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Water management practices and antibiotic-resistant *Pseudomonas aeruginosa* contamination in Ethiopian tertiary hospitals: implications for waterborne healthcare-associated infections

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ABSTRACT

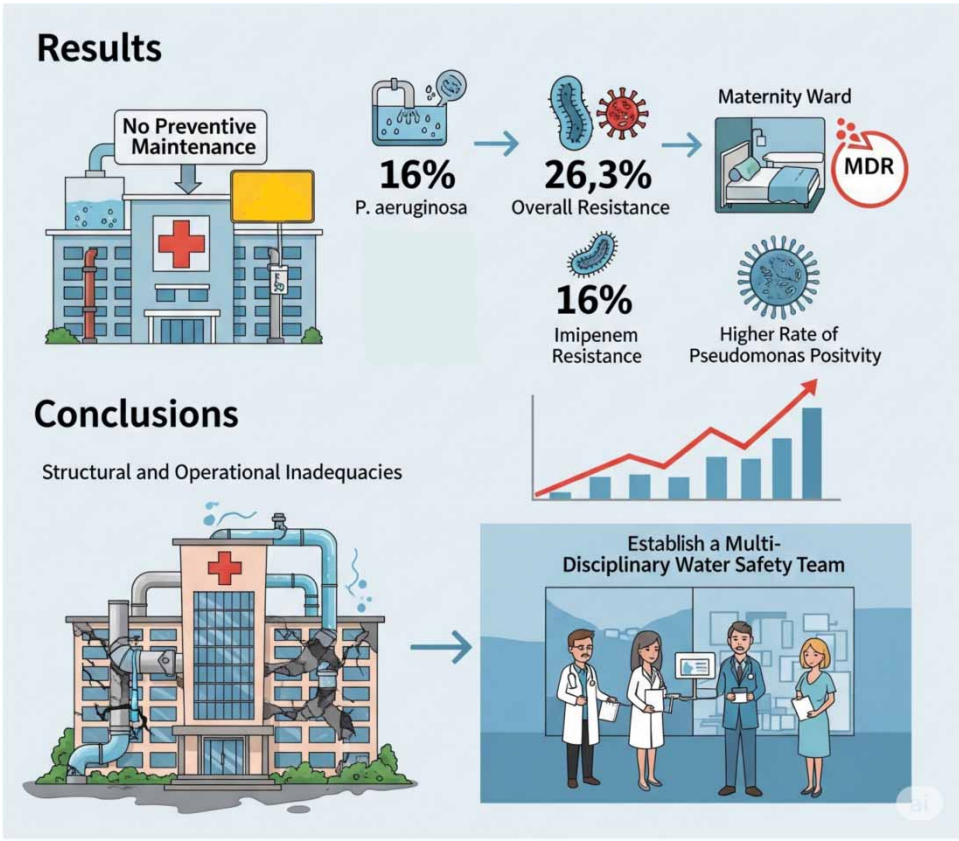
The threat of healthcare-associated infections is significantly heightened when caused by drug-resistant pathogens. This study evaluates water management practices and prevalence of antibiotic-resistant *Pseudomonas aeruginosa* in water systems of two tertiary hospitals of Ethiopia. We employed a mixed-methods approach, combining the qualitative data thematic analysis with quantitative microbiological results from 120 potable water samples. *P. aeruginosa* isolates were identified and subjected to antimicrobial susceptibility testing. Data collection was conducted between December 2023 and January 2024. The findings indicate that neither hospital had a dedicated water management programme for preventive maintenance. Microbial analysis revealed a 16% prevalence of *P. aeruginosa* in the water samples, with 26.3% of isolates demonstrating resistant to at least one antibiotic class. Notably, two isolates from the maternity ward of Hospital A exhibited multidrug resistance (MDR) to ciprofloxacin, amikacin, and imipenem. Overall, the structural and operational standard of the water management programmes in both hospitals were found to be non-conformant to international standards. A higher rate of Pseudomonas positivity, including resistant and MDR strains, indicates persistent hospital water contamination and a tangible risk for HAIs. These results underscore the critical need for the formation of multidisciplinary water safety team to optimize water quality management in these hospitals.

Key words: antibiotic-resistant *P. aeruginosa* in Ethiopia, healthcare-associated infections (HAIs), hospital water management, *Pseudomonas aeruginosa* in tertiary hospitals, waterborne nosocomial infections

HIGHLIGHTS

- The studied hospitals lacked a robust water safety management program for preventive maintenance.
- A significant prevalence of antibiotic-resistant *P. aeruginosa* was found in the hospital water systems.
- Multidrug-resistant strains were identified, showing resistance to critical, last-line antibiotic treatments.
- The findings indicate a tangible risk of healthcare-associated infections for critically-ill patients from contaminated potable water sources.

GRAPHICAL ABSTRACT



INTRODUCTION

The genus *Pseudomonas* consists of Gram-negative, curved, motile, non-spore-forming rod-shaped bacteria that thrive in aerobic conditions and can grow at pH levels below 4.5 (Mena & Gerba 2009). *Pseudomonas* species are oxidase-positive, lactose non-fermenters, and produce water-soluble yellow-green pigments. Common species include *Pseudomonas aeruginosa*, *Pseudomonas stutzeri*, *Pseudomonas putida*, *Pseudomonas fluorescens*, and *Pseudomonas mendocina* (Qin *et al.* 2022). Among these, *P. aeruginosa* is the most frequently isolated species in human infections, causing a wide range of diseases, including hospital-acquired pneumonia, urinary tract infections, bloodstream infections, skin infections, and ear infections. It poses a particular risk to patients on ventilators, with catheters, open wounds, or compromised immune systems (The US Centers for Disease Control and Prevention (CDC) 2024b). *Pseudomonas* spp. is commonly found in sea-water, soil, and freshwater systems, including institutional water systems (Garvey *et al.* 2018), due to their high adaptability to a variety of unfavourable environmental conditions (Mena & Gerba 2009).

