface water bodies or reaching the municipal sewage lifting station (Table 4)

Table 4. Observation of wastewater treatment systems in government and private hospitals in Dhaka, Bangladesh, 2022.

Hospitals	Treatment present (YES/NO)	Type of treatment	Number of containment compartments (both broken and functional)	Number of containments able to observe	Number of physically intact containments†	Proportion of wastewater passing through treatment**	Discharge location
General hospitals							
H1	Yes	*ABR	4	4	0	None	Community drain
H2	Yes	ABR	4	3	4	All	Surface water
Medical college hospitals							
H3	Yes	Septic tanks	9	3	8 (reported by staff)	Partially	Community drain
H4	Yes	ABR	4	4	1	Partially	Community drain
Specialized hospitals							
H5	Yes	ABR	1	1	1	Partially	Community drain
H6	Yes	ABR	2	2	2	All	Community drain
H7	No	-	0	NA	NA	NA	Community drain
H8	No	-	0	NA	NA	NA	Community drain
H9	Yes	ABR	2	2	2	All	Community drain
H10	Yes	ABR	1	1	1	All	Community drain
Private hospitals							
P1	No	-	0	NA	NA	NA	Community drain
P2	Yes	Septic tank	4	4	4	All	Community drain
P3††	Yes	Septic tank	4	4	4	All	Community drain

*ABR= anaerobic baffled reactors

†Containments were considered to be physically intact if they had a lid and/or no broken walls

‡Wastewater and fecal sludge directly discharged to the environment

§Any type of pipes (sewage or wastewater) exits from the hospital building

NA-Not applicable

**They categorized wastewater discharges as fully treated (when all effluent passed through a treatment process), partially treated (when some wastewater underwent treatment while the rest bypassed containment), or untreated (when no treatment was in place or when all containment structures were damaged).

††In hospital P3, the biological waste (such as body fluids) produced during procedures was collected separately and treated using a physico-chemical effluent treatment plant. The chemicals used in the treatment included alum, hypochlorite, and polymer.

Our KII revealed that PWD engineers, ward masters, and cleaners had a clear understanding of the availability of on-site HWW treatment options, such as primary systems like septic tanks, ABR, or advanced systems like sewage treatment plants (STP). However, ward masters and cleaners demonstrated limited understanding regarding the functionality of the treatment system within their respective hospitals. In our study, we found that all engineers (N=5) working in government hospitals highlighted the absence of advanced on-site wastewater treatment options, such as full-scale STP, within these facilities. Specifically, one engineer from a government hospital (H8) underscored this concern, stating, "*Our hospital had a number of septic tanks to treat the sludge but there are no advanced wastewater treatment options like (full-scale) STP in these (government) hospitals* " (Engineer, H6 and H8). Two out of three engineers from private hospitals also indicated the absence of advanced wastewater treatment options within their hospital premises. Specifically, one engineer from a private hospital (P1) highlighted this, mentioning that "*We do not have any full-scale STP or any septic tank in this hospital. So, we are directly connecting and disposing of it (sludge and liquid waste) to the WASA's (municipal) sewage line without any treatment" (Engineer, P1).* Most ward masters and cleaners provided similar information regarding the availability of wastewater treatment systems in the selected hospitals.

Most of the engineers (five out of seven) were not aware of the microbial efficacy of the treatment system used in the hospitals. When asked about the performance of the septic tank, the engineer at a specialized hospital (H5) mentioned that the septic tank is operating well, and he is satisfied with its efficacy. When questioned about how he tested the efficacy of the wastewater treatment system and whether there is any periodic testing done to assess the effluent quality before discharging, the engineer responded that there was no facility to test the samples in the laboratory. The engineer also acknowledged that, to assess the efficacy of the treatment plant, they need to test the effluent in the laboratory for pathogen removal. "*The septic tank here is operating well. However, if the water is tested, it is possible to know its results like the amount of water it can purify or the amount it cannot"* (Engineer, H5).

Leadership and management procedure for liquid waste and wastewater treatment

The management of HWW is complex and often faced prolonged delays in repair and maintenance, primarily due to staff shortages within the PWD, which necessitates the hiring of workers from local community vendors, and adherence to time-consuming government public procurement procedures for the purchase of major equipment or construction materials. The MoHFW is responsible for managing the overall WASH in HCFs [69]. Many hospitals in Bangladesh have dedicated WASH committees comprising healthcare professionals, administrators, and support staff. These committees are responsible for planning, implementing, and monitoring WASH activities in HCFs.

