A review of potential factors contributing to epidemic cholera in Yemen

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ABSTRACT

The menace of cholera epidemic occurrence in Yemen was reported in early 2017. Recent reports revealed that an estimated 500,000 people are infected with cholera whereas 2,000 deaths have been reported in Yemen. Cholera is transmitted through contaminated water and food. Yemen is the least developed country among the Middle East countries in terms of wastewater and solid waste management. The population of Yemen is about 24.5 million and generates about 70–100 million m^3 of sewage. An estimated 7% of the population has sewerage systems. It has been revealed that 31.2 million m^3 of untreated sewage is used for irrigation purposes especially for vegetables and Khat trees. In addition, more than 70% of the population in Yemen has no potable water. They depend on water wells as a water source which are located close to sewage disposal sites. The present review focuses on the current status of water, wastewater as well as solid waste management in Yemen and their roles in the outbreak of cholera. Future prospects for waste management have been proposed.

Key words | factors, outbreak, *Vibrio cholera*, wastewater, Yemen

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INTRODUCTION

Cholera is an acute diarrheal disease caused by *Vibrio cholera* which is transmitted to humans through the ingestion of contaminated food or water. Recent reports revealed that an estimated 500,000 people are infected with cholera whereas 2,000 deaths have been reported in Yemen (Al-Gheethi *et al.* 2015). Yemen is one of the Middle East countries located on the Arabian Peninsula in Southwest Asia. The country is bordered on the north by Saudi Arabia and the Sultanate of Oman on the East Arab Sea, the Gulf of Aden on the south and the Red Sea on the west. Yemen has 22 governorates with a population of 24,526,703 (MPHP 2012). The rapid growth rate of the population especially during the last two decades (1990 to 2010) has led to inadequate infrastructure for health establishments as well as water and wastewater sewerage systems. The civil war which has plagued Yemen since 2015 has led to the destruction of most of the facilities used in water and wastewater treatment. The absence of energy

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for operating sewage and drinking water treatment plants due to the civil war in Yemen epitomizes the problem that has led to the increase in cholera outbreaks. The present review focuses on the current status of water, wastewater as well as solid waste management in Yemen and their role in cholera outbreaks. Future prospects for waste management are proposed to protect the country from cholera outbreaks in future.

DISTRIBUTION OF DIARRHEA AND CHOLERA IN YEMEN

The distribution of diarrheal diseases in Yemen is more common as a result of the absence of clean water, considered one of the main factors behind the increase in diarrheal diseases. It has been reported that contaminated water contributes significantly to the distribution of diarrhea. UNICEF (2013) indicated that, globally, 2,000 children under the age of five die every day due to diarrheal diseases in which 90% of the deaths are directly linked to poor sanitation and contaminated drinking water.

According to MPHP (2011), the number of reported infected cases in Yemen in 2011 was 421,078, in which 269,947 of the cases were due to epidemics caused by different pathogens (MPHP 2011). About 80% of the cases consisted of diarrhea and gastroenteritis. The list of pathogens recorded in Yemen is presented in Figure 1, which gives an overview of the health status among the community in Yemen in the last few years. According to the Parliament's Water and Environment Committee (2006), waterborne diseases affected 75% of the population with 55,000 child deaths annually. Furthermore, three million people had hepatitis because of polluted water consumption (HOOD 2011).

The outbreak of cholera in Yemen has not been reported in the last few decades and even among developing countries in the Arabic regions, except for South Sudan in 2014 and 2015, where 6,269 cases of infection and 156 deaths in multiple areas of the country were reported (Abubakar *et al.* 2015). In Yemen, an estimated 500,000 people are infected with cholera and 2,000 deaths have been reported. Statistically, and based on a search through articles published between 2008 and 2017, there are 61 articles on cholera outbreaks but none of the studies were conducted in Yemen. As such, there seems to be a dearth of information on this epidemic in Yemen. Therefore, this work represents one of the few studies on the cholera

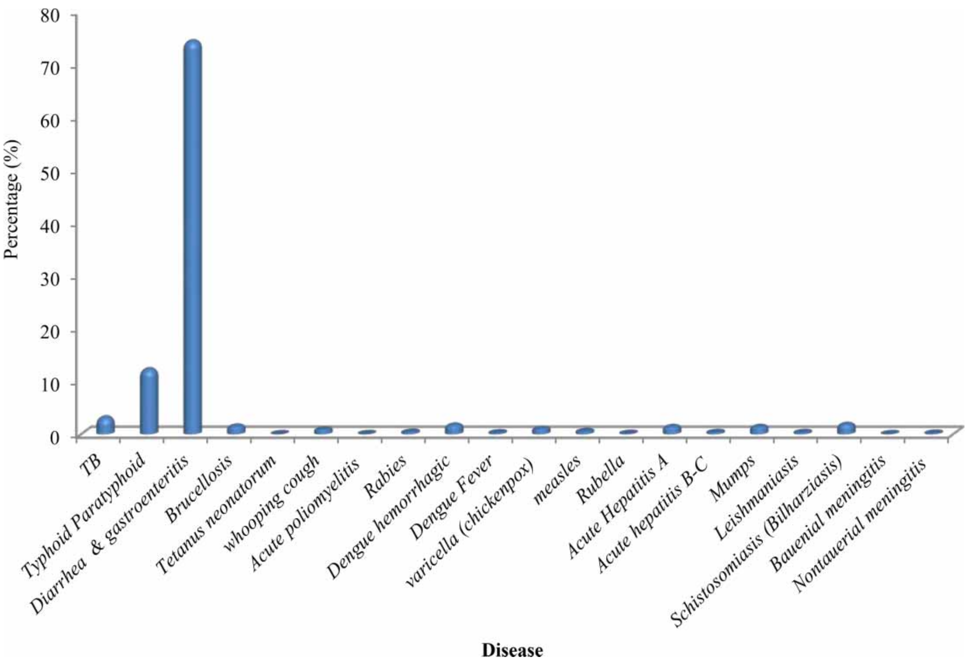

Figure 1 | Surveillance of epidemic diseases recorded in Yemen during 2011.

outbreak in Yemen. In comparison, according to the papers published, it was noted that among 61 articles published in the Arabic region, 36.6% of the studies were conducted in Saudi Arabia, which is the nearest country to Yemen. It has been reported that only one article was published in Egypt, which focused on the prevalence of *V. cholera* in the environment (Lotfi *et al.* 2016), while the others focused on the development of vaccines, the diagnostic process for cholera, and virulence factors of *V. cholera*. Precautions to prevent the spread of pathogens causing the occurrence of cholera outbreaks in Yemen and its surrounding developing countries have been overlooked. Hence, it is important to examine possible preventive measures in order to prevent the spread of cholera.

IMPROPER MANAGEMENT OF WASTEWATER IN YEMEN

Yemen is the least developed country in the Middle East in terms of the management of solid waste and wastewater. Moreover, there is a dearth of information on the management of wastewater in Yemen. Few studies have been conducted on the detection of pathogens in wastewater and solid wastes (Al-Zubeiry 2005; Al-Jaboobi *et al.* 2013; Al-Gheethi *et al.* 2014). Yemen has 16 sewage treatment plants (STPs) that are functional and nine under construction. The data in Table 1 indicate that the actual flow rate (m^3/d) of STPs in the capital city of Yemen (Sana'a) is more than the design flow rate which negatively affects the efficiency of treatment plants. Moreover, the absence of maintenance has caused the treatment plants to be less effective in reducing pathogens in effluents and biosolids to meet the standard limits. The use of effluents and biosolids in agriculture increases the risk of pathogens such as helminths, parasites, and bacteria being transmitted to humans through contaminated vegetables (Efaq *et al.* 2019; Al-Gheethi *et al.* 2019). Therefore, most cholera outbreaks have been reported in Sana'a. In comparison, the STP in Taiz was designed with a capacity of 17,000 m^3/d but the plant receives more than 25,000 m^3/d. Furthermore, the treatment process is performed by stabilization ponds which have very low efficiency in the reduction of pathogens in comparison to activated sludge treatment. However, there exists no information about the number of infection cases in Taiz due to the ongoing civil war in the city.

It has been reported that 9% of the STPs treat sewage from the primary to the secondary stage with activated sludge using Imhoff tanks (Figure 2). In contrast, 68% depend only on stabilization ponds which represent the main problem in Yemen since stabilization ponds are designed as a primary treatment process which has very low capacity to reduce pathogens in sewage (Al-Gheethi *et al.* 2015). STPs in Yemen are operated to produce chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total suspended solids that will meet the standards for wastewater discharge. The removal of pathogens from wastewater has been overlooked. As a result, the effluents generated from those STPs have high loads of infectious agents which might have adverse effects on humans through the food chain. Furthermore, the total capacity of the STPs in Yemen range between 230,388 m^3/d and 239,388 m^3/d, while the total quantity of sewage generated was 277,777.8 m^3/d from 1.7 million people (representing 7% of the total population which is 24.5 million). In comparison, Jelutong Sewage Treatment Plant, which is located in Penang, Malaysia (total population of Malaysia is 28 million), receives and treats 180,000 m^3/day of sewage from a population of 1.2 million (Al-Gheethi *et al.* 2017a). The STPs receive industrial and hospital wastewater from different facilities. Reports revealed that Sana'a has 164 general factories, 7 pharmaceutical companies, 75 hospitals and 34 clinical centers which discharge their wastewater into the sewerage system (IRIN 2009; National Information Centre 2011).

On the other hand, human activities are contributing significantly to water pollution as wet markets and slaughterhouses generate enormous amounts of wastewater during the washing process. Open food markets which sell poultry, fish, meats, fresh fruit, and vegetables are also associated with wastewater production. These wastewaters are discharged directly into the drainage system without treatment. As a result, the wastewaters serve as an important source of water pollution due to the high concentrations of nutrients which might cause eutrophication. Nevertheless, in Yemen, the wastewaters generated from different sources are disposed into drains along with storm and rain water into a large dam (Al-Gheethi *et al.* 2017b). In Taiz (one of

Table 1 | Characteristics of main sewage treatment plants in Yemen

(a)

Variables	IWWTP1	TWWTP	AWWTP1	AWWTP2	AWWTP	LWWTP	BFWWTP
Location	Ibb	Al-Borihi, Taiz	Al-Arish-Aden	Al-Shaab-Aden[c]	Ash Shaab (upgrade)	Al Hota/Lahej	Bait El Faqih (Hodeidah)
Type of city	Mountain city	Mountain city	Coastal city	Coastal city	Coastal city	Coastal city	Coastal City
PE	102,098	71,249	589,419	589,419	589,419	25,471	39,116
Started operation	1991/1993	1982/1983	2000	1970s, extended 1989	Designed	1985	1983
Type of sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage
Treatment process	Activated sludge	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds
Design capacity (m^3/d)	5,256	9,000–17,000[a]	70,000	11,000	30,000	1,300	2,544
Actual flow rate (m^3/d)	7,000–8,000	8,000–25,000[a]	17,000	15,000	NA	11,350	500
Current situation	Over loading	Over loading	In the range of the design capacity	In the range of the design capacity	New	Over loading	In the range of the design capacity
Last date of maintenance	NA						
Disinfection process of secondary effluents	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination
Disposal method of sewage treated effluents	Uncontrolled irrigation of crops and vegetables	Irrigation of Ornamental trees and gardens[b]	Sea disposal and irrigation	Sea disposal and irrigation	Sea disposal and irrigation	Sea disposal and irrigation	Sea disposal and irrigation
Disposal method of biosolids	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer

(b)

Variables	SWWTP1	SWWTP2	HWWTP	HOWWTP1	BWWTP	AMWWTP	DWWTP	MSTP
Location	Al-Rowdah-Sana'a	Rada'a Sana'a	Haja	Al-Hodida	Al-Baita	Amran	Dhamar	Al-Mahweet
Type of city	Mountain city	Mountain city	Mountain city	Coastal city	Mountain city	Mountain city	Mountain city	Mountain city
PE	145,314	145,314	4505	411,287	29,834	96,375	175,131	19,943
Started operation	2000	1996	1974/1998a	1983	NA	2002	1991	NA
Type of sewage	Domestic, industrial and hospital sewage	NA	Domestic and hospital sewage	Domestic and hospital sewage	Domestic and hospital sewage	Domestic and hospital sewage	Domestic and hospital sewage	Domestic and hospital sewage
Treatment process	Activated sludge	2 stage stabilization ponds	Imhoff tanks and 2 stage trickling filter	Three stabilization pond	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds	Stabilization pond
Design flow rate (m^3/d)	50,000	1,880	2,428	12,000	20,000	1,480	10,000–11,000	3,500
Actual flow rate (m^3/d)	50,000–56,000	1,500	1,200–1,400	18,000	20,000	1,100	6,000–9,000	3,500
Situation of WWTPs	Over loading	In the range of the design capacity	In the range of the design capacity	Over load capacity	Over loading	In the range of the design capacity	In the range of the design capacity	Over loading
Last date of maintenance	NA							
Disinfection process of secondary effluents	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination	Chlorination
Disposal method of sewage treated effluents	Uncontrolled irrigation of crops and vegetables[b]	Uncontrolled irrigation of crops and vegetables[b]	Uncontrolled irrigation of crops and vegetables	Sea disposal and irrigation	Uncontrolled irrigation of crops and vegetables	Uncontrolled irrigation of crops and vegetables	Uncontrolled irrigation of crops and vegetables	Uncontrolled irrigation of crops and vegetables
Disposal method of biosolids	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer	Fertilizer

(*continued*)

Table 1 | continued

(c)

Variables	YWWTP	ZWWTP	RWWTP	SHWWTP	ATWWTP	BWWTP	MWWTP	HOWWTP2	TWWTP	IWWTP2
Location	Yarim-Ibb	Zabid Al-Hodida	Al-Rugoom Al-Mahweet	Shibam Al-Mahweet	Al-Tawilah Al-Mahweet	Bajil (Hodeidah)	Mukalla	Al-Hodida (Upgrade)	Tarim, Hadramout	Ibb (upgrade)
Type of city	Mountain city	Coastal city	Mountain city	Mountain city	Mountain city	Coastal city	Coastal city	Coastal city	Coastal city	Mountain city
PE	23,014	21,440	75,708	39,163	58,862	55,016	176,942	411,287	100,212	102,098
Started operation	2005	Under construction	Under construction	Under construction	Under construction	Under construction	Under construction	Under design	Designed	Designed
Type of sewage	Domestic, industrial and hospital sewage	Domestic, industrial and hospital sewage	Domestic and hospital sewage	Domestic and hospital sewage	Domestic	Industrial and hospital sewage	Domestic	Industrial and hospital sewage	Domestic	Industrial and hospital sewage
Treatment process	3 stage stabilization ponds	Imhoff tank/2 stage stabilization ponds	Reactor/stage stabilization ponds	Reactor/stage stabilization ponds	Reactor/stage stabilization ponds	Three stabilization ponds	Three stabilization ponds	Three stabilization ponds	Three stage stabilization ponds	Imhoff tanks/ activated sludge
Design flow rate (m^3/d)	1,771	1,146	500	500	500	4,151	14,000	51,500	16,000	10,000
Actual flow rate (m^3/d)	530	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA, not available.

[a]Not confirmed.

[b]The treated secondary effluents are stored in metal tanks until utilization.

[c]The sludge is mixed with desert sands before utilization.

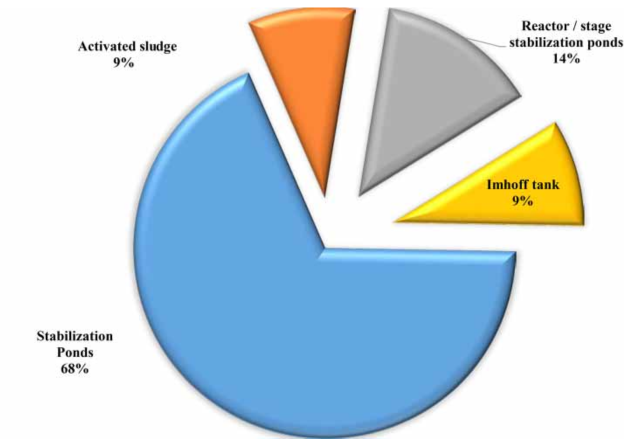

Figure 2 | Sewage treatment plants in Yemen.

the largest cities in Yemen), these wastewaters are collected in the AL-Ameriaa dam which was established for groundwater recharge in the 1990s with a capacity of 758 m^3. However, it recently represents a site for pollution due to the lack of strategies to recycle the wastewater. Moreover, the dam is located in an open area and receives sewage from the surrounding areas. Hence, the presence of many pathogenic microorganisms such as *Salmonella* sp. fecal coliform, viruses, and protozoa which might cause diseases among human and animals poses a serious health risk. The AL-Ameriaa dam is surrounded by agricultural lands where the locals use water from the dam especially for the irrigation of vegetables (Al-Gheethi *et al.* 2017a, 2017b).

In order to protect humans and the environment from the adverse effects of wastewater, several countries have adopted regulations for the proper management of wastewater. In fact, there are laws and regulations for the disposal of wastewater in Yemen. However, due to the lack of awareness among farmers about the health risks associated with the reuse of wastewater for irrigation purposes, several diseases have been reported among farmers and animals in the last few years (Al-Gheethi *et al.* 2015).

In view of the research conducted on the evaluation of STPs in Yemen, it was noted that the plants have a very low efficiency as none of the existing STPs produce effluents which comply with the effluent quality regulations (ACWUA 2010). Al-Gheethi *et al.* (2014) evaluated secondary effluents and biosolids generated from four STPs in Yemen. The study revealed that concentrations of fecal coliforms (FCs) were more than that recommended by the World Health Organization (WHO) guidelines in all wastewater samples. FCs in 50% of the biosolids were more than the standard limits recommended by the United States Environmental Protection Agency (US EPA) Class B. The study detected 88.88% of *Escherichia coli*, 70.37% of *Streptococcus faecalis*, 66.67% of *Klebsiella pneumonia*, 59.23% of *Enterobacter aerogenes*, 33.33% of *Salmonella typhi*, 25.93% of *S. typhimurium,* 25.93% of *Shigella sonni*, and 22.2% of *Yersina pestis* in the samples.

On the other hand, *Cryptosporidium parvum* and *Giardia lamblia*, as well as helminth ova are important opportunistic intestinal pathogens due to their ability to form cysts which persist in hard environmental conditions. They can be transmitted into humans via contaminated drinking water and vegetables irrigated with contaminated sewage (Rangel-Martınez *et al.* 2015). Moreover, *Ascaris lumbricoides* and *Ancylostoma duodenale* have a simple life cycle with no intermediate hosts. They are capable of causing infection via the fecal–oral route and have a high potential to survive and resist environmental stresses (Toze 2006).

Rotaviruses, adenoviruses, reoviruses, caliciviruses, and astroviruses have been found in wastewater. These viruses are obligate intracellular parasites, and more resistant to treatment processes and the environment than bacteria. Therefore, they pose an important risk to humans but are rarely a problem for other animals due to their low-dose infectivity (<10 viral particles) (Asano 2005).

SOLID WASTE MANAGEMENT IN YEMEN

The biological hazard inherent in solid waste should be considered during management, treatment, and disposal processes. Clinical wastes and solid garbage are discharged at 18 official open dump sites in Yemen. The official dump sites which are located far from the community were sited 40 years ago and are less expensive. However, as the population has increased in the last few decades (by 25%), the official dump sites have become closer to the communities. As a result, potential infections and health risks among the public have increased accordingly (Efaq & Al-Gheethi 2015). Toxic chemicals like dioxins and furans generated from the burning of plastic, syringes, and other garbage in

Yemen have an adverse effect on its inhabitants (Efaq & Al-Gheethi 2015).

The lack of separation and segregation of solid waste such as solid garbage, clinical waste, slaughterhouse waste, as well as wet poultry and fish lead to them being discharged directly into the drainage system. The civil war that has been ongoing in Yemen since 2015 has caused the suspension of workers involved in the management of solid waste. This has a negative effect on the health of the people since sewage and potable water cannot be treated, especially clinical waste (Efaq & Al-Gheethi 2015).

The quantities of solid garbage generated in 2011 were estimated to be about 3,682,669 tonnes which represents 40% of the total quantity of estimated garbage (MLA 2011). There were no reports on the quantities of clinical waste generated from health establishments in Yemen (Efaq & Al-Gheethi 2015). However, the WHO (2000) estimated the quantities of clinical waste from developing countries to be between 0.5 and 3 kg/bed/day. Thus, the total quantities of these wastes in Yemen ranged between 9,565.92 tonnes to 10,600.38 tonnes (MPHP 2012). The microbial loads of solid waste including clinical wastes were determined by several authors in the literature as stated by Efaq *et al.* (2015). The most common are *A. baumanii, Bacillus* sp., *E. coli, K. pneumonia, P. mirabilis, P. aeruginosa, S. aureus, S. epidermidis, Salmonella* spp., *Legionella, Kocuria* sp., *Lactobacillus* sp., *Micrococcus* spp., *Brevibacillus* sp., *M. oxydans, and P. acnes*. According to the WHO (2000), the human immunodeficiency virus (HIV) and hepatitis viruses B and C are among the infections which are transmitted via healthcare waste.

Among different types of clinical waste, human body fluids (HBFs) represent the most potent source of infectious agents. In some references, this waste includes identifiable human tissue, blood, and swabs (WHO 2005). Moreover, these wastes act as a vector for the transmission of pathogens from waste into humans and the environment during the disposal process. HBFs contain sugars, protein, fats, and starch that support microbial survival in harsh environments (Hall 1989). Clinical wastes are rich in nutrients and pathogens such as bacteria, fungi, and viruses. However, the potential infectious risks associated with HBF waste management and treatment are still unknown due to the absence of critical reports on infections caused by pathogens transmitted through clinical waste (Salkin 2003).

MICROBIAL PATHOGENS IN DISPOSED WASTEWATER AND REUSED WASTEWATER IN YEMEN

The disposal of sewage and wastewater into the environment is common in Yemen. In coastal cities such as Aden, sewage is discharged into the sea. In contrast, the disposal of these wastes into the valley is common in mountainous cities such as Sana'a (Al-Gheethi *et al.* 2015). In the villages, untreated sewage is discharged directly into the drainage system due to the absence of a sewerage network and centralized wastewater treatment plants. The adverse effects of sewage discharge into the environment and natural water bodies include the contamination of water resources, transmission of infectious agents, alteration of the ecological system, and algal bloom (Wurochekke *et al.* 2016). Some of these effects might occur within a short time while others have long-term effects. The microbes encountered in water bodies and food have the ability to survive and propagate. They can multiply to infective doses and become more hazardous to humans and animals. The microbial agents are able to survive at a temperature of 37 °C in sewage (Al-Gheethi *et al.* 2013).

The evaluation of the risks associated with sewage and wastewater pollution represents the main goal of the management process since the elimination of pathogens from wastewater might reduce biohazard risks. Pathogens in discharged sewage and wastewater have the potential to cause a wide range of infections. It has been reported that direct contact with gray water causes eye and skin infection (Winward 2007).

It has been revealed that farmers that live near the Sana'a sewage treatment plant (SSTP) suffer from several diseases caused by pathogenic microorganisms as a result of the use of sewage water for irrigation purposes (Haidar 2005). Most animals also suffer from intestinal diseases caused by pathogenic bacteria from sewage (Al-Gheethi *et al.* 2015). Sewage is used extensively for the irrigation of crops, especially the Khat tree which represents about 33% of the irrigated area in Yemen (Haidar

2005; Ministry of Agriculture and Irrigation 2012; Al-Gheethi *et al.* 2015).

Product safety risks, occupational health risks, and environmental risks are the health risks associated with the presence of pathogenic microorganisms in untreated sewage and wastewater (Strauch 1998). It has been estimated that the infections caused by pathogens from sewage and wastewater affect more than 250 million people annually and 10–20 million deaths have been reported (Anonymous 1996). *Salmonella* spp. found in sewage and wastewater has been reported to infect both humans and animals. *S. typhi* and *S. paratyphi* are among the 200 serotypes of *Salmonella* spp. which cause typhoid and paratyphoid fever (Bumann *et al.* 2000). In addition, enteropathogenic *E. coli* (EPEC), enterotoxigenic *E. coli* (ETEC), and enteroinvasive *E. coli* have been reported to cause gastrointestinal disorders (Buzrul 2009). *K. pneumonia* is the main infectious agent which causes bronchopneumonia and bronchitis. Furthermore, *P. aeruginosa* causes secondary infection among patients infected with autoimmune diseases or HIV. Meanwhile, *E. faecalis* has been reported as a major nosocomial pathogen (Facklam 1991). *Staphylococcus* spp. causes bacteraemia in humans. Methicillin-resistant *S. aureus* (MRSA) has also been reported to produce enterotoxins (class A, B, C, D, and E). It possesses high resistance towards numerous antibiotics (Vickery 1993). A recent report has revealed that *S. aureus* causes shock syndrome toxin-1 and produces epidermolytic toxins which damage the mucous polysaccharide matrix of the skin.

Clostridium perfringens produces enterotoxin and cytotoxin that cause diarrheal and necrosis diseases, respectively. *C. difficile* is another species which is classified as the third bacteria to cause diarrhea after *Salmonella* spp. and *S. aureus*. *V. cholera* is usually found in raw seafoods. They normally live on the outer surface of fish and other types of seafood. It has been reported that *V. cholera* can be transmitted into kitchen wastewater during the washing process of these foods (Vinnerås *et al.* 2003).

The microbial risk of wastewater can be assessed based on the survival periods of microbes in wastewater. It has been demonstrated that *Salmonella* spp. can survive for weeks in an aquatic environment and for more than one month in sediment and soil (Moore *et al.* 2003). Al-Gheethi *et al.* (2013) reported that *Salmonella* spp. survived for 28 days at room temperature in treated effluent while *E. coli* has the potential to survive for one year (AWWA 2006). *Giardia lamblia* and *Cryptosporidium oocysts* which possess a high ability to form cysts can survive for more than two months in natural water (DeRegnier *et al.* 1989; King *et al.* 2005). These parasites cause gastrointestinal illnesses in humans (Coupe *et al.* 2006).

V. cholera, *P. mirabilis*, *P. aeruginosa*, *E. coli*, *Salmonella* spp., *K. pneumonia*, and *Campylobacter* spp. have been reported to produce exotoxins and endotoxins. In addition, another virulence factor is the infective dose (ID). *Shigella* sp. has a low ID (10–100 cells) whereas *E. coli* and *Salmonella* spp. require a high ID (ranging from 10^3 to 10^6 cells) to cause infection in humans and animals (Gordon *et al.* 2002). *V. cholera* has a high health significance with 10^3–10^8 of ID (Vinnerås *et al.* 2003). The infective dose of *G. lamblia* is 10 cysts while *Cryptosporidium* spp. has an infective dose of 15 to 100 cysts (Robertson *et al.* 1992; Robertson & Nocker 2010).

Populations, exposure, and dose-response are factors associated with the presence of microbial health risk in wastewater reuse (Dixon *et al.* 1999). Irrigation using untreated wastewater poses health risks to farmers in Yemen. The level of risk associated with wastewater relies on the hazard level and exposure time (Figure 3) (Dixon *et al.* 1999). The figure shows that high health risk is associated with the reuse of wastewater at the source as well as at the point of use. However, epidemiological studies and quantitative microbial risk assessment (QMRA) have

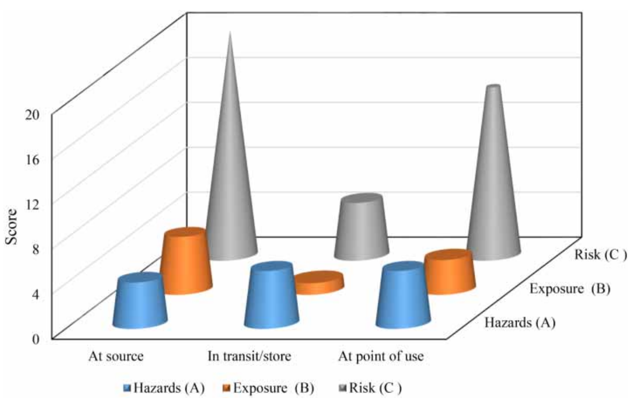

Figure 3 | The health risk associated with reuse of wastewater at source, in transit and at point of use: for A and B the score 1 is low; 3 (intermediate); 4 (interm–higher); 5 (higher). C is calculated as A*B, the score was calculated as 5 (low): 15 (intermediate); 20 (interm–higher); 25 (higher).

provided more details on the level of microbial and hazardous chemical risks correlated with the reuse of wastewater. The hazard identification (hazard ID), infective dose, and exposure levels are used to determine the presence or absence of health risks for specific pathogens (Figure 4). The figure shows that the risk level is associated with the exposure level dose and the dose level score.

NON-CENTRAL TREATMENT SYSTEM AS AN ALTERNATIVE METHOD FOR THE TREATMENT OF WASTEWATER IN YEMEN

One of the limitations which reduces the efficiency of STPs in Yemen is the absence of energy required for operating wastewater and sewage treatment plants. Consequently, the segregation or separation of black water from graywater is an option for increasing the efficiency of STPs and minimizing the health risks associated with wastes in Yemen. Matos *et al.* (2014) reported that 37.5% of energy was consumed for the treatment processes of graywater. Hence, the application of the separating process can save more energy consumption during the treatment process. The separation of graywater from black water is an important step in wastewater treatment as this will reduce the overloading of the current STPs and thus increase their efficiency.