Pseudomonas infections mostly occur in the healthcare environment, although community infections are also common (Maharaj *et al.* 2017). Hence, there is a growing public health alert for *P. aeruginosa* due to its role in healthcare-associated infections (HAIs). Recent estimates show HAIs' prevalence is about 0.14% globally (Raoofi *et al.* 2023). Strikingly, low-income countries experience higher HAI rates compared with high-income countries – 7% in high-income countries and 15% in low-income countries (World Health Organization 2022). A pooled prevalence study reported Sub-Saharan Africa to have about 13% HAIs, with Eastern Africa being a major contributor. Intensive care units (ICUs, 25%), neonatal (13%), and paediatric departments (10%) (Melariri *et al.* 2024) appear to be the hot spots of HAIs among hospital units. Ethiopia's HAIs prevalence is about 16.96% (95% CI: 14.10–19.82%), with ICUs and paediatric wards being the most at-risk units (Alemu *et al.* 2020). *P. aeruginosa* is among the top HAI-causing pathogens, accounting for approximately 10% of all HAIs globally (Pachori *et al.* 2019), 7.1% in the United States, 9% in the European Union (Qin *et al.* 2022), and 4.3% in Ethiopia (Asmare *et al.* 2024). Despite the improvements in healthcare delivery globally, *Pseudomonas* and other

HAI-causing pathogens continue to challenge healthcare systems by causing excess but largely preventable morbidity, mortality, and healthcare-associated costs. Hence, the global public health community prioritized *P. aeruginosa* for targeted interventions in recognition of its increasing resistance to conventional antibiotics. According to research, *P. aeruginosa* contributes to around 500,000 deaths annually across the world (Weimann *et al.* 2024).

Pseudomonas bacteria in healthcare settings find their susceptible patients through multiple modes of transmission, including contact with contaminated surfaces, medical devices, hands of health workers (Spagnolo *et al*. 2021), and drinking and inhalation of hospital water (Lefebvre *et al.* 2017). Studies show hospital potable water outlets are one of the significant sources of *Pseudomonas* spp. infection to patients in healthcare facilities (Halstead *et al.* 2021). If favourable conditions exist, *Pseudomonas* bacteria within hospital water pipe systems can integrate into biofilm structures, which in turn provide an environment that facilitates bacterial multiplication and the development of resistance to disinfectants. As more bacterial colonies grow, this leads to the detachment of the biofilm-carrying colonies, which will escape through the water outlets to find susceptible patients (Moore & Walker 2014). Hence, *P. aeruginosa* is referred to in the literature as one of the opportunistic premise plumbing pathogens (Falkinham 2015).

Like the other HAIs, *P. aeruginosa* has already become a pathogen with high public health importance for its drug-resistant strains that worsen patient prognosis in healthcare facilities (World Health Organization 2022). By forming biofilms and engaging in horizontal gene transfer, *P. aeruginosa* can acquire and propagate antibiotic resistance genes, which enhance its ability to persist in clinical settings and resist treatment, thereby contributing to the broader challenge of antimicrobial resistance (Qin *et al.* 2022). The continued rise in antibiotic resistance, along with the rapid dissemination of carbapenem-resistant genes, is severely undermining the effectiveness of conventional antimicrobial therapies against *P. aeruginosa*. Given the public health importance of this characteristic, the World Health Organization prioritized prevention of carbapenem-resistant Enterobacteriaceae, *Acinetobacter*, and *P. aeruginosa* for healthcare facilities in order to mitigate the risks of antibiotic resistance (WHO 2017). *P. aeruginosa* has also shown an increasing trend in developing high resistance to beta-lactams, posing a serious threat to the effectiveness of these drugs against *Pseudomonas* infections (Pachori *et al.* 2019).

P. aeruginosa and other waterborne pathogens are key targets of Infection Prevention and Control (IPC) programmes in healthcare facilities, aimed at preventing HAIs and ensuring patient safety. However, many low-income countries have yet to adopt hospital water safety measures as a strategy to combat HAIs (Cervia *et al*. 2008). In light of the epidemiological evidence linking both proximal and distal hospital water systems to the proliferation and spread of waterborne pathogens, a known contributor to HAIs (Decker & Palmore 2014), patient safety strategies must prioritize comprehensive water quality management. This requires implementing precautionary measures to ensure water safety from the point-of-entry to point-of-use in healthcare settings. This demands regular monitoring of microbial water quality, along with preventive interventions to mitigate risks such as addressing supply disruptions, pressure drops, disinfection failures, and pipe breakages through regular and proactive water system surveillance (Hanlin & Myers 2018). Infection prevention interventions designed to mitigate the risk of hospital water exposure to vulnerable patients are increasingly recognized as a key responsibility of healthcare workers. However, greater success can be achieved by coordinating IPC efforts with monitoring and maintenance of hospital plumbing systems to identify potential stagnation points – such as bends, dead-ends, and unused areas – and implementing investigative and corrective actions to prevent the proliferation of waterborne microbial communities associated with HAIs (Williams *et al*. 2013).

Ethiopia's Ministry of Health's national guidance on Water, Sanitation, and Hygiene (WASH) for Health Care Facilities (2021) has outlined a number of provisions to standardize WASH services across healthcare settings. It also covers key aspects of water supply, maintenance, disinfection, source protection, water requirements, quality, and distribution, which are critical to prevent HAIs in general (Federal Democratic Republic of Ethiopia Ministry of Health 2022). Notably, the current guidance omits the aspect of hospital water systems as potential reservoirs of waterborne pathogens and lacks actionable interventions to mitigate waterborne HAI risks in healthcare facilities.

To the best of our knowledge, there is no published research from Ethiopia on hospital water management practices and how infection risks from waterborne pathogens can be mitigated. This study aims to fill this gap by evaluating hospital water management practices and the extent of contamination of hospital water with antibiotic-resistant *P. aeruginosa* through a case study of two tertiary care hospitals in Addis Ababa. The findings are expected to reveal critical gaps in hospital water safety and associated microbial risks, providing evidence to inform targeted interventions aimed at reducing waterborne HAIs in Ethiopian hospitals.

METHODS

Study design

Data collection was conducted from December 2023 to January 2024. A mixed-methods approach was employed, combining a cross-sectional design for microbial water sample collection with a qualitative data collection through interviews and observations. We collected 120 water samples from 22 sampling points across hospitals, comprising 63 potable water samples and 57 biofilm samples. Additionally, we conducted interviews with two water focal personnel and one hospital administration from each facility.

Study setting

As of December 2023, Ethiopia's public healthcare system comprised 480 hospitals, including 26 comprehensive specialized hospitals. Given that Addis Ababa contains approximately 10% of the nation's hospitals, including those with the highest patient volumes (18), this study specifically focuses on two of Ethiopia's largest comprehensive specialized hospitals, hereafter referred to as Hospital A and Hospital B for confidentiality. We purposefully selected these two hospitals based on four key criteria: (a) large bed capacity (>700 beds each), (b) complex water distribution systems, (c) aging plumbing systems (>50 years old), and (d) their status as national referral centres serving patients from all regions. These facilities represent model cases for Ethiopia's public hospital system, as standardized policies, centralized funding from the Ethiopian Ministry of Health, and uniform oversight result in minimal variation in water management practices across public health facilities. Consequently, our findings likely reflect the most prevalent conditions in Ethiopian healthcare settings.

While data on WASH practices in Ethiopia's non-public hospitals – including private, faith-based, foreign-owned, and newly established institutions – remain limited, these facilities are likely to employ more advanced water management systems due to greater resource availability and closer alignment with international healthcare standards. Such institutions may exceed national WASH requirements and would have served as a valuable comparison group to the public hospitals included in this study. Nevertheless, due to resource constraints, this study focused on public hospitals, which deliver an estimated 75–80% of healthcare services nationwide, with an even higher proportion in rural areas.

Sample collection and transportation

The data collection team consisted of two members: a sample collector and a data recorder. Both of them were trained on the standard operating procedure (SOP) for water and swab sample collection, recording, and transportation. Sample collectors wore personal protective equipment (PPE), including aprons, gloves, and N95 masks, to ensure safety and prevent contamination during sample collection and transportation. Water samples were collected directly from taps as the aerators were not detachable. For biofilm samples, showerhead caps were removed to facilitate collection. Water samples from showerheads were obtained by tying a sterile plastic bag around the showerhead, cutting a small corner of the bag to create an outlet, and allowing the water to flow directly into a sterile bottle through the bag. This method ensured sterility and minimized the risk of external contamination.

Water samples were collected in sterile 250 mL glass bottles containing a 0.1N sodium thiosulphate solution to neutralize any residual chlorine. The water was collected after disinfecting the taps and allowing the water to flow for about 1 min to secure a representative sample. Biofilm samples were obtained using sterile polypropylene-tipped swabs, which were placed into sterile plastic test tubes containing buffered peptone water. On-site measurements for chlorine concentration, pH, and water temperature were performed using the Rakiro Aquasol AM-Al-01 device to ensure immediate and accurate assessment of water quality parameters (Rakiro Biotech 2025).

All samples were immediately placed in a cooler box containing ice cubes to maintain their integrity and were transported to the Ethiopian Public Health Institute laboratory within 2 h after collection. This ensured that the samples remained in optimal condition for accurate analysis (The Ethiopian Public Health Institute (EPHI) n.d.).

Sample preparations and culture techniques

For water samples, a 250 mL volume was filtered through a sterile S-Pak® membrane filter (47 mm diameter, 0.45 μm pore size; MilliporeSigma, Burlington, MA, USA) using aseptic techniques. The membrane containing sediment was placed on Cetrimide Agar, a selective medium for *Pseudomonas* spp., and the Petri dishes were incubated for 24 h at 37 °C (Aryal 2022; International Organization for Standardization 2006). Similarly, biofilm samples were vortexed in test tubes to

create a homogenous suspension, which was then filtered through 0.45 μm membranes that were also placed on Cetrimide agar and incubated under the same conditions.

The membranes on the Cetrimide agar were examined for microbial growth, focusing on characteristics of *Pseudomonas* spp., primarily the distinctive blue-green pigmentation. In cases where mixed colonies were observed, the isolates were sub-cultured to achieve purification. After 24 h of incubation, the Cetrimide agar plates were re-examined for microbial growth and characteristics indicative of *Pseudomonas* spp. The presumptive *Pseudomonas* spp. were stored in cryogenic vials containing Tryptic Soy agar liquid media for further identification.

Microbes' identification

Cryotube-preserved isolates were revived by sub-culturing on Cetrimide agar and incubated for 24 h at 37 °C to prepare them for the identification procedure. The presumptive *Pseudomonas* colonies were subjected to further identification using the JMS-S3000 Matrix-assisted laser desorption/ionization and the mass analyzer is time-of-flight (MALDI-TOF) Mass Spectrometer at two designated reference laboratories (the Ethiopian Animal Health Institute and Wudase Diagnostic Center) in Addis Ababa.

For the MALDI-TOF analysis, the matrix solution was prepared by dissolving 10 mg of α-cyano-4-hydroxycinnamic acid in 1 mL of 50% acetonitrile, followed by the addition of 0.1% trifluoroacetic acid. The mixture was vortexed until fully dissolved. Bacterial isolates were then mixed with the prepared matrix solution, and the mixture was pipetted onto a MALDI-TOF plate and air-dried. The plate was subsequently analysed using the MALDI-TOF mass spectrometer.

The resulting data were recorded, and isolates with scores above 2.0, confirming identification as *Pseudomonas* spp., were documented according to MALDI-TOF interpretation guidelines.

Antimicrobial susceptibility testing

We performed the antimicrobial susceptibility of *P. aeruginosa* colonies on Mueller-Hinton agar, following the Kirby-Bauer Disk Diffusion Susceptibility Test protocol. Fresh colonies were suspended in 2 mL sterile saline using a sterile loop, and the suspension was vortexed to ensure homogeneity. The suspension was uniformly inoculated onto Mueller-Hinton agar using a sterile biofilm spreader. Five antimicrobial-impregnated disks – piperacillin–tazobactam (TZP) 100/10 μg, ceftazidime (CAZ) 30 μg, ciprofloxacin (CIP) 5 μg, amikacin (AK) 30 μg, and imipenem (IPM) 10 μg – were placed center-to-center spacing on the agar media. Plates were incubated at 35 °C for 18 h in ambient air. Inhibition zone diameters were measured to the nearest 0.1 mm using rulers, with results interpreted against European Society of Clinical Microbiology and Infectious Diseases (EUCAST) 2023 breakpoints. Multidrug resistance (MDR) was defined as non-susceptibility to $\geq$1 agent in $\geq$3 antimicrobial categories. The AMR index is computed as the ratio of the number of resistant phenotypes to the total number of antibiotics tested.

Qualitative data collection on hospital water systems

The qualitative methodology involved interviews and observations of the water systems. Two water focal personnel and a hospital administration member from each hospital were interviewed using an open-ended questionnaire adapted from the U.S. CDC Healthcare facility water management programme checklist (The US Centers for Disease Control and Prevention (CDC) 2018). The key informant interviews broadly covered seven key areas, including the condition and design of the water system, the presence of a management team with defined roles and training, and the availability of documentation such as system plans and risk assessments. The interviews also evaluated operational controls like temperature and disinfection measures, monitoring practices, and record-keeping. Additional focus areas include high-risk equipment (e.g., cooling towers, humidifiers), corrective actions for test failures or system reactivation, and special precautions for high-risk healthcare areas such as ICUs and oncology wards.

The research team conducted observation of all inpatient departments, water points, and water infrastructure from water tanks to outlets, including pumps, faucets, showers, toilets, to inspect and document the hygiene status, monitor dead-ends, and identify potential contamination points. We prioritized the Adult ICU, Emergency Ward, Medical Ward, Obstetric Ward, Neonatal Intensive Care Unit (NICU), Surgical Ward, and Paediatric Ward, given the high-risk patients housed in these units.

The qualitative findings were categorized by hospital type and evaluated against key international standards, primarily those of the U.S. CDC. 'Compliance Status' was assessed based on whether each hospital's practices fully met, partially met, or did not meet the corresponding standard (Table 2).

Data quality

For each batch of water and swab samples tested, we included two (5%) distilled water samples as a negative control and one known positive sample spiked with *P. aeruginosa* as a positive control. Negative controls showed no growth on the media, and positive controls yielded growth on the culture media, validating the culture sensitivity.

To ensure data quality in our qualitative study, we applied triangulation across interviews (member-checked, transcribed verbatim), observations (standardized U.S. CDC checklists, observer validation), and document reviews (authenticated reports, thematic coding). Discrepancies (e.g., between staff accounts and observed leaks) were resolved through verification.

Study variables

To fulfil the study objectives, the following outcome and independent variables (Table 1) were analysed.

Bias-minimizing measures

To ensure sample integrity, we implemented an uninterrupted cold chain during transport and storage. Additionally, routine quality control measures were implemented for culture and antimicrobial susceptibility testing (AST) in alignment with the SOP set by the Ethiopian Public Health Institute.

Data management and analysis

Quantitative data were recorded on an Excel-based template and were analysed in STATA 13 using descriptive statistics, χ^2 tests, and logistic regression (95% CI). Qualitative data underwent verbatim transcription and inductive thematic analysis outlined by Braun and Clarke (Ahmed *et al.* 2025).

RESULTS

Evaluation of the hospital water management system

The qualitative data from six stakeholder interviews and two water system observations were thematically analysed and are presented below through narrative themes and summarized findings in Table 2.

Table 1 | List of study variables and definitions

Variable names	Type of variable	Data type	Operational definition
Structural and operational compliance of the hospital water management programme with the U.S. CDC standards	Outcome	Qualitative	This is a composite variable encompassing data on water system infrastructure, the presence of a water management programme and team, risk assessment practices, water quality monitoring, high-risk features and departments, and corrective actions, in alignment with the U.S. CDC Healthcare facility water. Management programme checklist.
Prevalence of *P. aeruginosa* in water samples	Outcome	Quantitative/ continuous	Refers to the detection of waterborne *P. aeruginosa* (overall samples and disaggregated by sample type and hospital name).
Prevalence of antibiotic-resistant *P. aeruginosa*	Outcome	Quantitative/ continuous	Determines whether *P. aeruginosa* isolates found in water and swab samples exhibit resistance to one or more anti-pseudomonal drugs.
Prevalence of MDR *P. aeruginosa*	Outcome	Quantitative continuous	Assesses whether isolated *P. aeruginosa* are resistant to at least three classes of anti-pseudomonal drugs out of the eight recommended groups.
Hospital departments	Independent	Qualitative/ categorical	The specific department within the hospital where the water or swab sample was collected.
Sample type	Independent	Qualitative/ categorical	Whether the sample was collected from surfaces such as faucets or showerheads, rather than directly from the water – swab/biofilm sample. Whether the sample was collected directly from a water source, such as a faucet or showerhead.

Table 2 | Key findings from the hospital water system assessment disaggregated by Hospital A and Hospital B and their status of compliance with international standards

	Hospital A		Hospital B	
Category of criteria	**Findings**	**Compliance status**	**Findings**	**Compliance status**
Water system infrastructure	- Single system (60+ years old, copper and polypropylene random copolymer pipes) - Underground water tank (municipal-only)	~ Partially present	- Dual-source supply (60+ years old) enhances continuity – PPR plumbing system - Two aboveground tanks (municipal + groundwater backup)	~ Partially present
Water management team	- No formal team; 2–3 staff from maintenance/environmental health - No microbiologists/infectious disease specialists - The IPC committee operates separately	~ Partially present	- Same as Hospital A	~ Partially present
Risk assessment and documentation	- No written water system plans/flow diagrams - No risk assessments for waterborne pathogens - No major maintenance in 5+ years	✗ Absent or not done	- Same as Hospital A	✗ Absent or not done
Water quality monitoring	- Quarterly testing (*E. coli*, bacterial counts) - Tank cleaned every 6 months - No residual chlorine/pH monitoring	~ Partially present	- Monthly testing (same parameters) - Quarterly tank cleaning - Same gaps in monitoring	~ Partially present
High-risk features	- Multiple non-functional showers - Faucet aerators (aerosol risk) - No thermostatic valves/water treatment systems	✗ Absent or not done	- Functional showers - Same aerator risks - Major construction ongoing (added contamination risk)	✗ Absent or not done
High-risk departments	- No prioritized water safety in ICUs/NICUs/oncology units	✗ Absent or not done	Same as Hospital A	✗ Absent or not done
Corrective actions	- No reactivation protocols after downtime - No systematic enforcement of water safety measures	✗ Absent or not done	Same as Hospital A	✗ Absent or not done

Water system infrastructure and characteristics

A significant challenge for both hospitals is the absence of up-to-date written descriptions or water safety plans; consequently, understanding the system layout, including piping, storage tanks, and flow directions, relies entirely on staff memory. Neither hospital has established water-specific guidelines or policies for comprehensive water system management, leading to inconsistencies in how water safety and system maintenance are handled. Both hospitals face considerable budgetary challenges that hinder effective supervision, maintenance, system risk assessment, managing risk, staff training, development of remedial actions in case of outbreaks, and regular quality control of their water systems. This scarcity limited hospitals' capacity to conduct regular water testing, implement piping system upgrades, and perform essential preventive maintenance measures such as cleaning water tanks, replacing aging pipes, or installing water treatment systems.