The PWD operates under the Ministry of Housing and Public Works in Bangladesh. It is tasked with constructing buildings and structures for various government organizations and agencies. The department is responsible for the design, construction, and maintenance of key structures within HCFs across the country. PWD plays an active role in providing fundamental infrastructure for appropriate fecal sludge and liquid waste management in public hospitals [70]. Additionally, PWD is responsible for the installation and management of wastewater treatment systems within hospitals. Each government hospital has an assigned engineer from the PWD health wing, supported by one or more assistant engineers. In some hospitals, these engineers have dedicated offices on the premises; in others, they operate from nearby departmental offices. When major repairs and maintenance of the sanitation system are needed (e.g., desludging, repair of ABRs), the hospital authority or ward master submits a request to the local PWD office. This request is then forwarded to the PWD head office, which is located further away. The head office directs the local PWD office on how to address the issue and allocates the necessary resources. Sometimes, due to staffing shortages, the PWD may need to hire workers from local community vendors, which can add to the delay. Additionally, the purchase of major equipment or construction materials requires adherence to government public procurement procedures, which are time-consuming. Consequently, this often results in prolonged delays in repairs or desludging.

In private hospitals, engineers are recruited directly by the hospital authorities and have dedicated offices within the hospital. They coordinate closely with the ward masters for any necessary repairs and maintenance. When repairs and maintenance of the sanitation system are needed, the engineer and hospital authority assess the situation together and then request resources from the hospital director. Once approved by the director, they engage a vendor to carry out the work. This streamlined process requires less time, enabling a quick response to any emergency management needs of the sanitation system.

Our results suggest that the MoHFW and PWD must collaborate to ensure the safely managed of sanitation in HCFs. Through our qualitative interviews, we identified critical communication and coordination gaps between PWD engineers and hospital authorities, which caused delays in the repair and maintenance, as well as in the pit emptying of the sanitation system. Many ward masters (7 out of 10) pointed out that delays in tank emptying or the repair of major structures were attributed to the delayed response from the PWD office. One of the ward-masters from hospital H5 stated, "*Whenever there was any breakage or overflow of the septic tank, we immediately informed the PWD office. We hardly get an* *immediate response from the PWD office, and it took a long time to resolve the issue. Sometimes it took several months.*"

Conversely, three PWD engineers held differing views to the hospital ward masters, and they stated that PWD have sufficient staff to manage the sanitation system in their assigned hospitals. They claimed that the hospital authority did not maintain the sanitation facilities after constructed, which is under their responsibility. One Engineer from hospital H5 stated, *"There are sufficient PWD staff for repair and maintenance of the hospital sanitation system. As a result, we can respond to every issue very quickly. Let's say if water is overflowing from the septic tank and we are informed by the hospital authority, we provided a prompt response. But quick response is not always possible due to multiple engagement of the staff. Suppose if they (hospital authority) inform us about the need for septic tank cleaning today but our team is busy with other tasks, we won't be able to clean the tank until tomorrow in that case (Hospital H5, Eng.)."*

However, four PWD engineers agreed that they have a shortage of manpower and due to the lack of manpower, the services were delayed. One engineer from government hospital stated *"The manpower shortage is caused because of a recent policy change by the ministry. We cannot keep permanent workers anymore (for repair and maintenance of the hospital), we have to outsource the workers from other organizations. We have some gaps outsourcing people currently and this requiring time*" (Engineer, H7).