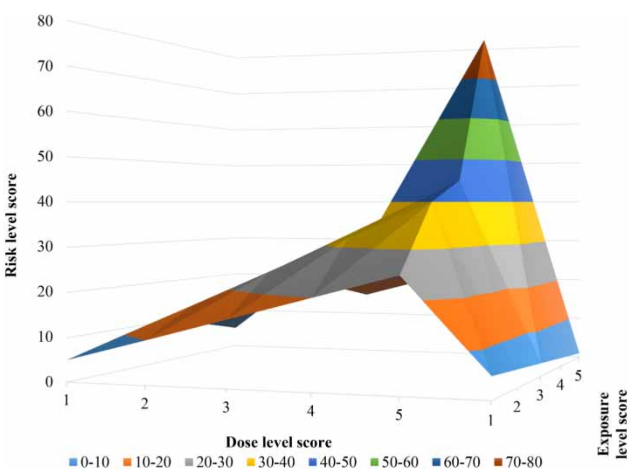

Figure 4 | The QMRA of pathogens in the wastewater; the dose, exposure and hazards levels is expressed in the range (1 to 5): very low (1); low (2); intermediate (3); interm–higher (4); higher (5). The risk level is divided into seven classes based on the correlation between dose, exposure, and hazard levels; the high risk level is above 30 (Al-Gheethi *et al.* 2019).

Separation and disinfection prior to final disposal are vital steps towards wastewater treatment.

A decentralized treatment system might be an alternative method for the treatment of wastewater and sewage at each cluster of houses or individual house in village regions. Decentralized treatment systems or on-site wastewater treatment systems are more applicable for developing countries such as Yemen. The decentralized graywater treatment is usually performed in rural areas where people use this system for separating graywater from black water before discharge into drainage systems (Capodaglio 2017).

Phycoremediation technology is one of the decentralized treatment systems for wastewater (Jais *et al.* 2017). It is a green technology with no secondary pollution or chemical additives. The process relies on algae with the potential to bio-absorb and reduce total nitrogen and total phosphate in wastewater (Jais *et al.* 2017). Phycoremediation is one of the most efficient technologies in which microalgae is used as a bio-decomposer due to the potential of microalgae in the bioremediation of wastewater (Razzak *et al.* 2013). This process reduces the nutrients in wastewater and prevents the occurrence of eutrophication in water bodies that receive discharged wastewater.

The phycoremediation system is more applicable for individual usage at village houses. Mohamed *et al.* (2017) reported that phycoremediation uses two tanks (storage and bioreactor tank) with a total capacity of 200 L/day. The maximum treatment period of the phycoremediation process is 21 days for 1,400 L of wastewater. As a result, the capacity of a storage tank is supposed to be 2,100 L although more than one phycoremediation tank can be used with a total capacity of 2,100 L. The flow rate of graywater into the phycoremediation tank is 139 mL min^{-1}.

Figure 5 shows a simple design for the treatment of graywater which might be separated and treated in an individual treatment unit to reduce the overloading of sewage treatment plants in Yemen. In this design, the flow of graywater from each house into the storage tank and later into the phycoremediation tank occurs seamlessly without water pumps. In addition, the process might supply air bubbles which could be used as an alternative for air pumps. According to a study conducted by Mohamed *et al.* (2017), the proposed design has the ability to reduce BOD_5 and COD by 98% and 85.47%, respectively.

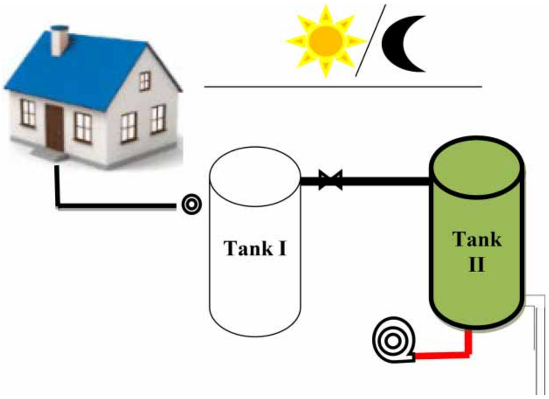

Figure 5 | Scheme of the proposed photo-reactor system: tank I (control); tank II (inoculated with microalgae).

Moreover, 98% of nitrate (NO_3^-) can be reduced after 18 days of treatment. The reduction of ammonia (NH_3) and orthophosphate ($PO4_3^-$) can reach 99% and 99.3%, respectively. However, more studies are required to study the removal efficiency of pathogens.

One of the advantages of the phycoremediation process is that energy is not required for the performance of the system. This could perhaps be an advantage for people residing in a village area where energy sources are scarce. Microalgae are used as dry mass to facilitate the utilization by people in the villages. The microalgae are inoculated only at the fixation stage of phycoremediation to initiate a

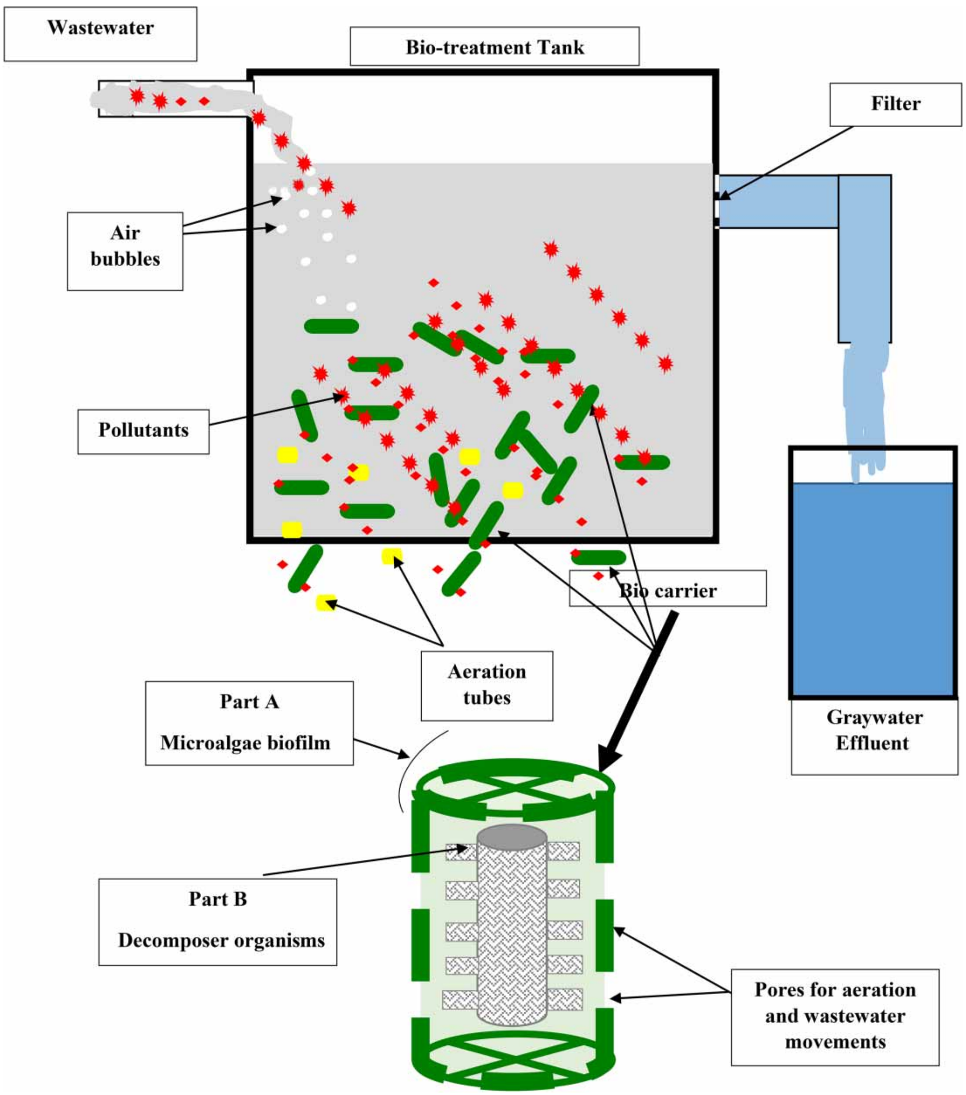

Figure 6 | Proposed bio-carrier treatment system.

semi-continuous operation of the process. Furthermore, the biomass generated during the phycoremediation process can be used as a source of biodiesel, food for animals and fish as well as fertilizers.

The bio-carrier system is another simple decentralized treatment system which removes pollutants and pathogens by introducing a novel consortium of fungi and microalgae species to antibacterial agents. The utilization of these organisms as free biomass leads to low efficiency due to the distribution of the organisms in wastewater. As a result, the best alternative is to upload the fungal and microalgae cells to the bio-carrier material (Figure 6).

Bio-carriers have been reported to have high intensity, resistance to shear and shock, as well as being capable of loading microorganisms for the biodegradation of pollutants (Chen *et al.* 2017). The inactivation of pathogens has also been ascribed to bio-carriers. Bio-carriers are known to be innocuous, nontoxic, recyclable, and effective in reducing or eliminating secondary by-products which improves the quality of natural water.

The design of non-centralized treatment systems is simple and therefore requires fewer personnel to operate the treatment system and lower maintenance. This is an alternative graywater treatment technology that has low cost, zero energy consumption, and high efficiency. Bio-carrier systems depend on natural processes, low-cost materials and do not require frequent maintenance or repair. The use of natural processes and locally available materials in the development of bio-carriers would be suitable for people with low incomes. This will encourage the use of bio-carriers for the treatment of wastewater before discharging it into the environment.

In retrospect, the outbreak of cholera in Yemen was due to the absence of potable water. The filtration system is conceivably an alternative method that is effective and economical for rural dwellers. The application of a filtration system will perhaps reduce water pollution and protect the public from *V. cholera* infections. In addition, the filtration system is designed using natural materials such as sand, wooden saw dust, charcoal, and coconut shells which will be affordable for the low-income group in Yemen. Current research has shown that the combination of reused materials and new materials including clamshells, limestone, and ceramic to design a simple and effective filter bed filtration unit will contribute effectively to the reduction of cholera infections (Mohamed *et al.* 2016). It has been reported that 54% of the population in Yemen is living below the poverty line and earning less than $1.25 per day, with 40% currently unemployed. These explain the reasons for cholera occurrences in the last six months in Yemen.

CONCLUSION AND PERSPECTIVE

It has appeared that the outbreak of cholera in Yemen was due to the improper management of wastewater as well as a lack of facilities required for high-quality wastewater treatment. Clinical wastes contribute effectively to the distribution of pathogens into the environment and water systems. More studies are required on the cholera outbreak in Yemen, especially among solid waste management workers because they could be cholera carriers.

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