Solar disinfection and lime stabilization processes for reduction of pathogenic bacteria in sewage effluents and biosolids for agricultural purposes in Yemen

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ABSTRACT

Yemen is the least advanced country among Middle Eastern countries in sewage reuse and safety control. The current sewage effluent quality in Yemen is generally poor as none of the existing sewage treatment plants produces effluents that comply with the effluent quality regulations. There is no plan to build tertiary treatment systems. However, the oxidation and stabilization ponds are considered most appropriate for the warm climate conditions in the country. Sewage effluents and biosolids generated from these ponds are used extensively for agricultural purposes. This review discusses the potential use of solar disinfection (SODIS) and lime treatment for the reduction of pathogens in sewage effluents and biosolids before reuse. SODIS and lime treatment are natural processes, simple, easily implemented, produce non-toxic by-products and are low cost. The merits of these processes are enormous, and they are suitable for application in developing countries such as Yemen.

Key words | biosolids, lime treatment, pathogenic bacteria, sewage effluents, solar disinfection, Yemen

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INTRODUCTION

Sewage effluent is the treated liquid that comes out of a treatment plant after completion of the treatment processes, while biosolids are the solid and semi-solid residues generated during the sewage treatment processes (US EPA 2009). Sewage treatment is a multistage process that ranges from a main process for the treatment of raw sewage to advance processes for removing pollutants that remain in secondary effluents (Gupta *et al.* 2000; Heritage *et al.* 2003).

In Yemen, oxidation and stabilization ponds are considered the most appropriate treatment system (UN 2012). There are 32 oxidation/stabilization ponds, 16 septic tanks, five Imhoff tanks, and only two sewage treatment plants (STPs) have activated sludge systems in the country (Figure 1). ACWUA (2010) and Al-Nozaily *et al.* (2012) have reported that the loading of these plants is greater than the designed capacity and hence the current sewage effluent quality in Yemen is generally poor as none of the existing STPs produces effluents that comply with the effluent quality regulations (UN 2012). The characteristics of the main STPs in Yemen are presented in Table 1.

The direct disposal of industrial wastewater to sewerage systems in Yemen leads to weak efficiency of STPs, due to increased concentrations of heavy metals and organic contaminants (UN 2012). Almost 164 factories in Sana'a, Yemen discharged untreated wastewater to STPs (IRIN 2009). Many STPs cannot eliminate heavy metals (ACWUA 2010). Also, wastewaters from hospitals, medical laboratories, and pharmaceutical factories in Yemen are discharged into the sewerage system (IRIN 2011). In Sana'a there are 75 hospitals, 34 clinical centers, and seven pharmaceutical factories (National Information Centre

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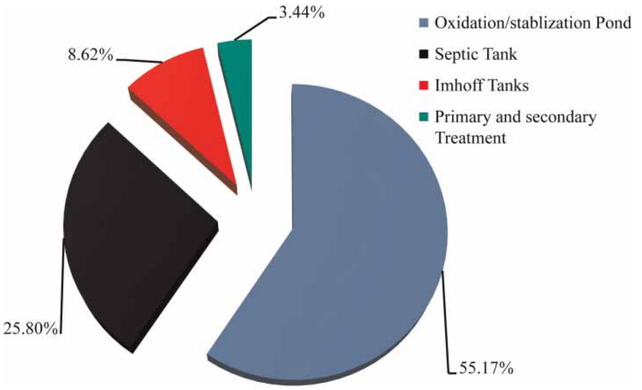

Figure 1 | Sewage treatment plants in Yemen.

2011). The treatment processes for sewage are insufficient to remove antibiotics. Many antibiotics have been detected in large quantities in sewage-treated effluents and in surface waters receiving effluents (Spongberg & Witter 2008).

The rapid growth of communities and cities in Yemen has increased during the last few decades. According to the World Bank (2013), the population equivalents (PE) have increased by 25% during the period from 2000 to 2012. The total amount of raw sewage produced annually is approximately 70–100 million m^3, and the total amount of treated sewage is 46 million m^3, with 31.2 million m^3 of treated sewage effluents used for irrigation (FAO 2008). Only 25% of PE is served by sewerage systems.