Day to day staff operation and maintenance activities

The study revealed notable disparities in the management of septic tanks and ABRs between government and private hospitals. In private hospitals, day-to-day operations and maintenance were relatively straightforward and managed by their own staff. In contrast, government hospitals faced a more complex process that primarily depends on PWD office staff for regular wastewater fecal sludge management. In government hospitals, the emptying of septic tanks, major repair and maintenance was performed by the PWD staff. One ward master from a government hospital (H10) stated, *"Septic tank is cleaned jointly by the city corporation staff and our (PWD) staff when the tanks need to be cleaned. Usually, if there is any issue with the septic tank in the hospital, our hospital (cleaning) staff tried to fix it (tank). If we fail to fix the problem, we call PWD staff."*

Another ward master from a government hospital also stated, "*If there is any need for minor repair and maintenance of the sanitation system, we manage them with our own staff. For example, cleaning drains is our regular task to maintain the flow of the water. If any sewage pipes are clogged, we call the sweeper (local sanitation worker/pit emptier), and he fixes the problem. But for septic tank emptying or major repair and maintenance, we have to call the PWD engineers. This is not our responsibility." (Ward master, H2)*

In private hospitals septic tanks and sludge was managed by the hospital staff with the help of their own engineers. The engineer of a private hospital (P2) stated *"There are three sweepers and a number of cleaners in this hospital. We have a machine (pump/suction) that cleans/remove all waste thoroughly, even pads or solids. We manage everything (sanitation system) by our own."*

Broader hospital supporting infrastructure to manage liquid wastes

The hospital buildings had complex designs, and many of them were outdated. The regulations for hospital building structures in Bangladesh have their origins in the rules established during British colonial rule. Various urban planning and construction regulations were introduced during this time, one of which was the Building Construction Act, originally formulated in 1952 [66]. Key aspects of these building regulations include guidelines on Floor Area Ratio, Maximum Ground Coverage, land use policy, and other construction standards to ensure safety and environmental sustainability [67]. However, there are no specific instructions regarding hospital liquid waste discharge and its management. Many hospitals still operate with major treatment services in buildings constructed during the British era, underscoring the need for updated infrastructure to meet modern healthcare demands.

The pipe networks and discharge mechanism of liquid waste, including wastewater discharge, was difficult to understand, since they were often hidden from sight. Almost all healthcare workers (ward masters and cleaners) stated that they do not have any idea about the pipe network, discharge mechanism or pathways of liquid waste from the hospital to the environment. Although, all engineers we interviewed were able to explain the pathways of wastewater generated from toilets, they were less clear on the details of how and where body fluid, chemicals and other liquid wastes were discharged. One of the engineers from a government hospital stated, "*our hospitals had two separate lines (i.e., pipes/channels) for greywater and blackwater discharge, but I am not sure where the medical liquid waste discharged or how is it generated (Engineer, H1)*."

The building structure and component infrastructure were identified as one of the critical factors for effectively treating HWW, as stated by the PWD engineers. Three out of seven engineers mentioned that buildings with old structures faced serious challenges in managing wastewater because the pipes and drainage networks were prone to breaking. Due to the narrow pipes in the old buildings, the pipe networks (including both internal and external pipes) often become clogged, leading to liquid waste overflow into the environment. Additionally, the number of patients has increased significantly over the last two decades, but the old hospital buildings were not modified to accommodate the increased patient load and associated wastewater flows.

Discussion

This study provided a crucial understanding of the interplay between social and technical factors influencing HWW treatment technology and management practices. This approach integrated complex relationships among human behaviors, institutional frameworks, and technological infrastructure within healthcare facilities in LMICs. Using STS theory, we identified seven critical gaps hindering safe and sustainable wastewater management in major hospitals in Dhaka: 1) lack of prioritization for healthcare wastewater and fecal sludge management; 2) insufficient policy and regulatory frameworks with ineffective implementation; 3) inadequate awareness and training programs on liquid waste management; 4) inappropriate sanitation infrastructure and wastewater treatment technology; 5) weak coordination and communication between healthcare professionals and PWD personnel; 6) limited manpower and resource allocation for wastewater management activities; and 7) limited understanding of health and environmental impacts from untreated wastewater discharge.

We found that only a few hospitals in Dhaka possessed basic facilities for treating highly hazardous wastewater. While some hospitals had septic tanks or ABRs for effluent treatment, most of these systems were broken, resulting in the direct release of untreated wastewater into the environment. This study is aligned with a recent study conducted in large hospitals in Dhaka city during COVID-19 pandemic [9]. Another study conducted in similar settings assessed the treatment efficacy of HWW and found high concentration of organic pollutants and microbial contamination in the effluent which raised concerns regarding environmental contamination [18]. Although recent WHO report suggested that achieving the SDG target 6.2 in HCFs requires at least secondary treatment options for HWW [71], academic literature suggests that secondary technologies like septic tanks or ABRs are inadequate for the complex composition of HWW [15]. These and other authors highlight the need for full-scale, multi-stage advanced treatment technologies to effectively remove fecal pathogens, chemicals, drug residues, and laboratory reagents. Further research is essential to investigate and identify technologies that can supplement existing treatment processes in LMICs [3].

Our results indicated a lack of understanding among PWD engineers regarding liquid waste discharge. PWD engineers were mostly responsible for managing fecal sludge management and only aware of sewage and black water discharge from toilets to primary treatment. Most of them were not aware of the discharge path of different liquid waste from hospital. Effective HWW and liquid water treatment in LMICs depends not only on treatment technologies but also on infrastructure, such as the building's drainage network, and how wastewater is discharged from toilets to the treatment facilities. Understanding the types of liquid waste (black water, body fluids, laboratory reagents/chemicals, drugs, antibiotics, grey water) produced, their discharge routes, and mixing mechanism is crucial [57]. Without proper source segregation of liquid waste, achieving appropriate wastewater treatment efficacy is challenging [3, 15]. If the sources of liquid discharge are not separated, large volumes of grey water contribute to high volumes of combined wastewater in the system and may increase the cost of wastewater treatment due to the increased volume (Rousso et al., 2024). From our search, we did not find any published articles about the source segregation of liquid waste for HCFs. Further research is needed to understand waste types and volumes generated from hospitals and cost-effective management. Studies on source segregation can provide valuable insights into improving wastewater treatment efficacy and reducing treatment costs.

A key gap identified in this study was the low prioritization of wastewater and fecal sludge management by hospital staff, especially ward masters and cleaners, who did not see it as part of their regular duties. Hospital staff were primarily occupied with administrative tasks, including patient management, leaving them little time to improve WASH in HCFs, particularly in the areas of wastewater and liquid waste management. Studies have found that healthcare professionals are resistant to accepting new roles and responsibilities [72], especially those related to non-clinical tasks [73]. Unlike solid medical waste, liquid waste is not visible to healthcare professionals as it is discharged outside the hospital and does not interfere with their daily clinical care. Improving the knowledge and awareness among health professionals, including the leadership team, policymakers, community WASH practitioners, and relevant ministries (e.g., Ministry of Environment), about hospital liquid waste management through is critical for enhancing safely managed sanitation in large hospitals in Bangladesh [73].

Another critical challenge highlighted in our study for managing HWW was the poor coordination and lack of role clarification related to wastewater management between healthcare professionals (i.e., ward masters) and PWD engineers. Hospital staff, including ward masters and cleaners, frequently reported that the lack of coordination and support from PWD engineers led to delays in repairing and maintaining sanitation systems. These delays in septic tank emptying resulted in the overflow of sludge from the septic tanks, causing severe environmental contamination. Conversely, several PWD engineers reported that hospital staff can manage the sanitation facility and perform minor repairs and maintenance of the sanitation system. Staff shortages at the PWD office and hospital were a common issue, further hindering quick responses to sanitation management needs in hospitals. Hospital cleaners had a lack of understanding about the periodic monitoring and emptying schedule of septic tanks in hospitals. Most septic tanks and ABRs were only emptied when they required repair or became overfilled. To address these issues, it is imperative to enhance the capacity of the PWD and develop a clear strategy to improve coordination between the PWD and hospital authorities for effective and safe sanitation services management.

This was the first study to utilize STS theory to comprehensively assess the social and technical dimensions of HWW treatment technology and management strategies, specifically in major hospitals in Dhaka, a densely populated city in a LMIC. While STS theory has been applied in various disciplines [25], its use in constructing, designing, and managing critical infrastructure in institutional buildings, especially in LMICs, remains underexplored. Our search revealed only one study using STS theory to examine water infrastructure as critical hospital infrastructure, with no similar applications to wastewater management identified. This study emphasized that understanding critical infrastructure through STS can help assess complex interlinkages between factors that enable or hinder better preparedness [32]. Furthermore, many community-based studies have used STS theory for planning and managing centralized wastewater treatment technologies [74, 75], concluding that incorporating STS can improve wastewater management adaptation and efficiency [74, 76]. Our study suggests that integrating STS theory with existing sanitation improvement plans (e.g., designing internal sewage networks and wastewater treatment technologies) in HCFs is critical for achieving safely managed sanitation services. Deeper behavioral changes among health professionals, PWD sanitation engineers, policymakers, and users, especially in their motivation to take responsibility for HWW, are essential. Leadership and the adaptation of STS theory are necessary for meaningful changes in HCFs.

Although the MoHFW developed a National Strategy for WASH in HCFs from 2019 to 2023 to enhance the comprehensive Quality of Care (QoC), the implementation of this policy by healthcare authorities is infrequent [41]. WASH FIT is a risk management tool for HCFs at various levels, and it offers a framework to devise, track, and implement continuous infrastructure improvements and prioritize WASH actions [5]. While many governments in LMIC have adopted the WASH FIT tool for assessing WASH in HCFs [77, 78], there is limited evidence of its utilization in Bangladeshi HCFs, except for those in Rohingya camps in Cox's Bazar [79]. Healthcare professionals in Bangladesh should prioritize learning about this tool and integrating it into their daily practice to assess and quantify the gaps in achieving safely managed sanitation services. Government leadership is crucial for ensuring long-term success through regular financing, technical support, and mentorship. This government support encourages partners to use a unified approach to training, assessment, technical design, behavior change, and data sharing [5].

Our study revealed that most hospitals in Dhaka faced limited human resources to manage sanitation services. Additionally, large hospitals in the country exhibit an excessively high patient-to-doctor and patient-to-nurse ratio [4, 80]. Moreover, in LMICs like Bangladesh, the management of WASH and environmental cleaning within HCFs is typically overseen by a WASH committee comprised of existing hospital staff, including administrators (e.g., directors), healthcare professionals (e.g., doctors and nurses), and support staff (e.g., cleaners, ward attendants) [81]. A recent study conducted across 14 LMICs hospitals found that only 39% of hospitals had an active WASH committee, and they rarely manage time to meet to discuss on WASH related issues in hospital. Given these challenges, expecting the hospital WASH committee to effectively manage HWW may be unrealistic. Strengthening policies on liquid waste management at healthcare facilities is crucial, but equally important is the establishment of a dedicated sanitation workforce and their training on the health and environmental impacts of untreated wastewater discharge, both within hospitals and at the community level [15].

The management of HWW differs significantly between government and private hospitals. Private hospitals tend to maintain their infrastructure better, largely because they can make quick decisions and implement solutions without the delays that typically accompany government procurement processes. In private hospitals, decision-making is streamlined, allowing hospital directors, in consultation with on-site engineers, to quickly allocate funds and approve procurement. Simpler procurement policies and the presence of engineers on-site enable faster responses to emergencies and more effective maintenance of wastewater systems. However, government hospitals operate within a more bureaucratic framework overseen by the MoHFW and the PWD. While each government hospital has an assigned PWD engineer, these engineers may not always be on-site, instead working from local or regional offices, which leads to slower communication and response times. The process for repairs and maintenance often involves multiple steps, from submitting a request to obtaining approval and resources from the PWD's head office. Additionally, the procurement of materials and the hiring of workers must follow strict public procurement procedures, causing further delays. To improve wastewater management in government hospitals, reforms are needed to streamline decision-making processes, decentralize certain powers, and revise procurement policies to allow quicker responses to maintenance and repair needs [5, 15].

Although our study has many strengths, incorporating robust methodology and collecting information from diverse groups of people, as well as observational data under the framework of the STS theory, it also has some limitations. First, we did not include interviews with stakeholders from other relevant ministries, such as the Ministry of Environment (MoE). Insights from the MoE could have provided a broader perspective on regulatory compliance and the environmental impact of HWW discharge. Second, we did not examine the details of financing mechanisms behind managing sanitation systems in hospitals. Understanding how budgets are allocated for sanitation management in both government and private hospitals would have given us a clearer picture of resource distribution and funding-related delays in maintenance and operations. Lastly, our interviews focused on hospital cleaners responsible for maintaining the interior of the hospitals. While these staff members play a crucial role in ensuring hospital hygiene, we did not engage with sanitation workers from the PWD or local community vendors who are directly involved in repairing and desludging septic tanks or ABRs [82]. This gap in our interviews might have led us to overlook critical insights into the operational challenges and logistical issues involved in managing external sanitation facilities. Future studies should aim to address these limitations by including a broader range of stakeholders, examining financing mechanisms in more detail, and engaging with those responsible for the external management of hospital sanitation systems.

