GLOBAL WATER PATHOGEN PROJECT

PART FOUR. MANAGEMENT OF RISK FROM EXCRETA AND WASTEWATER

ANAEROBIC SLUDGE BLANKET REACTORS

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Summary

Upflow anaerobic sludge blanket (UASB) reactors and anaerobic baffled reactors (ABRs) are sanitation technologies that are designed to remove organic matter (measured as BOD or COD). They can also recover methane, which can be managed to produce energy. They are considered sludge blanket reactors because the influent wastewater receives treatment by passing through flocculent or granular sludge blankets. These sanitation technologies are part of a centralized or semi-centralized treatment plant for a sewered sanitation system. Anaerobic sludge blanket reactors replace conventional primary and secondary treatment with sludge digestion, but the resulting sludge will contain pathogens that requires post-treatment to meet most regulatory guidelines for safe disposal or reuse. The removal of pathogens and several water quality constituents is not particularly high in this type of sanitation technology; therefore, they require post-treatment, which can be readily accomplished using other sanitation technologies, such as waste stabilization ponds, media filters, and/or constructed wetlands. A UASB reactor is expected to provide 0.8 to 1.6 $\log_{10}$ removal for bacterial pathogens, negligible to 0.7 $\log_{10}$ removal for viruses, 0.3 $\log_{10}$ removal for protozoan pathogens (based on only one study), negligible to 1.0 $\log_{10}$ removal for helminth eggs, and 0.4 to 2.2 $\log_{10}$ removal for fecal indicator bacteria. There is less information available for ABRs.

ANAEROBIC SLUDGE BLANKET REACTORS

1.0 Brief Technology Description

In vertical flow UASB and EGSB reactors, a sludge blanket floats as the wastewater passes through it, as illustrated in Figure 2a; in an ABR, the sludge blanket moves upward and downward through the compartments as the wastewater flows through the reactor, as shown in Figure 2b. The upper part of a UASB reactor contains a solid-gas-liquid separator, which allows biogas to be collected in one compartment and solids to settle and return to the reactor body. This configuration increases the biomass concentration. EGSB reactors are similar to UASB reactors, with the main difference being that EGSB reactors are taller, have a higher height to diameter ratio, and include the recirculation of a portion of the wastewater in order to get better contact between the sludge blanket and the influent wastewater. However, EGSB reactors are less used than UASB reactors for the treatment of domestic wastewater., This section will concentrate on UASB and ABR reactors because of their wide applicability with more emphasis on UASBs because of greater data availability (Figures 3 and 4).

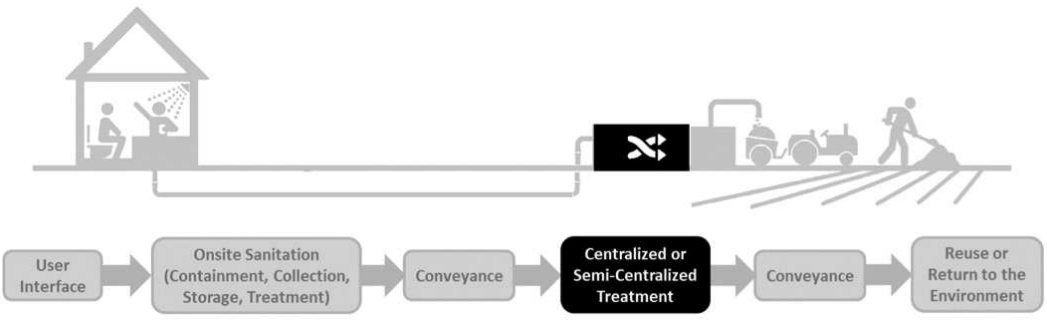

Figure 1. Location where anaerobic sludge blanket reactors are used within the sanitation service chain

In vertical flow UASB and EGSB reactors, a sludge blanket floats as the wastewater passes through it, as illustrated in Figure 2a; in an ABR, the sludge blanket moves upward and downward through the compartments as the wastewater flows through the reactor, as shown in Figure 2b. The upper part of a UASB reactor contains a solid-gas-liquid separator, which allows biogas to be collected in one compartment and solids to settle and return to the reactor body. This configuration increases the biomass concentration. EGSB reactors are similar to UASB reactors, with the main difference being that EGSB reactors are taller, have a higher height to diameter ratio, and include the recirculation of a portion of the wastewater in order to get better contact between the sludge blanket and the influent wastewater. However, EGSB reactors are less used than UASB reactors for the treatment of domestic wastewater., This section will concentrate on UASB and ABR reactors because of their wide applicability with more emphasis on UASBs because of greater data availability (Figures 3 and 4).

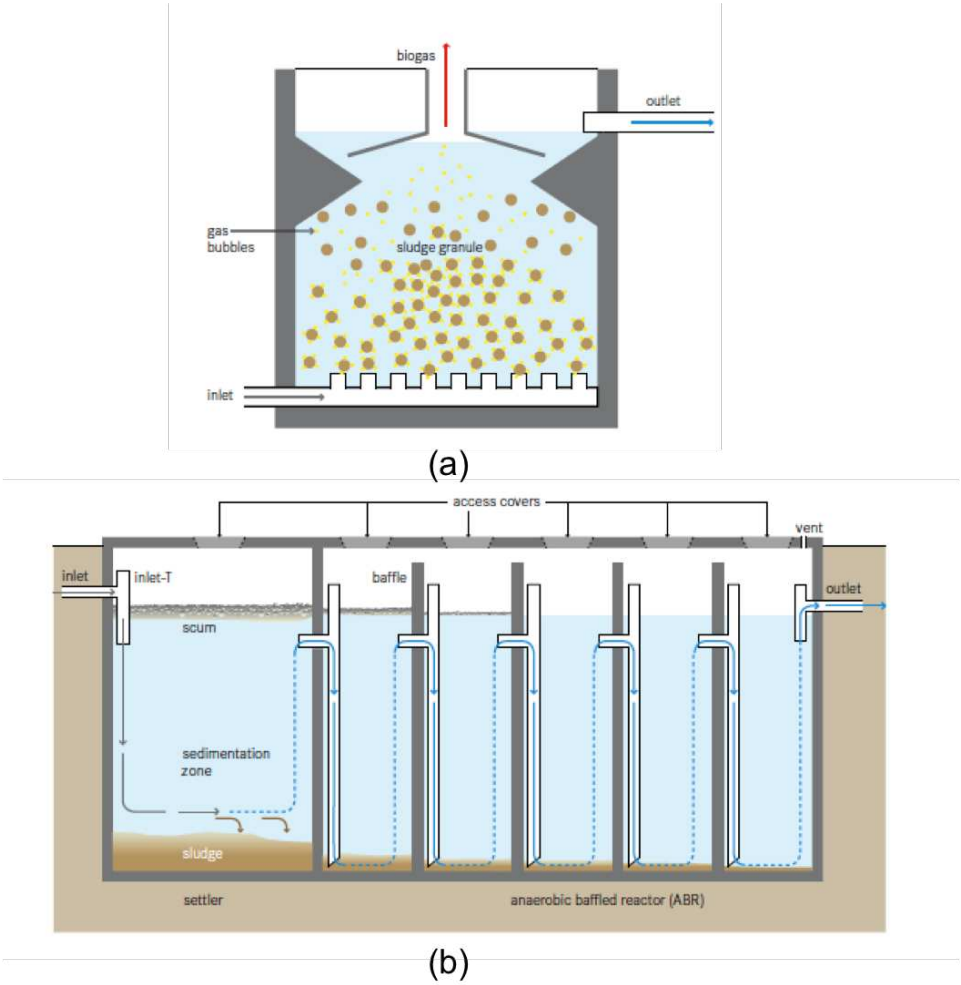

Figure 2. Anaerobic sludge blanket reactors: a) Upflow anaerobic sludge blanket (UASB), where the sludge blanket floats above the influent as a result of the liquid upflow velocity; and b) Anaerobic baffled reactors (ABR), where the sludge blanket moves from one upflow/downflow compartment to the next. Both reactors require periodic sludge wasting and sludge dewatering processes. Reprinted with permission of Eawag: Swiss Federal Institute of Aquatic Science and Technology, