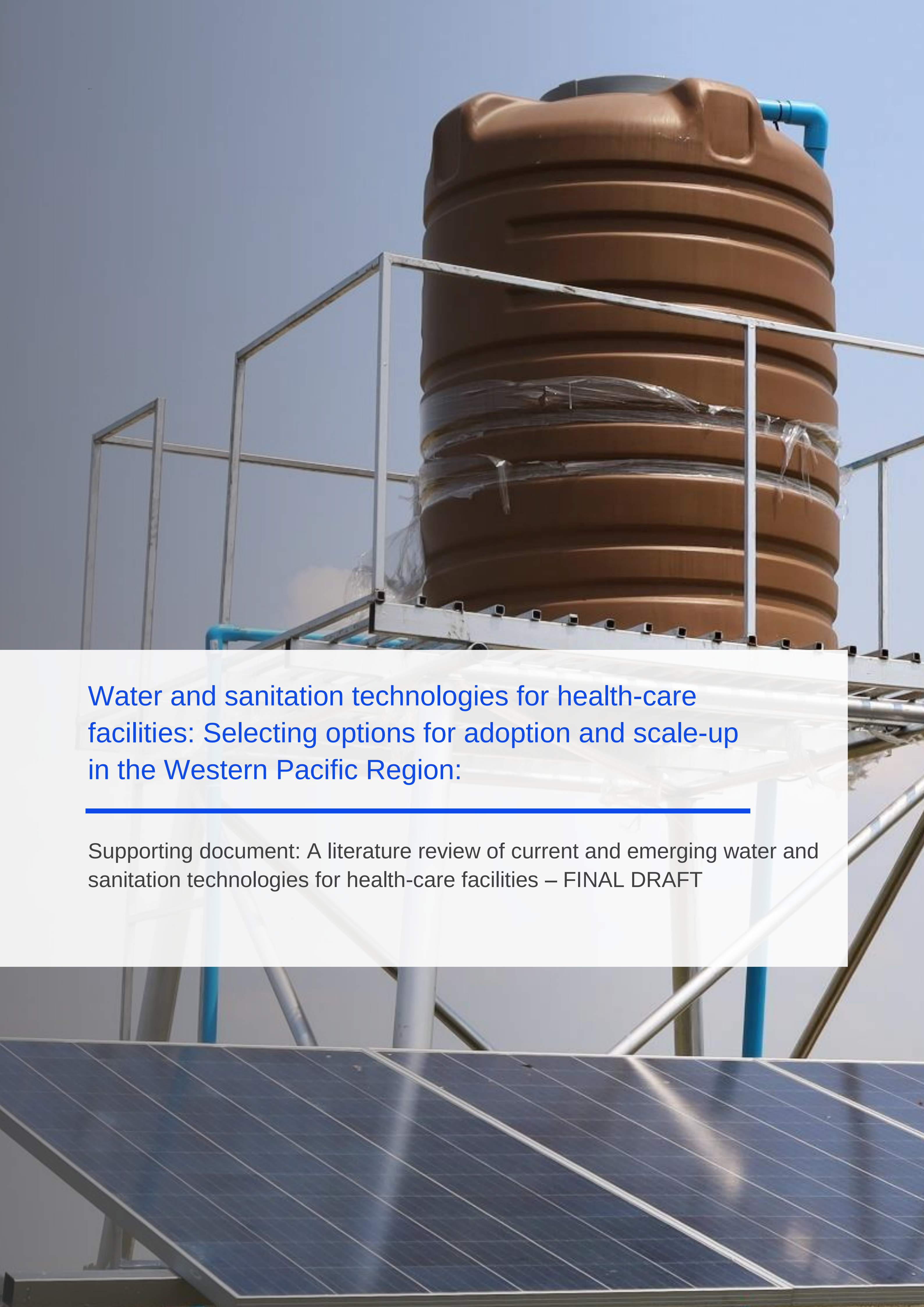

Water and sanitation technologies for health-care facilities: Selecting options for adoption and scale-up in the Western Pacific Region:

Supporting document: A literature review of current and emerging water and sanitation technologies for health-care facilities – FINAL DRAFT

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Executive summary

Introduction

Water and sanitation in health-care facilities (HCFs) are essential for public health, economic development and quality health care, preventing infection outbreaks and reducing the number of avoidable deaths. Water supply and wastewater treatment in HCFs require specific technologies to meet the unique demands of maintaining a safe and sterile environment despite exposure to potentially hazardous substances used in medical activities. Furthermore, for sustainable provision of water and sanitation services in HCFs, technologies must be appropriate to the specific local context.

The World Health Organization (WHO) has identified the need to enhance knowledge about appropriate water and sanitation technologies as a key priority for improving water and sanitation services in HCFs in low- and middle-income countries (LMICs) in the Western Pacific Region. In addition, the evolving nature of these technologies, including new and emerging options, highlights the need for increased awareness among key stakeholders responsible for managing water and sanitation in HCFs. In this context, this document identifies relevant existing and emerging water supply and wastewater treatment technologies for HCF-specific needs based on a review of academic and grey literature.

The scope of the review is limited to water supply and wastewater processes, and does not cover other health-care waste technologies and processes.

Water supply technologies for health-care facilities

Water supply in HCFs must be consistent, reliable and of high quality to meet the demands of patient care. HCFs have higher water consumption and continuous supply needs compared to residential or commercial needs, requiring the use of backup water supply and storage systems. To ensure patient safety and prevent infections, HCFs need to address potential risks from external sources of pollution and minimize internal contamination, such as the proliferation of antibiotic-resistant bacteria in plumbing systems. Point-of-use treatment at taps is commonly implemented in HCF water supply systems to provide ultra-pure or sterile water for specific activities.

Relevant water supply technologies for HCFs were grouped into four categories: adaptations to centralized piped water systems, on-site water supply and treatment technologies, point-of-use treatment within HCFs for specialized uses, and non-conventional sources of water for on-site and centralized supply.

Adaptations to centralized systems involve additional storage and treatment to address intermittent piped water service and prevent cross-contamination. On-site technologies for water supply in HCFs range from established solutions such as groundwater and surface water pumping with filtration and disinfection, as well as rainwater harvesting, treatment and storage, to emerging technologies such as membrane systems including ultrafiltration and nanofiltration.

Point-of-use treatment technologies involving distillation, reverse osmosis, deionization and carbon filtration are suitable for providing high-purity water for specialized uses within HCFs on a small scale. Solar disinfection offers a low-cost method to achieve sterile water with minimal material and maintenance requirements. In regions with water scarcity, non-conventional sources like seawater and recycled water can be utilized for specific purposes within HCFs. Desalination technologies, although energy-intensive and requiring economies of scale for drinking-water supply, may merit consideration, while wastewater reuse can be integrated into the plumbing system of HCFs for non-drinking uses through proper design.

Wastewater and faecal sludge treatment technologies for health-care facilities

Wastewater generated by HCFs poses a higher risk compared to domestic and municipal or domestic wastewater due to the elevated concentrations of pathogens and emerging contaminants, such as antibiotic-resistant bacteria and pharmaceuticals. Introducing advanced wastewater treatment technologies capable of reducing the concentration of these pollutants is therefore crucial to safeguard public health and the environment.

However, in many LMICs where HCFs still lack basic sanitation systems and dispose of their effluents directly into the environment, installing and maintaining advanced wastewater treatment technologies may not be practical given the constrained resources. In such cases, simplified systems like pit latrines, septic tanks and anaerobic baffled reactors can help reduce public health risks compared to direct disposal. However, these simplified systems will not eliminate the risks associated with the emerging compounds found in many HCF effluents, particularly hospitals or larger HCFs. Treating HCF effluents together with municipal wastewater is also not an optimal solution as conventional wastewater treatment plants are not designed for effective removal of emerging pollutants from HCFs. While advanced forms of wastewater treatment might not be viable for many HCFs, particularly in LMICs, they can still enhance existing treatment approaches. Concurrently, partnering with municipalities to strengthen secure wastewater services is crucial.

In addition to simplified systems, advanced on-site wastewater treatment technologies can be employed in HCFs. These include physicochemical technologies such as activated carbon and zeolite adsorption, and biological systems such as activated sludge and constructed wetlands technologies, which are widely used, as well as the emerging membrane bioreactors technology. Advanced oxidation processes such as Fenton and photo-Fenton systems, photocatalytic systems and electrochemical advanced oxidation processes are a group of novel technologies which show the most promising results for elimination of emerging pollutants in HCFs. Finally, it is important to highlight that measures other than technology adoption are important to mitigate the wastewater risk in HCFs – such as source control and separation – as well as appropriate treatment and safe disposal of the faecal sludge generated in the wastewater treatment process.

Conclusion

This report describes a wide range of water supply and wastewater and faecal sludge treatment technologies for HCFs, including existing and emerging technologies. These technologies are described in terms of their suitability for HCFs based on academic literature, with insight into their strengths, shortcomings and applicability for different conditions and situations. This document can serve as a resource for stakeholders and professionals to strengthen their understanding of diverse water and sanitation technologies in the context of HCF requirements.

Contents

Abbreviations

˚C	degrees Celsius
µm	micrometre
AOP	advanced oxidation processes
ARB	antibiotic-resistant bacteria
AS	activated sludge
CW	constructed wetland
DBP	disinfection by-product
EPA	United States Environmental Protection Agency
FS	faecal sludge
FSM	faecal sludge management
GAC	granular-activated carbon
HCF	health-care facility
LED	light-emitting diode
LMICs	low- and middle-income countries and areas
MBR	membrane bioreactor
PAC	powder-activated carbon
PhCs	pharmaceuticals
POU	point-of-use
ppm	parts per million
SDG	Sustainable Development Goal
SODIS	solar water disinfection
UV	ultraviolet
WHO	World Health Organization

1 Introduction

Water and sanitation play a vital role in promoting public health, driving economic development and ensuring quality health-care services. Access to clean water and proper sanitation in health-care facilities (HCFs) is crucial for providing quality care and preventing infectious disease outbreaks and avoidable deaths. HCFs serve as essential components of national health-care systems, delivering a wide range of medical services to the population.

1.1 Unique requirements and challenges of water and sanitation in health-care facilities

Given the nature of the activities conducted within HCFs, water supply and wastewater treatment must be specifically designed to meet their unique requirements. In contrast to municipal water supply and wastewater treatment, water supply and wastewater treatment in HCFs have distinct needs driven by the priority of maintaining a safe and sterile environment despite the higher degree of exposure to hazardous compounds resulting from medical activities. There are two specific requirements:

- **Water supply requirements:** Water supply in HCFs should be consistent and reliable to meet the demands of patient care. Water consumption and the need for a continuous supply in HCFs often exceed those of residential or commercial buildings and require the installation of backup water supply and storage systems. HCFs must adhere to high water quality standards to ensure patient safety and prevent infections. This involves addressing potential risks from external sources of pollution, such as pathogens (e.g. through faecal contamination) and heavy metals, as well as minimizing internal contamination within the HCFs themselves, such as the proliferation of antibiotic-resistant bacteria in plumbing systems. Given that some activities in HCFs may require ultra-pure or sterile water, the inclusion of point-of-use treatment at taps is a common practice in HCF water supply systems.
- **Wastewater and faecal sludge treatment requirements:** Wastewater treatment and faecal sludge management in HCFs must effectively remove a wide range of hazardous compounds, including chemicals, biological agents and radioactive substances, from their effluents before disposal into the environment. Unlike domestic and commercial effluents, which typically have non-significant concentrations of these compounds, some HCFs generate effluents that necessitate advanced treatment technologies in comparison to the conventional treatment methods commonly employed to treat municipal and domestic wastewater.

Due to their specific needs, providing adequate water and sanitation services to HCFs is crucial not only to allow them to function effectively in supporting the health-care system but also to safeguard public health and protect the environment on a broader scale. Innovation through smart practices and technology is also recognized as an accelerator to achieve the Sustainable Development Goals (SDGs) (UN Water, 2021).

1.2 Objective, scope and methods

This is a supporting document supplementing the main output from a study to support informed decision-making on water and sanitation technologies in HCFs: *Water and sanitation technologies for health care facilities: Selecting options for adoption and scale-up in the Western Pacific Region*.

The objective of this document is to **identify key existing and emerging water supply and wastewater treatment technologies that are suitable for the specific needs of HCFs**, as well as to provide a preliminary assessment of their suitability within the broader context of the Western Pacific Region.

A comprehensive review of academic and grey literature on water and wastewater treatment technologies was conducted to achieve this objective and is presented in this report. The scope of the review was limited to water supply technologies and wastewater technologies. Health-care waste disposal and environmental cleaning are beyond its scope.

2 Water supply treatment technologies for health-care facilities

Water supply systems deliver water from a water source to end users, meeting quality and quantity needs. In HCFs, a reliable water supply is important not only for medical activities like patient care and laboratory analysis but also for non-medical functions such as meal preparation, irrigation of green areas, and sanitation and hygiene services for patients, staff and visitors. The range of possible end uses, influenced by factors such as the HCF's scale and setting, impact the selection of water supply technologies.

Water supply systems can be broadly classified into two categories: centralized and decentralized systems. Centralized systems consist of a large intake, surface reservoir or groundwater aquifer, and water treatment plant, from which water is distributed through a network to serve a wide area. In contrast, decentralized systems are physically smaller and can be limited to a small communal area or a single household or facility. The latter is often referred to as an on-site system, specifically designed to meet the water supply needs of a single location.

The decentralized approach allows for a wider range of technologies to be employed, which can vary based on factors such as specific user requirements, local water resources and economic viability. However, decentralization typically entails that end users are responsible for management of the system, including its operation and maintenance, rather than relying on water authorities.

Water treatment technologies must attain treatment levels that guarantee the safety and purity of drinking-water. Acceptable treatment thresholds are governed by national guidelines and standards, which may differ based on location. In cases where national standards are lacking, international benchmarks − such as those provided by the World Health Organization (WHO) (WHO, 2022) − can serve as suitable alternatives. Water quality can also vary according to its end use, with higher standards for water usage in surgical procedures and delivery of newborns in comparison to garden watering and toilet flushing.

The water supply technologies typically employed in HCFs vary based on the presence or absence of centralized systems, commonly referred to as "piped water". Furthermore, point-of-use treatment technologies, typically implemented at individual taps, are employed within HCFs regardless of the overall water supply system used. Lastly, non-conventional sources of water, such as seawater and recycled water, are emerging alternatives to fulfil water supply needs in the face of water scarcity. Consequently, this section is divided into four categories of water supply technologies:

- technologies to meet specific HCF requirements when connected to centralized piped water systems;
- on-site water supply and treatment technologies;
- point-of-use treatment implemented within HCFs for specialized uses; and
- non-conventional sources of water (on-site and/or centralized).

2.1 Connection to piped systems and associated technologies to meet HCF requirements

Centralized piped water systems commonly exist in urban areas and some small towns, and are ideally designed to supply water reliably and continuously. However, this may not always be the case in many low- and middle-income countries and areas (LMICs). Water treatment occurs in large water treatment plants using a series of treatment units usually following a sequence of **coagulation, filtration, sedimentation, filtration and disinfection, followed by distribution**. Because of the scale of such systems, the technologies used in large water distribution plants are out of the scope of this review, and the reader is referred to other literature (Davis, 2010; Verma et al., 2017). Specific technological arrangements may vary and, depending on the context, resultant water quality may also vary, with only some locations in LMICs achieving drinking-water quality at SDG standards. Piped water has the potential to be a safely managed water service (WHO and UNICEF, 2020) and is suitable for most end uses in HCFs. However, in practice, reliability and water quality can significantly vary, with special implications for HCFs in LMICs.

Key issues with centralized piped water systems in LMIC are **intermittency** and **cross-contamination**. Water distribution networks require regular inspections and maintenance to prevent supply disruptions, as well as water quality testing to ensure water quality standards are met. Tasks such as leak repairs and infrastructure replacement are vital for an uninterrupted service (Scheidegger et al., 2015). Unfortunately, in many LMICs limited maintenance and repair of water distribution networks often lead to frequent system failures, resulting in an intermittent water supply and cross-contamination due to undetected leaks (Lee and Schwab, 2005; Chalchisa et al., 2018). In simplified piped systems, often found in rural areas, treatment may be completely absent prior to distribution, which increases the health risk due to contamination at the source. In addition, leaks are common. This decreases the reliability and safety of piped water in practice, which particularly affects HCFs requiring consistent and clean, safe water. Common options to mitigate cross-contamination include increasing the residual chlorine in treated water issuing from the drinking-water treatment plant, and chlorine dosing at key water distribution network points (Amin et al., 2016; Pickering et al., 2019).

A common practice in LMICs to mitigate piped water reliability issues in HCFs is the addition of storage tanks, and a common practice to mitigate water quality issues is the disinfection of piped water (WHO and UNICEF, 2019; WHO 2019). These are put into effect immediately after transition from the water mains to the HCF internal plumbing system (usually after the water meter).

- **Storage tanks** can be raised to take advantage of distribution network pressure, minimizing continuous internal pumping, although this requires a robust infrastructure to support the water tanks. Raised water tanks may also hinder tank maintenance and cleaning. Regular cleaning of water storage tanks, aided by a tank design that allows effective washouts, is imperative to reduce the formation of disinfection by-products (DBPs), which are habitual with all disinfection methods if they involve organic matter or other precursors. However, despite the potential formation of DBPs, pathogen removal should be prioritized over attempts to control DBPs (Xiao et al., 2020).
- **Disinfection** can be performed by application of heat (e.g. boiling at point-of-use), chemicals (e.g. chlorination), filtration (e.g. ceramic filtration) or light (e.g. ultraviolet disinfection). Even though disinfection methods have trade-offs in terms of energy, time and equipment requirements, all of them to a considerable extent remove most intrusive pathogens (Xiao et al., 2020).

2.2 On-site water supply and treatment technologies

On-site water supply is required when there is no access to piped water or when existing piped water is too unreliable and contaminated. This is the case particularly in rural or remote areas.

In such settings, HCFs need to establish their own water supply and treatment system using nearby water sources. The configuration and technologies implemented will depend largely on the water source available, scale of the HCF, and available resources to implement and operate the system. **Wells**, **boreholes**, **rainwater harvesting**, **compact water treatment systems** and **wastewater reuse** are alternatives that can be used for both drinking and non-drinking purposes in HCFs. Relevant on-site water supply technologies are described below, ordered by water source (groundwater, surface water, rainwater or wastewater reuse).

2.2.1 On-site water supply using groundwater

Compared to surface waters, groundwater stored in aquifers offers greater protection against pollution from human activities and animal sources. In addition, natural processes like filtration and movement through rocks and granular media contribute to the purification of groundwater, making it a relatively clean water source. Groundwater is widely used in LMICs in the South Asia and South-East Asia as a relatively clean water source compared to surface water (Carrard et al., 2019; Foster et al., 2021).

Groundwater intake technologies

Wells, boreholes and springs, with waters acquired wither through motorized pumps, handpumps of manual collection using buckets are are commonly employed to access groundwater, including for HCFs.

While motorized pumps offer convenience, they require electricity or fuel and periodic maintenance, access to spare parts and skilled personnel for repairs. Solar-powered setups are increasingly cheaper and viable alternatives for locations with extended periods of sunlight throughout the year. However, they also require access to spare parts and skilled personnel, and the lack thereof can ultimately lead to system failure (Ward et al., 2023).

In contrast, manual water collection via handpumps does not require electricity or skilled personnel for system operation but has significantly lower volume capacity than motorized systems and requires staff time, which may present a constraint. It often necessitates additional storage solutions, which can heighten the risk of contamination if proper treatment and disinfection measures are not implemented.

It is important to regularly monitor both the quality and quantity of groundwater, as these factors can vary significantly depending on geological conditions (e.g. presence of limestone formations leading to hard water), contamination from nearby sanitation systems, and human activities such as agriculture or mining. Over-pumping can also impact groundwater availability and, in coastal areas, lead to seawater intrusion.

Groundwater treatment technologies

When the water is used for drinking purposes, it should be free of microbial contamination before consumption or for specific end uses in HCFs. Potential treatment technologies are described below:

- **Chemical treatment** may be required depending on the characteristics of the groundwater for removal of minerals, such as iron, manganese, arsenic and chromium, and demand advanced treatments such as nanofiltration (Katsanou and Karapanagioti, 2019).
- **Disinfection** may not be needed in some groundwater sources, and the most common treatment scheme for boreholes and wells is a combination of softening, aeration and disinfection (Katsanou and Karapanagioti, 2019). Chlorine dispensers have been used as an emergency treatment in Africa (Yates et al., 2015; Kahuho et al., 2019), and novel in-line piped water dosers can increase safe water access without electricity or moving parts (Powers et al., 2021).
- **Softening** water is particularly beneficial for activities such as washing, as it reduces soap requirements and improves cleaning efficiency. In addition, it is important for plumbing maintenance, especially in hot-water pipes, where the accumulation of precipitates from hard water can cause issues.

2.2.2 On-site water supply using surface water

Surface water is more susceptible to contamination and requires more treatment than groundwater. Typically, removal of suspended solids, dissolved compounds and disinfection is required for most surface water. This can be achieved with technologies employing physical (e.g. filtration), chemical (e.g. adsorption) or biological (e.g. depuration) processes, or a combination of these.

Like groundwater, surface water intake can be motorized or may be gravity-fed, with similar trade-offs in terms of requirements for electricity, skilled personnel, storage and treatment.

Among the wide range of water treatment technologies, granular filters and membrane-based systems are two important surface water treatment technologies suitable for HCFs.

Surface water treatment technologies

- **Granular media filters:** Removal of suspended materials can be achieved by means of media filters with or without coagulation. Media filters not only remove suspended materials but also remove portions of dissolved materials by adsorption and biologically active microorganisms in biofilms developed over the media. Slow sand filtration is often used for community water treatment in LMICs, in combination with a roughing filter when maintenance or transport of chemicals is limited or not possible (Abdiyev et al., 2023). However, media filters per se often do not meet drinking guidelines, especially during periods of excessive raw water turbidity during wet seasons (Peter-Varbanets et al., 2009). Inadequate operation of filters and lack of maintenance also affect filter performance, and natural disinfection relying exclusively on such systems is often not achieved and requires complementation. Sand filters are widely used in municipal water treatment plants and have been implemented as on-site water treatments to improve water quality delivered to hospitals (for example, in Indonesia − see Fitrianingsih et al., 2022); they are therefore recognized as an established mature technology.

- **Membrane-based systems:** An emerging area of technology is compact water treatment plants relying on membrane technologies. Membrane technology can be an attractive solution because it produces high-quality water with reduced treatment stages and infrastructure (Churchhouse and Wildgoose, 2000). Membrane systems are constructed in a modular form, which enables easy adaptation of process scale. Membrane processes employ a semipermeable film (membrane) and a driving force to achieve water treatment objectives. This driving force can be pressure, temperature or electric potential. Most membrane processes are pressure-driven and known as membrane filtration processes. However, electrically driven methods like electrodialysis and thermally driven processes can also be used for water treatment. The pore size of the membranes will affect which compounds can be removed, as well as how the unit should be operated (Ang et al., 2015). Membrane systems for water potabilization have been identified as an emerging technology to ensure drinking-water in LMICs, including safe and clean water provision to hospitals (for example, in Ecuador − see Arnal et al., 2001).
    - *Ultrafiltration* membranes have tiny pores that can remove microbiological hazards such as *Cryptosporidium* spp., *Giardia* spp., bacteria and most viruses.
    - *Nanofiltration and reverse osmosis* are used to remove inorganic contaminants from water. Nanofiltration is good for removing bivalent ions, while reverse osmosis is needed for monovalent ions. Reverse osmosis is commonly used in desalination to turn seawater or brackish water into freshwater. Affordability and operational costs, along with the need for skilled personnel, pose challenges to implementing membrane technologies for water treatment in poorer regions of LMICs.

2.2.3 On-site water supply using rainwater

Rainwater collection is a common form of water supply in the Pacific region (Foster et al., 2021). Rainwater is a clean water source, even though it can present significant alterations in pH due to reaction with compounds in the atmosphere, particularly in industrial areas, resulting in acid rain (Abbasi et al., 2013). The most significant source of contamination for rainwater is during the harvesting and storage processes.

Rainwater harvesting and distribution

Rainwater harvesting involves collecting rainwater from a designated catchment area, typically the roof of a building. The rainwater is then directed through gutters and downpipes to storage tanks. From there, it can be distributed to various points of use as needed using a pump. Alternatively, it can be conveyed to an elevated storage tank for gravity-fed distribution, or it can be manually collected through taps installed in the storage tank itself.

To ensure the quality of the harvested rainwater, specific treatment practices are commonly employed to address potential contamination from debris accumulated in roofs and gutters, and cross-contamination from construction materials such as asbestos and lead (Gould, 1999; Vieira et al., 2014):

1. **First flush diversion:** This practice prevents excessive concentrations of suspended solids, pathogens and organic matter from entering storage tanks by diverting the initial runoff during rainfall.
2. **Gross filtration:** Strainers are installed to prevent the ingress of large pollutants (e.g. leaves).
3. **Fine filtration:** Filters are utilized to further reduce pathogens and enhance the aesthetic quality of the water by removing smaller particles and impurities.

4. **Disinfection:** To meet potable water standards, disinfection is essential. This can be achieved through ultraviolet (UV) treatment (traditional or light-emitting diode [LED]), chemical disinfection or boiling.

Due to the variable nature of rainfall, it is important to appropriately size rainwater tanks to meet water demands during periods of drought. HCFs relying exclusively on rainwater tanks may require excessively large tanks that are impractical within the available space. However, underground tanks are also possible. To address this challenge, rainwater harvesting can be combined with other water supply technologies to meet specific water demands in HCFs, especially for non-potable uses where disinfection is not required.

2.2.4 On-site wastewater reuse

In HCFs, not all water uses require drinking-water quality. By implementing changes in the plumbing design of water and wastewater systems, it becomes possible to reuse certain types of wastewaters for less strict purposes with minimal or no treatment.

Integrated precinct plumbing design

The integrated precinct plumbing design approach involves segregating different wastewater streams. Kitchen greywater, which contains higher concentrations of fats, can undergo a simplified wastewater treatment, such as a primary treatment to separate fats through decantation before being used for garden irrigation (Allen et al., 2010). Other solutions include directing water from sinks to toilets to minimize use of potable water for flushing.

These solutions primarily aim to alleviate stress on water resources and are typically implemented in situations where water scarcity is a concern. However, in many countries where water is abundant and inexpensive, there may be little economic incentive for water conservation measures, such as alternate plumbing designs. Retrofitting existing HCFs with these systems can be economically unfeasible, and it may be more practical to prioritize such solutions in new HCFs where non-potable water uses are significant.

2.3 Point-of-use treatment within health-care facilities for specialized uses

Point-of-use (POU) treatment in HCFs is an important aspect of water treatment to safeguard patient and staff safety and provide water of high purity for specific medical activities at appropriate scale and cost.

Patients in HCFs, especially those with weakened immune systems, are particularly susceptible to waterborne diseases. Implementing POU water treatment provides an extra layer of protection by removing potential cross-contamination at precinct level.

In addition, plumbing systems in HCFs can harbour resistant microorganisms. Biofilm grows naturally within pipes filled with water, and the frequent exposure to strong antibiotics in HCFs can result in resistant microorganisms thriving within plumbing systems despite the presence of disinfection stages in the water supply system (Cervia et al., 2008). POU treatment directly before water use helps minimize the presence of these microorganisms, safeguarding both patients and health-care workers from infections.

Moreover, specialized medical activities such as laboratory analysis, diagnostics and other procedures require ultra-pure water that is free from impurities, such as minerals found in potable water. POU treatment ensures the provision of ultra-pure water directly at the tap in appropriate volumes, meeting the stringent requirements for these specialized applications.

2.3.1 Point-of-use sterilization

There are four main types of POU treatment that support sterilization of small quantities of water for specific uses.

- **Filtration at the tap** is the most common practice in hospitals to prevent the passage of bacteria, and has been shown to be effective to control antibiotic-resistant bacteria (ARB) outbreaks arising from the internal plumbing system in hospitals (Ortolano et al., 2005; Cervia et al., 2008). Characteristics of the filter include a maximum porosity of 0.45 micrometres (μm), even though practitioners recommend opting for filter grades of up to 0.2 μm (Macdonald et al., 1989). Membrane filters are also an emerging technology. Regular maintenance and replacement of POU filters is required to avoid microorganisms building up on the filter itself, which depends on the volume of water filtered and characteristics of the filter (Szewzyk et al., 2000).

- **Exposure to sunlight** is a low-cost and simple alternative for on-demand sterilization via systematic exposure of water to sunlight in a process known as solar water disinfection (SODIS). SODIS can be performed in batches by placing the water in bottles or plastic bags or in continuous flow systems (SODIS reactors), the latter method being designed to provide disinfected water to institutions such as hospitals and schools (Sommer et al., 1997). SODIS is not an instantaneous POU treatment, requiring a few hours for disinfection to occur.
- **Boiling** water is another simple method for sterilizing it, since a high temperature (> 77 degrees Celsius [˚C]) kills most pathogens present in HCFs (Ortolano et al., 2005). However, it is an energy- and time-intensive solution that becomes impractical for large volumes.
- **UV filters using LEDs** is another emerging technology which requires further testing.

2.3.2 Point-of-use high-purity water

Water with high purity is essential for various medical laboratory activities, such as analytical chemistry, microbiology and molecular biology, cell cultures and clinical diagnostics. POU water treatment is an economically viable solution for activities that require smaller quantities of highly purified water, providing on-demand high-purity water supply. Common methods used to produce water with high purity include distillation, reverse osmosis, deionization and carbon filtration, as described below:

- **Distillation** involves heating water to create steam and then condensing it to remove impurities. It is a relatively cheap method that does not require sourcing specific materials, but it can be time-consuming and energy-intensive.
- **Reverse osmosis** utilizes pressure to force water through a semipermeable membrane, effectively removing dissolved solids and contaminants. It is a relatively expensive process that produces high-grade water (Williams, 2022).
- **Deionization** employs ion-exchange resins to remove ions from water, achieving water suitable for most analytical chemistry tests (Volfkovich, 2020). It rapidly removes both positive and negative ions but requires supply and maintenance of specific resins.
- **Carbon filtration** passes water through activated carbon filters to remove chlorine, organic compounds and volatile contaminants. It can enhance the taste and odour of water and provide additional purification (Bhatnagar et al., 2013). Carbon filters are more readily available than other materials, such as deionizing resins and semipermeable membranes, but require frequent replacement.

POU treatment methods can be combined to meet specific purity requirements in HCFs, considering impurity type and concentration in the feed water, desired water quality and specific activity needs.

2.3.3 Complementary actions to point-of-use technologies: plumbing management strategies

Operation and maintenance practices can be implemented to prevent biofilm growth in plumbing systems, as well as intensive treatment to remove biofilm build-up after outbreaks. **Stagnant water** within the plumbing system provides favourable conditions for bacterial colonization and proliferation. Special attention should therefore be given to specific points in the plumbing system, including dead-legs, heat exchangers and holding tanks, as they are prone to creating suitable environments for biofilm development (Chinn and Sehulster, 2003). By actively avoiding stagnant water and implementing appropriate maintenance practices, HCFs can help control biofilm growth and minimize the risk of bacterial contamination in their water systems.

Systematic disinfection of the plumbing system is a response action to remove established microorganisms within pipes. Two common methods used are chemical disinfection and heat treatment. Chemical disinfection, typically employing chlorine-based compounds, can effectively eliminate microorganisms; however, it can be costly and challenging to implement. It requires a minimum contact time between the disinfectant and microorganisms, often ranging from 10 to 50 parts per million (ppm) for 12 to 24 hours for shock treatment and 1 to 2 ppm for continuous treatment (Le Dantec et al., 2002). This process may temporarily impact the water supply during the disinfection period. In addition, the use of chemicals for disinfection can potentially accelerate corrosion of pipes. In hot water plumbing systems, another option is superheating the water to temperatures between 71 to 77 ˚C, followed by system flushing (Le Dantec et al., 2002). This method can effectively eliminate microorganisms present in the hot water plumbing system.

2.4 Non-conventional sources of water (on-site and/or centralized)

Non-conventional sources of water, such as seawater desalination and wastewater reuse, are emerging as innovative solutions for water supply. Utilizing advanced technologies like reverse osmosis and membrane filtration, seawater can be converted into freshwater, providing a reliable and sustainable source in regions facing freshwater scarcity. Furthermore, treating and reusing wastewater offers a dual benefit: it alleviates strain on freshwater resources and provides an alternative water source for non-potable purposes such as agriculture and industrial processes.

2.4.1 Seawater and brackish water desalination

Seawater and other brackish water sources have increased levels of salts, affecting their usability as this kind of water cannot be used for most drinking (e.g. cooking) and non-drinking end uses (e.g. washing). Advancements in water treatment technologies now enable water desalination from saline and brackish sources (Qasim et al., 2019).