In both hospitals, water is pumped from the tankers for distribution. However, limitations in pumping capacity at Hospital A impact consistent water access across all sections, providing sufficient pressure only up to the 4th floor. This necessitates manual water transport to higher floors, affecting accessibility for essential services and potentially hindering consistent infection control practices.

Water management programme and team

Due to small team size, water management staff members are often overwhelmed by daily operational challenges and reactive maintenance needs. Environmental health specialists generally lead these efforts, with ward nurses reporting issues like leaks.

The infection prevention and control (IPC) committees operate independently from water management, focusing on general infection prevention practices without direct roles in water systems or safety.

Documentation and risk assessment

Both hospitals demonstrate a significant lack of formal documentation and proactive measures for their water systems. No written scheme, flow diagram, or operational manual exists to guide maintenance or emergency responses, leading staff to rely solely on informal, experiential knowledge. The absence of site-specific cleaning or disinfection procedures leaves a critical gap in maintaining water quality and safety.

Quality controls and monitoring

Both hospitals demonstrate significant deficiencies concerning temperature control, disinfection, and monitoring. For disinfection, both rely solely on municipal water treatment, with no supplemental local chemical controls like chlorine dosing or anti-scaling treatments on-site. Neither hospital maintains documentation of water turnover monitoring and tank flushing activities.

Crucially, neither hospital has a formal, written water management programme that outlines comprehensive protocols for monitoring, treating, and managing water quality to minimize the risk of waterborne infections. Both hospitals also lack essential water treatment systems (softeners, filters, recirculation systems) and thermostatic mixing valves.

High-risk features

The oldest structures of both hospitals date back to before the 1960s, with additional buildings added subsequently, impacting infrastructure management as more buildings demand greater coordination for consistent water quality and safety. Bed occupancy rates fluctuated, and significant patient rooms were out of service in both hospitals.

Humidifiers in both hospitals pose a risk due to improper water treatment/maintenance and operate without documented control measures. Water used in bathing equipment is also not properly cleaned, potentially exposing patients to harmful bacteria.

Both hospitals do not own high-risk equipment and systems often associated with waterborne pathogens in other healthcare facilities, such as cooling towers, evaporative condensers, hot tubs, whirlpools or hydrotherapy spas, decorative fountains, misters, centralized humidification systems, ice machines, and irrigation systems.

High-risk departments

In both hospitals, there is no prioritization for water safety measures in high-risk clinical areas (e.g., ICUs, NICU, Emergency, oncology, obstetric care), which house immunocompromised patients. Patients in both settings are in close and continuous contact with various water-based systems through daily activities and medical equipment use, significantly heightening the potential for encountering waterborne pathogens.

Corrective actions and compliance

Both hospitals face critical gaps in their water management protocols concerning system reactivation and response to water quality issues. Documented procedures for safely reactivating water systems after downtime are absent, risking reintroducing stagnant water and contaminants. While staff are involved in water-related activities, there is no formal system to ensure consistent adherence to water infection control measures. Observations reveal inconsistent adherence across the hospitals.

Further data presented in Table 2, assessed against key U.S. CDC criteria, reveal critical system-wide deficiencies in water safety management across both hospitals. While certain elements such as water system infrastructure, management teams, and basic monitoring are in place, there is a general absence of formal planning, risk prioritization, and corrective action mechanisms.

Contamination of hospital water samples with *Pseudomonas* spp.

On the basis of the observational tour of the hospital departments and water systems, the assessment team determined approximately 22 water sampling points covering almost all the departments where admitted patients are exposed to water from faucets and showerheads, as well as where water is used for medical equipment or cleaning purposes. A total of 120 water and biofilm samples were collected. From the 120 samples, 63 were potable water samples, while 57 were biofilms. Hospital A contributed 56% of the samples, while Hospital B produced 44%. ICUs, emergency wards, and paediatric

departments are the sections with the greater number of samples collected. Table 3 provides further details on the distribution of samples across hospitals and their respective departments.

Only cold-water samples were collected, as hot water was not available in either of the hospitals during the data collection period. Microbial analysis revealed that at Hospital A, the average free chlorine residual was about 0.4 mg/L, the temperature was 24.2 °C, and the pH was 8.5 at all the sites where samples were collected. In contrast, Hospital B's samples showed an average free chlorine residual of 0.6 mg/L, a temperature of 26.6 °C, and a pH of 8.3.

Microbial colony identification was performed using a MALDI-TOF mass spectrometry device. We found 16% (95% CI: 15.1–35%) prevalence of *P. aeruginosa* in both sample types and both hospitals. The higher detection was in biofilms compared with water samples. Across the two hospitals, Hospital B showed higher positivity compared with Hospital A. Figure 1 presents specific data on the prevalence of *Pseudomonas* spp.

The 19 *Pseudomonas* isolates were further subjected to antimicrobial sensitivity testing against 5 antimicrobial groups by Kirby-Bauer Disk Diffusion Susceptibility Test protocol and applying the European Society of Clinical Microbiology and Infectious Diseases technical guidance (EUCAST 2021). Refer to Table 4 for detailed information on antimicrobial susceptibility results.

Overall, 26.3% (95% CI: 9.1–51.2%) of the isolates demonstrated resistance to at least one type of antibiotic from the five categories. All the colonies exhibited intermediate susceptibility (increased dose) to TZP. Excluding two colonies that showed resistance, 90% isolates have intermediate susceptibility (increased dose) to CAZ.

Table 3 | List of hospital departments by the number of samples collected, stratified by hospital name and sample type

	Hospital name		Sample type		
Hospital departments	**Hospital A**	**Hospital B**	**Water**	**Biofilm**	**Total number of samples**
Cardiology	0	2	1	1	2
Dental clinic	0	2	1	1	2
Diabetic centre	2	0	1	1	2
Emergency	14	0	6	8	14
Ear nose throat	0	5	3	2	5
Gastroenterology	0	2	1	1	2
Haematology	1	3	1	3	4
Intensive care unit	16	4	10	10	20
Kangaroo mother care (KMC)	0	2	2	0	2
Maternal child health	6	4	6	4	10
Medical	5	0	3	2	5
Mental health	0	1	1	0	1
Nephrology	0	2	1	1	2
Nephrology	0	6	3	3	6
Nuclear medicine	3	0	2	1	3
Oncology	2	2	2	2	4
Outpatient department	5	4	5	4	9
Orthopaedics	2	0	1	1	2
Paediatrics	5	3	4	4	8
Pathology	2	0	1	1	2
Pulmonology	0	2	1	1	2
Surgical	6	5	5	6	11
Water tank	0	2	2	0	2
	69	51	63	57	120

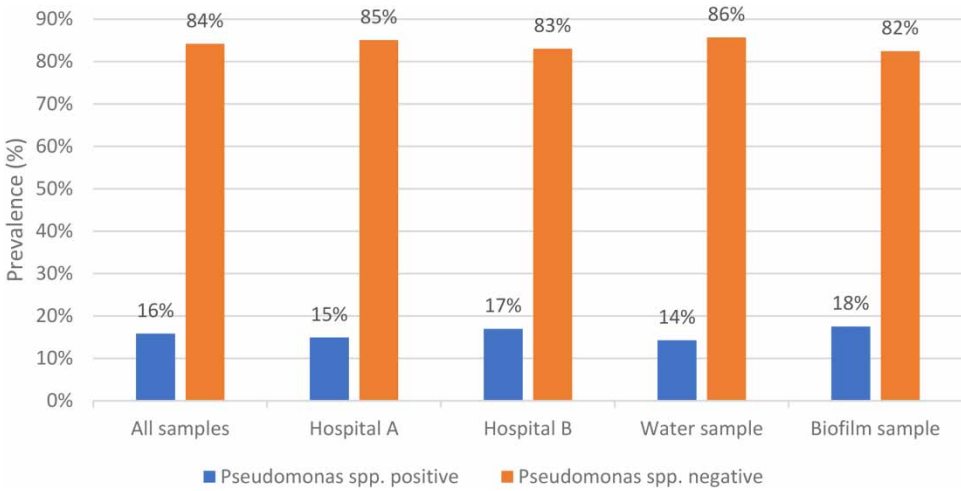


Figure 1 | Prevalence of *P. aeruginosa* in hospital water samples disaggregated by hospital name and sample type.

Table 4 | Microbial agents and susceptibility results of *P. aeruginosa* colonies isolated from potable water samples

	Hospital A			Hospital B			Total		
Antimicrobial agents	**S**	**I**	**R**	**S**	**I**	**R**	**S**	**I**	**R**
TZP	0	100%	0	0	100%	0	0	100%	0
CAZ	0	90%	10%	0	89%	11%	0	90%	10%
CIP	0	80%	20%	0	100%	0	0	90%	10%
AMK	0	80%	20%		100%	0	0	90%	10%
IPM	80%		20%	89%		11%	84%	0	16%

The highest resistance, at 16% ($n = 3$), was observed against IPM, and it accounted for 60% of the total resistant isolates.

Sensitivity profiles of *P. aeruginosa* colonies disaggregated by sample types show that all water and biofilm isolates exhibited high levels of intermediate susceptibility to TZP, CAZ, CIP, and AMK, with no full susceptibility observed except for IPM. IPM demonstrated the highest susceptibility in both water (87.5%) and biofilm (81.8%) samples, while a small proportion of resistance (up to 18.2%) was noted primarily in both sample types. Figure 2 presents further details on the sensitivity characteristics of *Pseudomonas* spp. isolated from water and biofilm samples.

We identified two isolates from the maternity ward of Hospital A that exhibited MDR to CIP, AMK IPM, giving a prevalence of 10.5% (05% CI: 1.3–33.1%) (EUCAST 2024). We saw a higher AMR index in the maternity ward of Hospital A (Table 5).

Bivariate and logistic regression analyses revealed no significant difference in *P. aeruginosa* presence rates between Hospital A (23.3%) and Hospital B (26.5%) ($p > 0.05$). Similarly, no significant difference was observed in *P. aeruginosa* presence rates between water (20.9%) and swab (27.8%) samples ($p > 0.05$). Overall, neither sample type (water/swab) nor hospital location significantly predicted *Pseudomonas* spp. presence ($p > 0.05$ for all coefficients).

DISCUSSION

Hospital water systems are critical to infection control, as they have the potential to harbour and spread pathogens that can cause HAIs. Given the significant burden of HAIs, which strain the already meagre healthcare resources in low-income countries, implementing robust IPC practices integrated with water management programmes is not optional; it is essential to save lives and prevent unnecessary loss of life and resources.

This research aimed to generate crucial evidence from the Ethiopian health system, highlighting the urgent need to prioritize water management programmes to prevent *P. aeruginosa* and other waterborne nosocomial pathogens, and to reduce their impact on patient outcomes and healthcare costs.

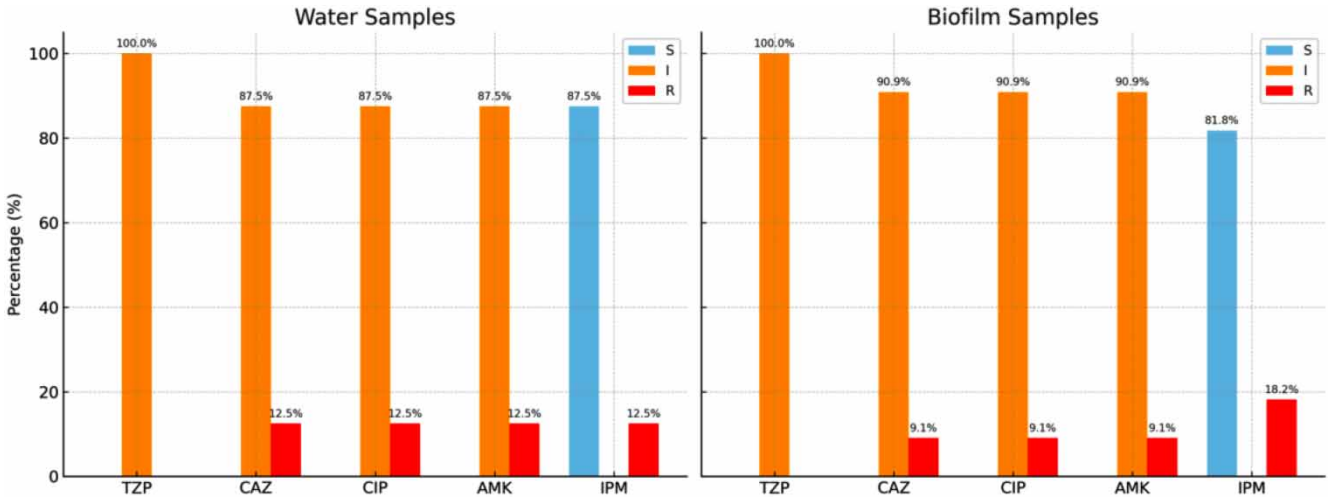


Figure 2 | Antibiotic susceptibility profiles of *P. aeruginosa* isolates disaggregated by water and biofilm sample types.

Table 5 | Antimicrobial resistance and AMR index profile of *P. aeruginosa* isolates from water and biofilm samples disaggregated by hospital name and wards

	Sample type	Hospital names	Hospital departments	Resistant drugs	AMR index
1	Water	Hospital A	Maternity ward	CIP, AMK, IPM	0.6
2	Biofilm	Hospital A	Maternity ward	CIP, AMK, IPM	0.6
3	Biofilm	Hospital A	Emergency	CAZ	0.2
4	Biofilm	Hospital B	KMC	IPM	0.2
5	Water	Hospital B	KMC	TZP	0.2

Evaluation of the hospital water management system

Our findings indicate that both hospitals have implemented a very basic water safety action plan that primarily focuses on water quality testing and routinely cleaning the water tanks. While these action plans are consistent with the national requirements, they fall short of being a comprehensive, risk-focused hospital water management strategy when seen through the lens of preventing waterborne nosocomial infections (The US Centers for Disease Control and Prevention (CDC) 2018). These challenges appear to be compounded by a lack of adequate budgeting and staffing, as reaffirmed by the national Healthcare Facilities WASH Guideline (Ethiopia 2021). This finding aligns with a recent study from Iran, which identified resource deficiency as a key factor contributing to hospital water crisis (Kameli *et al.* 2025). The absence of a water management programme suggests that hospitals are likely missing opportunities to systematically identify, prevent, and respond to potential waterborne pathogen risks associated with their water systems.

Both hospitals face challenges due to the ongoing water rationing programme in Addis Ababa (Unto 2024). This often results in reduced water pressure and intermittent water interruptions in the hospital water systems (Asefa & Moreda 2023). While one hospital has mitigated this issue by developing a groundwater system, the ongoing water shortages and pressure drops likely contribute to backflow from non-potable sources or stagnant water in the plumbing systems of the hospitals. These issues not only affect the availability of water for basic needs, patient care, and sanitation services but also promote the growth of waterborne pathogens in the water system (The US Centers for Disease Control and Prevention (CDC) 2024a). This finding aligns with Chawla *et al.*, who highlighted that suboptimal water supply in hospitals in low-income countries impacts both the quality of care and the prevalence of HAIs (Chawla *et al.* 2016).

Our study showcased that Hospital A's water tank did not meet the basic design standards, with the tank at risk of surface runoff draining into it. This is inconsistent with the national as well as the International WHO standard for healthcare facilities, which require water tanks to be designed in a way that eliminates contamination risks (World Health Organization

2023). The situation is further compounded by the lack of local water treatment efforts, as the hospitals rely solely on municipal chlorination. Consequently, any reduction in residual chlorine levels within the hospital's plumbing system, whether due to floodwater infiltrating the tank, prolonged water stagnation, or a drop in chlorine levels before distribution, significantly increases the risk of contamination (Bearman *et al.* 2018).

Sinks in both hospitals are equipped with aerator faucets, which introduce air into the water system and may facilitate the spread of aerosols containing pathogens if the water supply is contaminated (Carling 2018). Proper maintenance and regular monitoring of these faucets are crucial to reducing infection risks, particularly in high-risk areas such as ICUs, oncology wards, surgical wards, and dialysis units. Furthermore, drains in sinks, showers, and toilets also pose contamination risks, as stagnant water, especially in poorly drained or inadequately cleaned areas, can harbour bacteria and serve as a breeding ground for pathogens (Volling *et al.* 2021). Additionally, showerheads and toilet plumbing are not cleaned regularly, leading to the accumulation of biofilms that can preserve pathogenic microbes (Weinbren *et al.* 2021). These biofilms can be aerosolized during use, increasing the risk of infections, especially among vulnerable patients.

Our observations highlight that patients are in inescapable contact with various water outlets through regular activities like hand washing at faucets, bathing with showerheads, and using toilets. This frequent interaction directly increases the probability of exposure to waterborne pathogens. For immunocompromised or seriously sick patients, even a low level of exposure to these opportunistic pathogens can lead to severe HAIs. The continuous nature of this exposure means that the potential for waterborne infection is an ongoing, rather than intermittent threat and underscores the critical need for improved water management practices to prevent contamination and protect patient health (Williams *et al.* 2013).

Overall, the structural and operational compliance of the hospital water management programmes in both Hospital A and Hospital B falls significantly short of the U.S. CDC standards. Both hospitals operate with aging infrastructure, lack formal multidisciplinary water management teams, and crucially, have not performed risk assessments for waterborne pathogens or developed written water safety plans or flow diagrams. While some water quality monitoring and tank cleaning are 'partially present', there are critical deficiencies in continuous monitoring, residual disinfectant tracking, and the absence of essential water treatment systems. Furthermore, neither hospital has prioritized water safety in high-risk departments nor established systematic procedures for corrective actions, including reactivation protocols, indicating widespread non-compliance across most critical water management criteria.

Contamination of hospital water with *Pseudomonas* spp.

Microbial analysis shows that the average free chlorine residual at Hospital A is approximately 0.5 mg/L, with a temperature of 24.2 °C and a pH of 8.5 at sample collection points. In comparison, Hospital B has an average free chlorine residual of 0.4 mg/L, a temperature of about 26.6 °C, and a pH of 8.3. The pH level in this study is consistent with a previous study by Negash *et al.* on water quality at Hospital B, which reported a pH level of 8.3 for groundwater is 8.3, similar to the results of this study (Negasha *et al.* n.d.). The low level of chlorination in the two hospitals is below the WHO recommendation and the national WASH guideline. This insufficient chlorination can potentially favour microbial survival, persistence, and proliferation within the water systems, thereby increasing the risk of infection for patients (Bearman *et al.* 2018). The high pH levels, while typical for groundwater, could further influence the stability of chlorine, reducing its effectiveness in controlling microbial contamination and increasing the risk of waterborne infections in patients.

This study detected *P. aeruginosa* in 16% of potable water samples from the two hospitals. The positivity rate was slightly higher in biofilm samples (53%) compared with water samples (47%). Our findings are notably higher than a similar study in Tehran, where 28% of biofilms and 22% water samples tested positive for *P. aeruginosa* (Gholipour *et al.* 2024). They are also much higher than a study in Italy, where only 2% of the water samples turned positive for *P. aeruginosa* (Cristina *et al.* 2021). However, this result is still lower than a study in Tanzania, which reported an 82% positivity for hospital water and 44% for biofilms (Moremi *et al.* 2017). The higher contamination rates observed in the two hospitals in Addis Ababa, compared with those reported in Iran and Italy, may reflect a lower level of implementation of hospital water management programmes and infection control procedures. This was supported by findings from the qualitative study, which indicated weaknesses in these areas and may have contributed to the increased water colonization by *Pseudomonas*.

Our study found that hospital water from the ICU department had the highest *P. aeruginosa* positivity rate, followed by the surgical ward, maternity and KMC and emergency wards. These findings are concerning, as these departments primarily care for critically ill patients. The results align with existing literature, which highlights the presence of microbial colonization in distal water fixtures in ICUs (Garvey *et al.* 2016), with proven evidence of pathogen transmission to vulnerable patients

(Loveday *et al.* 2014). This situation is even more alarming in light of the numerous documented outbreaks of *P. aeruginosa* in paediatric ICUs and surgical departments, where water systems were identified as the source, leading to both loss of life and significant resource expenditure (Walker *et al.* 2014).

All the colonies of *P. aeruginosa* tested in this study exhibited intermediate susceptibility to TZP, suggesting the potential need for higher dosing or avoidance of TZP monotherapy for effective treatment. This finding may indicate an evolving resistance pattern in *P. aeruginosa*, particularly when compared to a 2021 study from Jordan, in which water isolates showed 100% susceptible to TZP (Tarazi *et al.* 2021). The contrast highlights a possible rapid decline in the effectiveness of TZP over just a few years. Moreover, when viewed alongside a 2021 Indonesian study that reported a 4% resistance rate to TZP among *P. aeruginosa* isolates from hospital water sources (Kusuma *et al.* 2021), these results point to emerging regional variations in resistance. Such differences are likely influenced by local environmental conditions, antibiotic use practices, and selective pressure, emphasizing the importance of continuous global surveillance and setting specific antimicrobial stewardship approaches.

Ninety percent of *Pseudomonas* colonies demonstrated intermediate susceptibility to standard doses of CAZ, CIP, and AMK, indicating that these drugs remain largely effective against these isolates. This result aligns with findings from a Jordanian study, where hospital water isolates of *P. aeruginosa* were reported to be 100% sensitive to AMK (Tarazi *et al.* 2021). The consistency of these findings across locations suggests that environmental factors, together with pathogenic variables, continue to work synergistically to maintain the drug's efficacy in the current situation.

Among the drugs tested, imipenem showed the highest resistance, with 16% of the isolates identified as resistant. This finding contrasts with an Indonesian study on hospital water, where resistance to meropenem, a similar carbapenem, was only 4% (Kusuma *et al.* 2021), and a Jordanian study where water samples showed 100% susceptibility to imipenem (Tarazi *et al.* 2021). These variations highlight the influence of local factors, including environmental conditions and pathogen-specific variables, in shaping resistance development in microbes.

A 10.5% prevalence of MDR *P. aeruginosa*, as classified by EUCAST, was identified among the tested samples, with all MDR isolates originating from the maternity ward of Hospital A (EUCAST 2024). This observation aligns with findings from an Indian study, which reported that *P. aeruginosa* isolates from the labour room in the maternity department demonstrated a higher level of resistant isolates compared with other hospital sites (Kalpana *et al.* 2022). Such findings underscore the critical need for targeted infection control measures in maternity wards to address the elevated risk of antimicrobial resistance in these settings.

Strengths and limitations

This study's strength lies in the use of a combined culture method with state-of-the-art MALDI-TOF mass spectrometry to confirm microbial pathogens, which is an advanced methodology compared with the use of just traditional culture and biochemical tests. This guaranteed high accuracy in the identification of bacterial colonies.

The water sampling strategy employed convenience sampling, which has a limitation in its ability to provide a comprehensive representation of the entire hospital water system. Consequently, the findings from this study might not fully reflect the actual risk and contamination levels throughout the water system.

We acknowledge as a potential limitation that this study focused exclusively on public hospitals, which may not fully represent the broader hospital landscape in Ethiopia, including private, faith-based, and international hospitals.

CONCLUSIONS

Our findings indicate that both hospitals exhibit systemic deficiencies, highlighting structural and operational inadequacies in their existing water management programmes when assessed against international standards. These shortcomings are further corroborated by the high rate of *Pseudomonas* positivity, including an elevated prevalence of MDR strains – particularly in the maternity wards. This suggests ongoing environmental contamination is likely associated with inadequate water management practices and a tangible risk for waterborne HAIS to patients.

Given these findings, we recommend that both hospitals establish a multidisciplinary water safety team to oversee and optimize water quality management, including carrying out comprehensive risk assessments and developing detailed system flow diagrams to identify critical control points for contamination. Furthermore, continuous disinfection must be maintained through routine monitoring of residual chlorine levels and pH.

Future studies should consider conducting comparative analyses across a broader range of hospitals, including non-public facilities, to assess differences in contamination and resistance patterns. Additionally, applying molecular sequencing methods to directly identify pathogens from environmental samples and cross-referencing these results with patient isolates would enhance understanding of transmission dynamics.

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AUTHOR CONTRIBUTIONS

Concept and design: E.B.H., A.F.D., G.T., S.R.G., and W.A. Data collection: E.B.H. Data analysis and interpretation: E.B.H., A.F.D., G.T., S.R.G., W.G., A.A., and W.A. Drafting the manuscript: E.B.H. Critical revision of the manuscript: E.B.H., A.F.D., G.T., S.R.G., W.G., A.A., and W.A. Final approval of the version to be submitted: E.B.H., A.F.D., G.T., S.R.G., W.G., A.A., and W.A. Funding: E.B.H.

ETHICAL CLEARANCE

Free and informed consent of the participants was obtained, and the study protocol was approved by the appropriate Committee for the Protection of Human Participants (Institutional Review Board (IRB) in the College of Health Sciences in Addis Ababa University, Addis Ababa, Ethiopia, Protocol # 077/21/SPH and July 12, 2023).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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