It has been reported by UNICEF (2013) that 2,000 children under the age of 5 die every day in the world due to diarrhoeal diseases, with 90% of these deaths directly linked to poor sanitation and contaminated drinking water. In Yemen, poor sanitation and leakage of old sewerage systems that contaminate underground drinking water pipes are the main causes of polluted water. According to Parliament's Water and Environment Committee (2004), waterborne diseases affected 75% of the population, 55,000 children die annually, and three-million people had hepatitis because of consuming unclean drinking water (HOOD 2011).

Sewage sludge contains many pathogenic bacteria, which can cause several human diseases and may pose a risk to human health if not properly controlled (Scott *et al.* 2003). Hence, this review presents an overview of solar disinfection (SODIS) and lime treatment to reduce pathogenic bacteria in sewage sludge before land application.

PATHOGENIC BACTERIA IN SEWAGE EFFLUENTS AND BIOSOLIDS IN YEMEN

Several pathogenic bacteria have been reported in sewage effluents and biosolids, and most of these are fecal pathogens (US EPA 2003; Wen *et al.* 2009). These pathogens can cause several gastrointestinal diseases (Geldreich 1996). The diversity of pathogenic bacteria in sewage effluents depends on public health, size of the local community, presence of hospitals and factories, as well as sewage treatment processes (Harrison *et al.* 1999, US EPA 2003, Bitton 2005). A wide range of pathogenic bacteria has been detected in sewage effluents, such as *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Salmonella typhimurium*, *Vibrio cholera*, *Shigella* sp., and *Staphylococcus aureus* (Toze 1997; Synnott *et al.* 2009; Dungeni *et al.* 2010; Ellafi *et al.* 2010; Coronel-Olivares *et al.* 2011).

In Yemen, few studies have been conducted on the pathogenic bacteria in the sewage effluents and biosolids. *Streptococcus pneumoniae*, *S. aureus*, *P. aeruginosa*, *E. coli*, and *Salmonella* spp. have been isolated from raw sewage and secondary effluent generated from STP in Ibb (Al-Zubeiry 2005). *Enterobacter aerogenes*, *E. coli*, *Klebsiella* sp., *Enterobacter amnigenus*, *Enterobacter intermedius*, *Citrobacter* sp., *Serratia* sp., *Staphylococcus* spp., *Vibrio* spp., *Proteus* spp., and *Salmonella* spp. have been detected in sewage effluents from STP in Sana'a (Al-Jaboobi *et al.* 2013). *Escherichia coli*, *Klebsiella pneumoniae*, *E. faecalis*, *E. aerogenes*, *S. typhimurium*, *Salmonella typhi*, *Yersinia pestis*, and *Shigella sonnei* have been recovered from secondary effluents and sludge generated from five STPs located in Ibb, Sana'a, Taiz, and Aden (Al-Gheethi *et al.* 2014).

REUSE OF SEWAGE EFFLUENTS AND BIOSOLIDS FOR AGRICULTURAL PURPOSES IN YEMEN

Direct disposal of sewage effluents is suspected as the major source of waterborne diseases (Huttly 1990). In Yemen, the common practice for sewage-treated effluents in coastal cities is discharge into natural waters (UN 2012). The disposal of sewage effluents to the valley ('wadi') is common in the mountain cities (UN 2012). The disposal of sewage effluents could increase the concentration of pathogenic bacteria

Table 1 | Characteristics of main sewage treatment plants in Yemen

Variables	**ISTP**	**TSTP**	**ASTP1**[a]	**$ASTP_2$**	**SSTP**[b]	**HSTP**	**HOSTP**	**BSTP**	**AMSTP**	**DSTP**	**MSTP**
Location	Ibb	Al-Borihi, Taiz	Al-Arish- Aden	Al-Shaab-Aden	Al-Rowdah-Sana'a	Haja	Al-Hodida	Al-Baita	Amran	Dhamar	Al-Mahweet
Type of city	Mountain city	Mountain city	Coastal city	Coastal city	Mountain city	Mountain city	Coastal city	Mountain city	Mountain city	Mountain city	Mountain city
Started operation	1993	1983	2000	1979	2000	1974	–	–	–	2009	–
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 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	Stabilization pond	Stabilization pond	Stabilization pond	Activated sludge	Imhoff tanks	Stabilization pond	Stabilization pond	Stabilization pond	Stabilization pond	Stabilization pond
Design flow rate (m^3/day)	5,256	17,000	70,000	15,000	50,000	2,400	18,000	20,000	2,000	10,000	3,500
Actual flow rate (m^3/day)	8,000	25,000	17,000	15,000	50,000	1,400	18,000	20,000	1,400	9,000	3,500
Situation of WWTP	Over load	Over load	In the range of the design capacity	In the range of the design capacity	Over load	In the range of the design capacity	Over load capacity	Over load	In the range of the design capacity	In the range of the design capacity	Over load
Last date of maintenance	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded	No maintenance was recorded
Disinfection process of secondary effluents	Chlorination	Chlorination	Chlorination	Chlorination	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	Sea disposal and irrigation	Sea disposal and irrigation	Uncontrolled irrigation of crops and vegetables	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	Fertilizer	Fertilizer	Fertilizer

[a] Sludge in ASTP1 is mixed with desert sands before utilization.

[b] Secondary effluents in SSTP are stored in basin storage until utilization.

and heavy metals in surface water, groundwater, and landfills (Al-Sabahi *et al.* 2009).

The reuse of sewage effluents for irrigation is considered as an important alternative water source in the new national water management strategy of the mountain cities in Yemen (ACWUA 2010, UN 2012). However, the use of effluents at excessive rates may produce detrimental effects on soils and crops (US EPA 2004a; Al-Sa'ed 2007). The reuse of sewage effluents and biosolids for agricultural purposes may lead to transfer of pathogenic bacteria to humans via the consumption of effluent-irrigated vegetables (Heyman 2004).

Studies have reported that the survival of pathogenic bacteria is susceptible to environmental factors (Geldenhuys & Pretorius 1989; Berry *et al.* 1991). The environmental factors, which affect survival of pathogenic bacteria in the environment, include temperature, sunlight, moisture, the availability of organic matter, soil pH, soil particles, and the presence of toxic substances in landfill (Ibenyassine *et al.* 2007). For example, in sandy soil and at lower temperatures, *E. coli* increases to three times the initial counts, and has more prolonged survival and slower inactivation rates. At higher temperatures, the death rate increased due to more intense solar radiation, decrease in moisture, and a faster decomposition rate of soil nutrients (Melek 2012).

Zhang *et al.* (2013) investigated the relationships between *E. coli* O157:H7 survival time and soil pH. *E. coli* O157:H7 was undetected after 7 days in acidic soils. However, in neutral soils, *E. coli* O157:H7 survived for 38 days. The sorption of *E. coli* O157:H7 to soil minerals would result in a high loss of viability of *E. coli* O157:H7 (Cai *et al.* 2013). In addition, the low biological availability of phosphorus and organic nitrogen and the high toxicity of Al^{3+} and Mn^{2+} at low pH might indirectly affect *E. coli* O157:H7 survival and activity in acidic soils (Aciego-Pietri & Brookes 2008; Devau *et al.* 2009).

Yemen is the least advanced country among Middle Eastern countries in sewage reuse and safety control. It has a predominantly rural setting, limited sewer connection, deteriorated STPs, which do not meet the national quality requirement, and reuse patterns, which are completely uncontrolled (ACWUA 2010). Regardless of the quality of sewage effluent, farmers living near the disposal sites of sewage, especially in some of the large cities such as Sana'a (Figure 2), Taiz (Figure 3), Aden, and Ibb, are already practicing reuse of non-treated or partially treated sewage effluents. They are pumping sewage directly from stabilization ponds to irrigate agricultural crops (Figure 4) (Boydell *et al.* 2003; UN 2003).

Figure 2 | Dam contaminated with sewage (Al-Mosireqa-Al-Rawda, Sana'a, Yemen) (Parliament's Water and Environment Committee Report 2004).

Figure 3 | Google map of stabilization pond, Al-Burihi, Taiz, Yemen (see the agricultural area around the stabilization ponds).

Al-Sharabee (2009) reported that the farmers around Sana'a sewage treatment plant (SSTP) reuse about 95% of sewage to irrigate a wide range of crops, especially the qat crop, which represents about 33% of the irrigated area in Yemen (Al-Asbahi 2005; Haidar 2005; ACWUA 2010; Ministry of Agriculture and Irrigation 2012; UN 2012).

It has been reported that most animals in the zone area near the STP in Sana'a, Yemen suffer from intestinal diseases caused by pathogenic bacteria from sewage. The farmers of these areas also suffered from several diseases caused by the pathogenic bacteria, because they did not wear gloves during the irrigation process (Haidar 2005).

Figure 4 | Yemeni farmers are pumping sewage directly from stabilization pond to irrigate agricultural crops (IRIN 2009).

On the other hand, STPs are responsible for spreading antibiotic-resistant bacteria into the natural environment (Laroche *et al.* 2009; Servais & Passerat 2009; Garcia-Armisen *et al.* 2011). This is due to the random use of antibiotics among the population that leads to increased concentrations of antibiotics in sewage and increased antimicrobial resistance among the bacterial population in the sewage. On average, 51% of the drugs used in Yemen are antibiotics (Al-Shami *et al.* 2011). A study conducted by Akhali *et al.* (2013) revealed that most of the antibiotics are used without medical prescription. In addition, most doctors prescribe antibiotics without culture and sensitivity testing. These practices lead to an increase in the distribution of antimicrobial resistance among pathogenic bacteria in sewage.

Sewage treatment processes could not eliminate antibiotic-resistant bacteria such as *Enterococcus* (Silva *et al.* 2006). Al-Gheethi *et al.* (2013a) revealed that *E. coli* isolated from sewage-treated effluents in Penang, Malaysia exhibited high resistance for cephalexin, ampicillin, and ciprofloxacin. Al-Gheethi & Norli (2014) indicated that sewage-treated effluents contain a high diversity of bacteria resistant to antibiotics. They found that among 68 bacterial isolates obtained from sewage-treated effluents, 83.82% were multiresistant for antibiotics studied (resistant to three antibiotics or more). These studies indicate that the elimination of antibiotic-resistant strains from sewage effluents and biosolids should be performed before reuse for agricultural purposes.

DISINFECTION PROCESSES OF SEWAGE EFFLUENTS AND BIOSOLIDS IN YEMEN

Stabilization ponds and oxidation ponds, which are the most common STP in Yemen, were reported to reduce only 96 vs. 38% of fecal coliforms (FC) and 89 vs. 16% of enterococci, respectively (Samhan *et al.* 2007; Reinosoa *et al.* 2008). Sewage effluents and biosolids generated from STPs in Yemen still contain pathogenic bacteria due to lack of efficient sewage treatment processes. Therefore, more effective disinfection processes have become necessary to improve the performance of STPs for removal of pathogenic bacteria (Dungeni *et al.* 2010).

In addition, the sewage effluents and biosolids generated from STPs are not subjected to any further treatment before disposal or reuse, apart from some of the STPs, which use chlorination. However, one of the main disadvantages with chlorine disinfection is that of free and combined chlorine residues being toxic to aquatic organisms. Therefore, the requirement to dechlorinate or to remove chlorine before it is discharged to the environment has increased in recent years due to the potential health hazards of nitrosodimethylamine, which is reported as a probable human carcinogen (Pehlivanoglu-Mantas *et al.* 2006).

To maintain safe disposal or reuse of sewage effluents, the WHO (1989) reported that FC should be less than 1,000 cells/100 mL. However, US EPA (2004b) recommended that FC should not exceed 14 cells/100 mL. The US EPA Part 503 regulations for the use or disposal of sewage sludge (CFR 1995) divided stabilization sludge into Class A and Class B. Class A biosolids must meet either an FC limit of less than 1,000 MPN g^{-1} total solids (TS) or less than three *Salmonella*/4 g TS. Class B biosolids should meet FC limits of less than 10^6 MPN g^{-1} TS.

STORAGE SYSTEM OF SEWAGE EFFLUENTS AND BIOSOLIDS IN YEMEN

Storage basins are one of the methods used for storage of wastewater in the USA until the rainy season, when the facility is allowed to discharge into the receiving water body. Storage systems are used typically for accumulating wastewater before its ultimate disposal, or for temporarily holding batch streams before treatment (US EPA 1989).

In Yemen, STPs that are located in the mountain cities store sewage effluents in storage basins before disposal or reuse. The construction of storage facilities below STPs is one of the methods suggested if the sewage effluent is not used for irrigation (WEC 2006). Storage basins are also common among Yemeni farmers located downstream of sewage effluents (ACWUA 2010). Some people have constructed holes to store the sewage (treated or untreated), and then pump it to the fields for irrigation (Al-Nozaily 2004). The sewage effluents are stored to be used for irrigation during the dry season. However, the basin groundwater can be contaminated by pathogenic bacteria. The techniques to optimize sewage effluent quality for irrigation purposes (post-treatment and storage) need further study (WEC 2006).

Studies of storage systems have been conducted by Al-Gheethi *et al.* (2013b). The study was performed to simulate a storage system for sewage effluents. They noted that FC density in stored effluents dropped by more than 3 $\log_{10}$ CFU/100 mL, while *E. faecalis* reduced to below detection levels after 1 week of the storage period. They reported that the storage system of sewage effluents could effectively reduce FC to meet WHO guidelines. However, they observed that the antimicrobial resistance increased among TC and *Salmonella* spp., which survived during the storage period. This is due to the sewage effluents being rich in nutrients and having high bacterial density, which is an ideal environment for cell-to-cell contact and gene exchange (Dionisio *et al.* 2002; Sorensen *et al.* 2005; Haines *et al.* 2007; Zhang *et al.* 2009).

Farmers who live a long distance from the STPs have to store sewage effluents (transported by vehicles) in small tanks (Huibers 2010). In Yemen, these tanks are made of metal sheets, and the temperature of sewage in these tanks varies from 27 to 42 °C depending on the ambient temperature (FAO 2008). The effect of storage at 45 °C on the reduction of fecal indicators bacteria was also studied. Al-Gheethi *et al.* (2013b) simulated the storage of treated effluents at 45 °C. They noted that storage temperature at 45 °C for 192 hour was sufficient to reduce FC to the standard limits recommended by the US EPA. The standard limits required by the WHO were achieved after 48 hour, where the FC numbers were less than 3 $\log_{10}$ CFU/100 mL.

On the other hand, the storage system for biosolids can strongly affect the survival of pathogenic bacteria. Deportes *et al.* (1998) reported that during the storage of biosolids, indicators and pathogenic bacteria remained either undetectable or at a low level. Al-Gheethi *et al.* (2014) revealed that the storage of biosolids for 24 weeks was effective for reduction of FC to meet the Class A standards limits recommended by US EPA.

DISINFECTION OF SEWAGE EFFLUENTS BY SOLAR RADIATION

SODIS was able to inactivate pathogens in water or wastewater when contained in transparent polyethylene terephthalate bottles and exposed to solar radiation for several hours (WHO 2002). The inactivation of pathogenic bacteria occurs due to the lethal effect of ultraviolet radiation and high temperature (Acra *et al.* 1990; WHO 2002; Gomez-Couso *et al.* 2009). A synergistic effect of UV-A radiation and temperature reduced FC by more than 4 logs (99.99%) in midday summer sunlight (Caslake *et al.* 2004; Berney *et al.* 2006). Sewage-treated effluents have been reported to meet US EPA (2004b) standards after 6 hours of SODIS, with more than a 4 log reduction of FC, *E. faecalis*, *Salmonella* spp., and *S. aureus* being achieved (Al-Gheethi *et al.* 2013c).

Sánchez-Román *et al.* (2006) investigated the SODIS of domestic sewage in Brazil. They estimated the surviving *E. coli* population after SODIS from its initial population, depth of water treated, and solar energy received. They revealed that SODIS was effective in reducing TC and *E. coli* populations after 8 hours of exposure to direct sunlight. The SODIS reduced *E. coli* by 4 log with a wastewater depth of 0.05 m in the SODIS reactor. The inactivation rates of *E. coli* did not significantly vary due to turbidity or dissolved oxygen.

Ramachandhran *et al.* (2012) studied the SODIS of *E. coli*, *E. aerogenes*, *S. typhimurium*, and *Enterobacter cloaceae* in sewage sludge in Iran. They found that *S. typhimurium* was highly sensitive to SODIS treatment. They also concluded that SODIS is bactericidal rather than bacteriostatic.

Giannakis *et al.* (2014) investigated the inactivation of *E. coli* in secondary effluents by solar irradiation. They revealed that solar irradiation at 800 and 1,200 W/m^2 inactivated *E. coli*, especially at 50 and 60 °C. Total inactivation was achieved within 4 hours by more than 99.9%. *E. coli* decreased to less than 1,000 CFU/100 mL at 800 W/m^2 and 50 °C. They concluded that treatment time, temperature, and intensity are the critical parameters for the disinfection process, while the initial population is insignificant for reduction efficiency.

One of the proposals submitted by Parliament's Water and Environment Committee in Yemen (2004) to reduce environment pollution by sewage effluents from STPs is by extending the sewerage network to the desert. The climate of Yemen is semi-arid to arid and the temperatures in the cities in summer vary from 27 to 42 °C (FAO 2008). The desert temperatures vary from 45 to 50 °C in summer and from 7 to 35 °C in the winter. The sunlight intensity ranges from 5.2 to 6.8 kWh/m^2/day (Al-Ashwal & Basalah 2012). The desert provides features necessary for the efficient workability of SODIS needed for sewage effluent treatment. The treated sewage could be reused for land reclamation in the desert.

SODIS has several advantages to reduce fecal indicators in sewage-treated effluents compared to other techniques such as chlorination, UV irradiation, and ozonation. SODIS is compatible in meeting the standards for disinfection processes of sewage-treated effluents. SODIS is cost-effective, more efficient, easy implementable and SODIS is a natural process, which means there are no toxic by-products from this process.

ALKALINE TREATMENT OF BIOSOLIDS

Alkaline treatment or lime stabilization is one of the advanced treatment processes for biosolids, which leads to the reduction of pathogenic bacteria and odor. Therefore, health hazards associated with biosolids are minimized and the biosolids could be beneficially reused as soil fertilizers following alkaline treatment (WEF 1995; Murthy *et al.* 2002; Erdal *et al.* 2004; Al-Gheethi 2008). The most commonly used alkaline additives are quick lime (calcium oxide, CaO) and its derivative hydrated lime or slaked lime (calcium hydroxide, $Ca(OH)_2$). Adding adequate volumes of CaO to the sludge, the pH increases to 12 (or higher) and the temperature rises to between 55 and 70 °C, and with sufficient contact time and appropriate mixing, pathogenic bacteria are inactivated or destroyed (Hansen *et al.* 2007).

Lime treatment of biosolids was effective for reduction of *S. typhimurium* after 60 minutes (Plachy *et al.* 1996). According to Reimers (1997), the effectiveness of lime in the reduction of pathogenic bacteria is due to the hydroxide ions and silicate components in lime. The raising of the pH to at least pH 12.5 for 2–4 months caused helminth reductions of 98.5% and virus inactivation of 90% (Schwartzbrod *et al.* 1997).

Alkaline stabilization of biosolids has been reported to reduce FC to meet Class B requirements if the pH of biosolids is increased to more than 12 for 2 hours. Biosolids would meet Class A requirements if pH was raised to more than pH 12 for 72 hours and the temperature increased to 52 °C for at least 12 hours (US EPA 2000). Alkaline treatment by hydrated lime ($CaOH_2$) has eliminated *Salmonella enterica* and *E. coli* O157:H7 within 2 weeks at pH 11 (Toth *et al.* 2012). However, the storage of biosolids treated by lime stabilization for long periods may lead to the pH of biosolids returning to normal pHs due to anaerobic processes at the hydrolysis stage and to the production of acids, such as lactic acid, in anaerobic conditions.

In a study conducted by Bina *et al.* (2004), FC was reduced by 99% after 2 hours, while *Salmonella* was inactivated completely after 24 hours. Biosolids treated with lime met US EPA standards for Class B and Class A biosolids after 2 and 24 hours, respectively. Farzadkia & Bazrafshan (2014) revealed that biosolids stabilization with hydrated lime reduced FC more than 99.99% and the stabilized biosolids met Class B US EPA standards.

In Yemen, Abdel-Monem *et al.* (2008) investigated the potential of lime treatment of biosolids to reduce fecal indicators and *Salmonella* spp. The results revealed that FC in biosolids reduced to meet US EPA standards for Class B after 2 hours and Class A criteria after 24 hours with 19.12 g of quick lime kg^{-1} TS. At high doses of CaO (133 g kg^{-1} TS), *Salmonella* and FC were inactivated completely after 2 hours and the biosolids met the Class A US EPA standards. They revealed that the biosolids treated by lime stabilization could be reused for agricultural purposes.

CONCLUSION

SODIS and lime stabilization are natural processes. These treatments are more suitable for application in developing countries, such as Yemen, with semi-arid to arid climates and that do not have the capacity for high-efficiency sewage treatment. Both treatments could reduce pathogens in sewage-treated effluents and biosolids generated from STPs effectively. SODIS and lime treatment are simple, easy implementable, produce no toxic by-products, and are cost-effective.

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