Conclusion and recommendations

In conclusion, our study underscores the critical challenges of wastewater and liquid waste management in hospitals in Dhaka city, Bangladesh, and potentially in similar contexts across LMICs. We observed a lack of adequate wastewater treatment facilities in most hospitals, with the available systems inappropriate for this type of wastewater, and many existing systems in disrepair, leading to hazardous liquid waste being discharged directly into the environment. This situation may be exacerbated by use of primary treatment technologies only, inadequate knowledge and practice of wastewater management, and inappropriate infrastructure and maintenance.

Management of wastewater in hospitals encompasses interconnected social and technical components. In this paper the STS approach served to emphasize the importance of the social and behavioural aspects within these critical infrastructure systems, including deficit in prioritisation, knowledge and attitudes to attending to this aspect of hospital management. This STS approach is particularly valuable for planning potential strategies to improve the current failure of wastewater technologies in this context.

Current HWW treatment technologies, such as septic tanks and ABRs, are insufficient for managing complex healthcare wastewater, necessitating advanced treatment solutions and improved staff training. Effective wastewater management requires collaboration between healthcare authorities, PWDs, hospital staff and city authority, along with future infrastructure designs that include segregated piped networks and on-site treatment facilities. To address these challenges, government leadership is crucial, with support required for financing, technical assistance, and capacity building. Addressing these issues comprehensively will lead to safer and more sustainable wastewater management practices in HCFs, ultimately benefiting both public health and the environment.

Supporting information

S1 File. S1 Table and S1 Fig.

(DOCX)

Acknowledgement

We would like to convey our gratitude to the Directorate General of Health Services (DGHS) under Bangladesh's Ministry of Health and Family Welfare (MoHFW) for providing approval and necessary support to conduct the research. We acknowledged the Director, Hospital and Clinic Sections, DGHS, for his strong leadership and continuous support during data collection. We are also thankful to the Directors, doctors, and support staff of all selected hospitals for their permission and support data collection, interviewing, and effective implementation at the facility. We are also indebted to icddr,b fieldworkers who contributed immensely to conducting field activities to make this study successful. icddr,b is grateful to the governments of Bangladesh and Canada, for providing core/unrestricted support.

CRediT Authorship contribution statement

Conceptualization: Nuhu Amin, Tim Foster, Supriya Sarkar, Shaikh Daud Adnan, Aninda Rahman, Mahbubur Rahman, Juliet Willetts.

Data curation: Nuhu Amin, Nafea Tabassum Shimki, Rizwana Khan.

Formal analysis: Nuhu Amin.

Funding acquisition: Nuhu Amin, Tim Foster, Juliet Willetts.

Investigation: Nuhu Amin, Tim Foster.

Methodology: Nuhu Amin, Tim Foster, Nafeya Tabassum Shimki, Aninda Rahman, Mahbubur Rahman, Juliet Willetts.

Project administration: Md Rezaul Hasan, Mahbubur Rahman.

Resources: Md Rezaul Hasan, Supriya Sarkar, Shaikh Daud Adnan, Juliet Willetts.

Supervision: Tim Foster, Shaikh Daud Adnan, Mahbubur Rahman, Juliet Willetts.

Validation: Nuhu Amin, Nafea Tabassum Shimki, Md Rezaul Hasan, Supriya Sarkar, Shaikh Daud Adnan, Aninda Rahman, Rizwana Khan, Juliet Willetts.

Visualization: Nuhu Amin.

Writing – original draft: Nuhu Amin.

Writing – review & editing: Tim Foster, Nafeya Tabassum Shimki, Md Rezaul Hasan, Supriya Sarkar, Shaikh Daud Adnan, Aninda Rahman, Rizwana Khan, Mahbubur Rahman, Juliet Willetts.

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Supporting information captions

Table S1: List of documents reviewed

Table S1: Summary of KII based on the STS components

Fig S1: Mapping drainage network in Hospitals in Dhaka city