Desalination technologies

The most common technology types to achieve desalination are **electrodialysis**, **multi-effect distillation**, **multistage flash**, **nanofiltration** and **reverse osmosis**. Reverse osmosis is the technology type most used since the early 2000s (Williams, 2022). The reverse osmosis process is based on the application of pressure over a solution with a high concentration of salts which flows through a semipermeable membrane into a solution with a low concentration of salts. This process is considerably energy-intensive because of the significant differences in osmotic pressure between the desired product water and the saline or brackish raw water. Dilution of seawater with other freshwater sources (e.g. groundwater, recycled water) is an alternative to reduce energy requirements during the desalination process (Pazouki et al., 2021).

Desalination technology can produce high-quality drinking-water with low levels of impurities and pathogens. However, the cost of desalination remains relatively high, especially in regions where freshwater resources are abundant and water is inexpensive. Advancements in technology design are pushing the boundaries for modular, low-intensity energy, operation and maintenance devices to desalinate water − such as ion exchange membranes for membrane capacitive deionization, which have been trialled in Viet Nam (Hellriegel et al., 2020).

Despite the cost, desalination plants offer advantages over traditional water management practices such as river dams and reservoirs. Desalination plants typically have a smaller physical footprint and can avoid the need for complex coordination and interregional cooperation for water transfers and riparian management (Williams, 2022). In addition, solar-powered desalination plants provide a way to address energy requirements.

However, it is important to note that a water supply using current desalination technologies is unlikely to be financially viable without economies of scale. The large capital expenditure combined with complex operation and maintenance required for desalination plants make their sustainable implementation in LMICs currently challenging. While desalination holds promise for addressing water scarcity challenges, affordability and scalability remain key considerations in making this technology more accessible and cost-effective.

2.4.2 Recycled water and wastewater reuse

Improvements in treatment technologies and water system design enable tailored solutions using wastewater as a water source. Using wastewater as a water source can alleviate the pressure on existing water supplies and protect remaining water bodies from being polluted. However, treatment and end use in the context of a HCF should be carefully controlled to minimize contamination risks.

The term “recycled water” generally refers to treated wastewater that meets specific water quality standards, allowing it to be reused for specific human purposes based on its classification. While state-of-the-art treatment technologies have the capability to transform pure blackwater into drinking-water, the economic viability of this approach for real water supply is often a challenge.

The primary goal of producing recycled water is to alleviate stress on freshwater resources by utilizing non-conventional water sources. To do so using wastewater, it is essential that pathogens are removed to significantly low levels to ensure public health. Removal can be effectuated either through engineering practices, also referred to as direct reuse, or indirectly through an environmental buffer (EPA, 2012; Gerrity, 2013). The treatment trains utilized are diverse depending on the end use and pathogen removal method (i.e. direct or indirect). The United States Environmental Protection Agency (EPA) has guidelines for water reuse with detailed examples of technologies and treatment train arrangements for large and medium recycled water systems, including key aspects such as maintenance and operation requirements (EPA, 2012).

While centralized recycled water supply systems exist in developed economies around the world (e.g. Australia, Israel, United States of America) where water scarcity is a major challenge, their implementation in LMICs is limited due to the associated costs of implementing a dedicated infrastructure, and the need for strengthened institutions to regulate, maintain and operate such systems. This said, there is an opportunity for LMICs to leapfrog towards adoption of these technologies where sufficient expertise exists.

2.5 Summary of water supply and treatment technologies

Provision of water to HCFs should focus on constant and safe water to ensure effective delivery of health services. The **diversity of water end uses** and consequent water quality requirements within HCFs may require a combination of several technologies to achieve a sustainable water supply. Key considerations in selecting appropriate technologies include cost, required land area, scale, operation and maintenance requirements as well as relevant end use.

To increase **resilience, including climate resilience** of the water supply system, relying on more than one water source and technology is encouraged if the capacity to operate and maintain the systems exists. For instance, rainwater systems can be used as backup systems to piped water during moments of service interruption, and vice versa during periods of extended drought.

Scale of the systems and associated costs are imperative considerations on top of treatment performances. Some technologies are viable only for large or small water volumes due to the associated cost of implementation. For instance, it may become unviable to construct a treatment train for softening, aeration and disinfection for very small volumes of water. Similarly, manual or hand pumping of groundwater for large volumes may become unfeasible due to the time and manpower needed to collect the requisite daily volume of water.

Integrated management and design solutions, such as design improvements in the HCF plumbing system, can reduce water requirements for less strict uses, such as toilet flushing and watering gardens. These measures are often in place where water scarcity is present and measures to reduce water loss well established. In many LMICs, however, this is not the case: water losses may be considerable and water not priced in line with its value.

3 Wastewater treatment and faecal sludge management

Wastewater treatment and faecal sludge management are essential components of HCF operations to ensure public health and environmental protection. Health-care services rely on the use of chemical substances for diagnosis, treatment, disinfection and patient recovery, accounting for approximately 20−25% of total medicine usage among humans, with some hospitals utilizing tons of medications annually (Oliveira, 2018). As a result, HCF effluents are five to 15 times more toxic than domestic wastewater (Akin, 2016). Because of this, unlike domestic and municipal wastewater, HCFs generate wastewater with elevated concentrations of emerging contaminants, such as ARB and pharmaceuticals (PhCs). The concentration of pathogens in HCF effluents can be a concern, particularly when patients with enteric infections seek treatment. Without proper treatment, the increased presence of pathogens poses elevated health risks, particularly in LMICs with inadequate basic sanitation systems. However, there is a scarcity of literature addressing this specific issue, underscoring the need for further research and attention in this area.

3.1 Antibiotic-resistant bacteria

The global prevalence of ARB has become a pressing issue in recent years, raising serious concerns about their impact on human health. ARB refers to bacteria that possess the ability to survive and proliferate despite the presence of antibiotics and conventional disinfection agents designed to target and eradicate them.

HCFs provide a conducive environment for the dissemination of ARB due to the elevated bacterial load and presence of PhCs. Many antibiotics are not extensively metabolized in the human body and many are primarily excreted in the urine. Moreover, some pathogens in infected patients are also eliminated via the same route. Consequently, hospital urine is often found to contain higher concentrations of ARB compared to effluent from the general population, and elevated levels of ARB are likewise to be expected in wastewater from HCFs.

3.2 Pharmaceuticals

HCF wastewater contains a diverse range of PhCs belonging to various therapeutic classes. These include antibiotics, psychiatric and cardiovascular drugs, lipid regulators, antidiabetics, analgesics, anti-inflammatories, contrast media, hormones and antiviral/anthelmintics.

Over the past few decades, the presence of anticancer or antineoplastic drugs in hospital wastewaters has also increased, and their detection in wastewater and surface water has raised concerns. These compounds exhibit cytotoxic, genotoxic, mutagenic, carcinogenic and teratogenic effects, posing risks to both wildlife and human health (Kümmerer et al., 2016).

While most PhCs in HCF effluents are typically found at concentrations below 10 micrograms per liter; some PhCs, such as paracetamol, cyclophosphamide, amoxicillin, iomeprol and iopromide, may exhibit higher concentrations (Verlicchi et al., 2010).

3.3 Wastewater treatment technologies for health-care facility wastewater

The composition of wastewater in HCFs is influenced by the specific activities conducted within the facility, which vary based on the HCF type and size (Zhang et al., 2020). Given the diverse range of activities performed in HCFs, multiple effluents with different compositions are generated. Consequently, treatment of these effluents may require the application of distinct technologies depending on the characteristics of each effluent.

The selection of wastewater treatment technologies in HCFs has to consider other factors besides effluent composition, such as wastewater volume and disposal requirements, compliance with regulations and environmental standards. Like water supply systems, wastewater treatment and faecal sludge management can be centralized or decentralized.

Centralized systems involve a sewerage network directing effluents from households and commercial establishments to a municipal wastewater treatment plant. However, HCF effluents differ significantly from typical sources, rendering municipal plants inadequate for their treatment. PhCs and ARB present in HCF effluents can disrupt biological processes and increase health and environmental hazards. Adaptations are therefore necessary for HCF effluents to be treated in municipal plants. The process of treating HCF effluents at both the HCF and municipal wastewater treatment plant is commonly referred to as "co-treatment".

In situations where HCFs are not connected to sewerage systems and centralized wastewater treatment plants, on-site treatment is necessary before the effluent is released into the environment. The extent of the treatment required is typically determined by local regulations establishing minimum water quality standards: these are based on factors such as the volume of effluent generated and characteristics of the receiving environment (e.g. surface water, sensitive areas such as wetlands, etc.). In the absence of local regulations, international guidelines such as those provided by WHO (WHO, 2013) set out safe levels for wastewater disposal and reuse for various activities.

It is important to note that current regulations for wastewater disposal often do not comprehensively address most of the micropollutants found in HCF effluents. These micropollutants may include pharmaceutical residues, personal care products and other compounds associated with medical activities. Additional measures may therefore be necessary to address these specific pollutants and safeguard water resources and ecosystems.

Wastewater treatment is commonly classified into three levels: primary, secondary and tertiary/advanced treatment.

- *Primary treatment:* This initial stage involves the physical removal of large solids and floating debris from the wastewater, resulting in a reduction of the organic load and concentration of suspended solids.
- *Secondary treatment:* Building on primary treatment, the secondary stage aims to further decrease the organic and biological content of the wastewater. This is typically achieved through biological processes that are carefully regulated and controlled hydraulically.
- *Tertiary/advanced treatment:* Tertiary treatment focuses on the removal of specific contaminants beyond what is achieved in primary and secondary treatment. It targets nutrients such as nitrogen and phosphorus, pathogens and other emerging contaminants – for example, antibiotics, endocrine-disrupting compounds and personal care products.

These three treatment levels work in conjunction to progressively improve the quality of the wastewater, addressing different types of pollutants and achieving specific treatment objectives. HCF effluents differ from those of households and most other commercial establishments due to the need for targeted treatment of specific pollutants, even though previous studies have shown that conventional primary and secondary treatment can partly remove some of these pollutants (Verlicchi et al., 2010; Verlicchi et al., 2015; Verlicchi, 2018; Khan et al., 2021). In addition, because of the variety of activities performed in HCFs, wastewater and liquid waste management can significantly influence the design of the wastewater treatment solution. This section is therefore divided into three categories:

- co-treatment: preliminary treatment at HCFs for disposal in sewerage systems;
- on-site wastewater and sludge treatment technologies; and
- wastewater and liquid waste management practices.

3.4 Co-treatment: preliminary treatment at health-care facilities for disposal in sewerage systems

Conventional municipal wastewater treatment plants use technologies to remove suspended and colloidal particulates, dissolved organics, nutrients and pathogens from wastewater; however, they are not designed for efficient removal of emerging contaminants such as PhCs, and ARB, present in significantly higher concentrations in HCF effluents (Akin, 2016; Tran et al., 2018). Elimination efficiencies for these compounds in municipal wastewater treatment plants range between 10% and 90% (Verlicchi et al., 2010).

Because of this, pre-treatment of the HCF effluent is required before it is evacuated into the sewers. This practice – often termed "co-treatment" – is performed in many countries (Al Aukidy et al., 2018), even though on-site treatment is generally preferred to co-treatment (European Directive, 2010). It is important to note that some authors do not consider co-treatment to be an adequate solution (Altin et al., 2003; Pauwels and Verstraete, 2006; Vieno et al., 2007).

Co-treatment at HCFs usually employs techniques which aim to oxidize resistant microorganisms and emerging compounds such PhCs, hormones and antibiotics. The use of chemicals such as chlorine can be a cost-effective option for removing microorganisms and is a recurrent practice in HCF wastewater co-treatment (Emmanuel et al., 2005). However, incorrect dosages of chlorine can increase ARB concentrations during co-treatment (Wang et al., 2020; Yao et al., 2021). Furthermore, the application of chlorine-based chemicals in the raw wastewater can promote significant production of mutagenic and cancerogenic DBPs due to the high concentration of organic compounds in wastewater.

Alternatives relying on advanced oxidation processes (AOPs) can improve disinfection efficiencies and biodegradability pollutants for subsequent treatment phases, while avoiding formation of DBPs. Ozonation, Fenton and photo-Fenton processes have been identified as suitable solutions for co-treatment at HCFs (Kajitvichyanukul et al., 2006; Berto et al., 2009), removing some, but not all, emerging contaminants and resistant microorganisms (Verlicchi et al., 2010; Khan et al., 2021). However, control of the process parameters is complex and crucial for effective treatment.

The plurality of micropollutants, all exhibiting different chemical properties, and the presence of resistant microorganisms means that there is no specific treatment able to remove, at a high percentage, every kind of micropollutant typically found in HCF wastewater (Verlicchi et al., 2010). Improved solutions should aim to perform a more comprehensive treatment, which is ultimately likely to favour on-site or near-on-site treatment (Altin et al., 2003; Pauwels and Verstraete, 2006; Vieno et al., 2007).

3.5 On-site health-care facility wastewater treatment

An HCF on-site wastewater treatment system must remove not only the specific pollutants that differentiate HCF wastewater from domestic and municipal wastewater but also common pollutants such as suspended solids, organic matter and nutrients. A complete treatment train comprising primary, secondary and tertiary treatment must therefore be implemented in on-site wastewater treatment in HCFs.

The possibilities for arranging wastewater treatment technologies in a treatment train are vast: an exact configuration requires a full and precise characterization of HCF wastewater and targeted micropollutants. A strong research effort has been made in the last decade to assess the performance of conventional and advanced treatment technologies and their combination, at various stages of wastewater treatment, to remove emerging contaminants in general (Verlicchi et al., 2015; Verlicchi et al., 2010; Khan et al., 2021; Rout et al., 2021), ARB (Herraiz-Carboné et al., 2021), PhCs (Pariente et al., 2022) and antibiotics (Khan et al., 2020).

Key wastewater treatment technologies for HCF effluents can be grouped into:

- *Physicochemical:* Chemical and electrocoagulation, flocculation, sedimentation, activated carbon adsorption, zeolites adsorption and chemical disinfection.
- *Biological systems:* Simplified biological treatment (pit latrines, composting, septic tanks, anaerobic baffled reactors) (noting limits to their treatment capacity), activated sludge (AS), bioreactors and constructed wetlands (CW).
- *Advanced oxidation processes (AOPs):* Ozonization, Fenton and photo-Fenton systems, photocatalytic systems and electrochemical advanced oxidation.

Each type of treatment technology has strengths and limitations in the removal of waste streams specific to HCFs. This review presents key technologies reported in the literature, highlighting information about their role in the treatment train (i.e. primary, secondary or tertiary treatment) and combination with other technologies, efficacy against emerging contaminants such as ARB and PhCs, and technology characteristics in terms of cost, area, operation and maintenance.

3.5.1 Physicochemical treatments

Physicochemical treatments can constitute either a single stage in the HCF wastewater treatment train, or an additional treatment during pre-treatment to improve the biodegradation of wastewater by secondary treatment: it usually employs a biological process or a polishing step for additional disinfection after tertiary treatment. Most physicochemical treatments target very specific compounds since characteristics (e.g. polarity, size, functional group and charge) vary significantly among PhCs (Rout et al., 2021).

Most of the studies assessing physicochemical treatments as a single stage in HCF wastewater treatment are incipient and have been performed to date only at bench scale, indicating that the technology is still in development (Pariente et al., 2022). The majority of the technologies are dependent on specific materials and equipment, such as carbon-based adsorbents, natural coagulants and titanium electrodes, which react with target-emerging contaminants, such as ofloxacin (Sponza and Alicanoglu, 2018), moxifloxacin (Van Doorslaer et al., 2015), iprofloxacin (Ahmadzadeh et al., 2017) and cefazolin (Esfandyari et al., 2019).

3.5.2 Activated carbon

Activated carbon adsorption is the most extensively used adsorbent for a broad spectrum of emerging contaminants, being used either as a powder-activated carbon (PAC) or a granular-activated carbon (GAC) (Rodriguez-Narvaez et al., 2017; Rizzo et al., 2019). PAC is often employed as an additional pre- or polishing treatment, while GAC is usually a dedicated treatment stage, often in tertiary treatment. PAC as a polishing step after tertiary treatment has been identified as one of the most promising alternatives for HCFs treatment, and accordingly attracts the bulk of research (Khan et al., 2021).

While removal of PhCs using PAC and GAC varies widely according to the compound, in general they can remove 90% of remaining PhCs after conventional treatment (Rout et al., 2021). A team investigated the removal of 66 PhCs using PAC and found that only nine had removal efficiencies of less than 50% (Snyder et al., 2006). PAC adsorption has displayed removal rates of up to 90% for endocrine disrupters (Schafer et al., 2003).

Activated carbon adsorption is a fairly compact treatment but requires relatively expensive materials that may not be easily found in some regions, besides requiring proper operation and cleaning to increase the lifespan of the material.

3.5.3 Chemical flocculation and disinfection

The addition of chemical flocculation as a pre-treatment has been shown to increase the removal of some PhCs during subsequent biological treatment (Sim et al., 2013). However, it is important to highlight that many other factors, such as biological treatment operation conditions, can also affect the removal of PhCs (Pariente et al., 2022).

Chemical disinfection as a polishing stage is usually performed after a biological process. Application of chlorine or ozone to kill pathogens is a common practice in water treatment but has shown limited efficacy in removing ARB (Herraiz-Carboné et al., 2021) and, in some cases, may even increase their concentration in wastewater (Yao et al., 2021). Chemical disinfection can produce DBPs if organic compounds are present. UV disinfection, as an AOP treatment, can achieve similar disinfection rates to chemical disinfection but with a reduced risk of DBP formation. Chemical disinfection is a widely implemented technology.

3.5.4 Zeolites

Metal-exchanged natural zeolites have emerged as a promising approach for mitigating ARB in wastewater. Zeolites, known for their high cation-exchange affinity, possess antibacterial properties. In one study, a metal-exchanged zeolite called clinoptilolite − enriched with silver in a bead filter system − was able to completely remove the ARB *Acinetobacter baumannii* when the zeolite was used as a polishing step after tertiary treatment (Ivankovic et al., 2019).

3.5.5 Biological treatment technologies

Biological treatments are the most employed method to treat wastewater, usually constituting the secondary and/or tertiary treatment stage. Treatment units are designed and manipulated to foster the development of microorganisms that use pollutants in the wastewater as a source of energy for their growth.

This environmental manipulation is mainly achieved by hydraulic design and operation, and by the addition of energy or air via mixers and aerators. Bed media to support the growth of microorganisms, besides providing a physical component to filter particles, can also be included in the biological treatment unit.

Consequently, an array of biological treatment methods exists. Some treatment methods have to be strongly manipulated to foster optimal conditions for microorganism growth and therefore pollutant removal, requiring more energy and operation but being more compact. In contrast, other technologies – often referred to as "nature-based" – receive little active intervention, requiring less energy and operation, but often needing a greater treatment area.

It is important to note that common on-site wastewater treatment and containment technologies in LMICs such as pit latrines, dry composting toilets, septic tanks and anaerobic baffled reactors are unable to significantly remove ARB, PhCs and pathogens. Despite being mature technologies, they are therefore not optimal solutions for treating HCF wastewater without additional treatment steps. However, these technologies do provide some level of primary and secondary treatment, and minimize health risk by containing and isolating effluent from the population. Wherever resources are scarce, they are therefore valid alternatives to direct disposal in the environment and should be put in place rather than having no treatment at all. The reference book *Compendium of sanitation systems and technologies* (Tilley et al., 2014) published by the Swiss Federal Institute of Aquatic Science and Technology, provides more details on the design, construction and operation of such systems.

3.5.6 Pit latrines

Pit latrines are one of the most widely used sanitation technologies, consisting of a lined chamber that contains excreta and cleaning materials, such as water or solids such as toilet paper. Pits aim to optimally accumulate waste by leaching the water phase of the wastewater into the soil while other compounds are partly removed through biological processes. The remainder of material that accumulates in the pit requires emptying, treatment and safe disposal. Because of the characteristics of HCF effluents, the treatment provided in the pit before leaching into the environment will not substantially remove ARB, PhCs or pathogens, potentially leading to environment contamination and public health risks.

Pits can be designed as single, double or ventilated. Double pits aim to reduce the time between emptying and ventilated pits reduce odour and risk of contamination through vectors.

3.5.7 Dry composting toilets

A dry toilet is a toilet that operates without flush water. The dry toilet may be a raised pedestal on which the user can sit, or a squat pan over which the user squats. In both cases, excreta (both urine and faeces) fall through a drop hole and are contained for organic matter and pathogen decay. The decayed material will be transformed into a compost that requires appropriate emptying, treatment and disposal.

Dry toilets do not require water, being suitable alternatives for locations with limited access to water. Because there is no water seal, odours may be a problem if adequate maintenance and cleaning are not performed. It is important to ensure that the composting chamber is isolated and sealed to prevent pollution or public health risks.

3.5.8 Septic tanks

A septic tank is a watertight treatment unit combined with an infiltration pit (soak-away) that is designed to perform primary treatment of the wastewater. Primary treatment is performed by solid particles sinking to the bottom of the treatment unit, while fats and scum float to the surface. At the same time, microorganisms consume organic matter and nutrients, developing into sludge which accumulates in the bottom of the treatment unit. Further treatment takes place in the infiltration pit and soil matrix. Septic tanks have an inlet and an outlet equipped with T-shaped pipe sections to direct the flow and improve sedimentation, flotation and biological degradation.

Because the environment in septic tanks is primarily anaerobic or anoxic, pathogen degradation is relatively low (Tilley et al., 2014). Furthermore, removal of PhCs and ARB is limited. Additional treatment steps are therefore required to remove specific pollutants from HCFs, particularly larger HCFs and hospitals.

3.5.9 Anaerobic baffled reactors

Anaerobic baffled reactors follow similar treatment principles to the septic tank. The main difference is that the treatment unit is compartmentalized into a series of baffles that redirect flow to the bottom of the treatment unit, often with multiple chambers. This greatly improves the removal of suspended solids through retention by the baffles, and removal of organic matter through increased contact with the sludge at the bottom of the treatment unit. Nevertheless, anaerobic baffled reactors still have limited removal efficiency for pathogens, ARB and PhCs, requiring additional treatment to treat HCF effluents containing these pollutants. This applies particularly to larger HCFs and hospitals, for which they should not be considered adequate.

3.5.10 Activated sludge

AS is a well-established and widely used secondary and tertiary wastewater treatment method in municipal and industrial plants. It efficiently removes organic pollutants, suspended solids and nutrients. PhCs and ARB are either removed through sorption in the sludge or by biodegradation. It is important to emphasize that the pollutants adsorbed in the sludge must be treated subsequently after it has been eliminated from the AS process.

Complete removal of PhCs and ARB can however be challenging because AS systems are not primarily intended to remove these compounds. Operational adjustments, such as modifying sludge and hydraulic retention times, as well as the redox potential, can enhance the treatment efficiency for PhCs and ARB (Herraiz-Carboné et al., 2021; Khan et al., 2021; Rout et al., 2021).

AS is a mature technology requiring skilled personnel for operation, and its effectiveness can be further enhanced when combined with physicochemical or advanced oxidation processes as pre- or polishing treatment steps. This integrated approach can be a suitable solution for HCFs with the necessary resources to implement and operate such systems.

3.5.11 Membrane bioreactor

Membrane bioreactors (MBRs) are secondary and tertiary wastewater treatment systems that combine biological processes with membrane filtration. They integrate AS treatment with a membrane separation process, typically using microfiltration or ultrafiltration membranes. In an MBR, the wastewater is treated in an aeration tank resembling a conventional AS system. However, instead of settling the sludge in a separate tank, membranes are used to separate the treated effluent from the biomass.

MBRs offer several advantages over conventional biological treatment systems like AS. The membrane barrier enhances solid–liquid separation, resulting in a higher-quality effluent with low turbidity and improved removal of particulate matter, pathogens and some dissolved substances. MBRs also have a smaller footprint compared to AS, as separation of solids and liquid occurs within the same tank. The retention of biomass in the system allows for a longer sludge retention time, promoting better degradation of organic compounds. Operation of MBRs requires skilled personnel, and optimization of operational controls for different effluents is still under active research for this emerging technology.

Studies have shown that MBR systems have 30–50% higher removal rates than AS processes for several PhCs, although for emerging pollutants such as ibuprofen, methyl paraben, galaxolide, triclosan and caffeine there was no significant difference in removal efficiencies between the technologies (Oppenheimer et al., 2007; Verlicchi et al., 2010).

MBRs have been shown to be effective in removing pathogens from HCF wastewater (Nielsen et al., 2013). Removal of *Escherichia coli*, total coliforms and total enterococci was higher than in conventional AS (Nielsen et al., 2013). However, ARB removal is still limited and polishing the treated effluent with physicochemical or AOP treatments is recommended (Herraiz-Carboné et al., 2021).

3.5.12 Constructed wetlands

CWs are engineered ecosystems with a large population of microorganisms and vegetation that promote physicochemical reactions able to degrade contaminants (Vymazal, 2005). In subsurface CWs, the wastewater passes through a bed medium which, besides acting as a filter and sorbent, also provides support to the development of microorganisms that degrade pollutants. CWs have plants that provide oxygen to the media through their roots, creating a mixture of anaerobic, anoxic and aerobic regions, which favours a comprehensive removal of pollutants. Furthermore, plants take up nutrients and other pollutants in the wastewater through their roots system and store them in their biomass.

CWs can be designed to be fully saturated, partly saturated or unsaturated, and to work as a single treatment unit or as several units in series (Rousso et al., 2019). CWs have been widely employed as primary, secondary and tertiary treatments for domestic, urban and industrial wastewaters, including HCF effluents (Li et al., 2014; Vymazal, 2014), and are recognized as a mature wastewater treatment technology.

CWs can remove several PhCs, with some being readily removed and a few hardly removed (Li et al., 2014). Some modalities of CWs are more suitable to remove specific PhCs: a combination of CWs − such as hybrid CW or vertical CW with bottom saturation − is recommended; they offer a variety of oxidizing and reducing environments which can remove a more comprehensive range of compounds (Vymazal, 2014).

As a nature-based technology, CWs are susceptible to changes in performance with variations in air temperature and rainfall precipitation. Removal of PhCs is generally higher during summer because high temperatures and sunlight enhance the activity of plants and microorganisms (Li et al., 2014). Intense rainfall can wash out the system and decrease performance temporarily, although CWs have been shown to be resilient systems which are able to recover their regular performance after short periods of extreme events (Rousso et al., 2019).

Regarding disinfection, CWs display a relatively larger pathogen removal rate than other nature-based biological treatments. However, removal of ARB is still limited and polishing the treated effluent with physicochemical or AOP treatments is recommended (Kaliakatsos et al., 2019; González et al., 2020).

3.5.13 Advanced oxidation process treatments

AOPs are an emerging group of tertiary wastewater treatment techniques used to remove complex and persistent contaminants that are not easily removed by conventional methods. These techniques encompass ozonization, Fenton and photo-Fenton systems, photocatalytic systems and electrochemical AOPs.

AOPs in general involve the generation of highly reactive hydroxyl radicals through either ozone (ozonation), a ferrous ion catalyst (Fenton), ferrous ion catalyst and UV (photo-Fenton), titanium dioxide (photocatalytic) or electric current (electrochemical) (Miklos et al., 2018). Hydroxyl radicals have strong oxidative properties and can effectively degrade recalcitrant organic pollutants such as PhCs, besides having a strong disinfectant power able to remove ARB.

A recent review (Pariente et al., 2022) points out that AOPs can generally achieve removal rates of greater than 90% for PhCs. Moreover, AOPs achieve higher removal rates for ARB than all other conventional wastewater treatment systems (Herraiz-Carboné et al., 2021).

AOP processes exhibit fast reaction kinetics, allowing for the use of more compact reactor designs. Moreover, AOPs often require minimal or reduced chemical dosing, resulting in lower residual concentrations. However, it is important to note that the oxidation reactions initiated by hydroxyl radicals may generate by-products which are more challenging to remove than the original organic pollutants and PhCs. Furthermore, some AOPs are still in the early stages of development, requiring ongoing optimization of operational parameters and the involvement of skilled and specialized personnel and equipment.

3.6 Wastewater and liquid waste management practices

The management of wastewater generated in HCFs can be addressed not only through treatment technologies but also through integrative design, reuse and segregation. For instance, simplified treatment of some wastewater streams can allow them to be used for less restrictive purposes, while source control of other wastewater streams containing PhCs, ARB and other hard-to-treat compounds can facilitate treatment of the bulk wastewater generated in the HCF.

Greywater, which refers to wastewater generated from sources such as sinks, showers and laundry, can be treated and reused for non-potable purposes within HCFs. One common application is toilet flushing, where treated greywater can replace fresh water. In addition, greywater can be used for tasks such as watering gardens and irrigation. Blackwater, referring to wastewater containing human waste from toilets, can also be reused. For instance, blackwater can go through simplified preliminary and secondary treatment using CW and subsequently be used for subsuperficial irrigation of gardens.

Source control and separation can be an effective precautionary measure and alternative to end-of-pipe upgrading of wastewater treatment plants. Liquid waste segregation is another management practice that can effectively support wastewater treatment in HCFs. Not all liquids should go down the drain together, and segregation can facilitate their treatment. For instance, laboratory chemicals such as strong acids and bases can significantly alter the pH of the wastewater, compromising biological processes downstream. WHO's handbook *Safe management of wastes from health-care activities* includes liquid wastes, setting out management strategies for minimization, reuse and recycling, as well as for segregation, storage and transport for specialized treatment (Chartier et al., 2014).

Patients subjected to radioactive treatments may excrete radioisotopes in their urine. The International Commission on Radiological Protection recommends its separation through published guidelines on how to manage this type of wastewater (Lecomte et al., 2019). Implementation of urine diverter toilets for those patients followed by appropriate storage, treatment and disposal is a valid alternative to minimize the impact of this source of pollution.

3.7 Wastewater sludge management

Wastewater sludge management, also commonly referred to faecal sludge (FS), is a by-product of the wastewater treatment process. FS consists of the solid residue that remains after the treatment of wastewater: it contains a wide range of organic and inorganic compounds including nutrients, pathogens, heavy metals and emerging pollutants such as PhCs and ARB (Englund and Strande, 2019).

Proper faecal sludge management (FSM) – including both active management and treatment – is essential to protect public health and the environment. There are several technologies for FSM: settling-thickening tanks (Koné et al., 2009), drying beds (Cofie et al., 2006), planted drying beds or CWs (Jain et al., 2022), anaerobic digestion (Dahunsi and Oranusi, 2013), mechanical dewatering (Nikiema et al., 2014), solar drying (Bennamoun, 2012), vermicomposting (Yadav et al., 2010) and black soldier fly larvae (Lalander et al., 2013).

Overall, FSM technologies aim to stabilize FS, removing pathogens, dewatering and reducing its volume in order to enable resource recovery (e.g. biogas production), reuse in targeted applications (e.g. agriculture) or safe disposal in the environment (Strande et al., 2014).

Most research has focused on FS originating from domestic or urban sewerage, either from on-site septic tank systems or centralized municipal plants. However, like wastewater, FS from HCFs may present higher concentrations of emerging compounds such as PhCs, ARB, heavy metals and pathogens. FS from HCFs may vary considerably in composition and volume compared to FS from other activities such as mine drainage, landfill liquid waste and municipal wastewater. Given the limited studies on the topic, recommendations on FSM in HCFs should be towards ensuring safe treatment and disposal of the sludge, in appropriately controlled facilities.

3.8 Summary of wastewater and sludge treatment technologies for HCFs

Wastewater is a complex matrix consisting of water and various compounds, and it can be effectively treated using a range of treatment technologies and arrangements. An essential factor to consider when selecting wastewater treatment technologies is a thorough characterization of the wastewater, including identifying target compounds that need to be removed. HCF effluents have unique characteristics including elevated concentrations of ARB and PhCs which require specific treatment trains and informed strategies for environmentally and public health-responsible disposal.

In LMICs, the release of PhCs and ARB into the environment can lead to severe infectious outbreaks. Consequently, it is crucial to implement rigorous treatment measures for HCF wastewater and sludge using appropriate technologies. These technologies play a critical role in the development and implementation of policy packages and vice versa (Koopaei and Abdollahi, 2017).

One approach commonly adopted in several countries is co-treatment, which involves treating a portion of the HCF effluent at the hospital and the remainder at municipal wastewater treatment plants. However, it is important to note that this practice has faced opposition from a significant number of researchers, despite its having been put into use (Altin et al., 2003; Pauwels and Verstraete, 2006; Vieno et al., 2007). Although not an ideal situation, co-treatment is preferred to direct disposal into the environment or stormwater systems.

Many of the wastewater treatment technologies recommended in the literature for HCFs may not be feasible for implementation in resource-constrained regions of LMICs due to their resource-intensive nature. Where basic sanitation facilities are lacking, it is crucial to prioritize their installation (e.g. toilets with sealed containment and enforced hygiene standards) as a first step to minimize health risks. Technologies such as the pit latrine, dry composting toilets, septic tanks and anaerobic baffled reactors are examples of technologies that are easier to implement and maintain; they represent an improvement to direct disposal into the environment, even if they do not completely mitigate the wastewater risks of HCFs and should not be considered suitable for larger HCFs or hospitals.

Investments in advanced wastewater treatment in HCFs should be complemented by the development of regulations and policies that encourage public investments in this essential area.

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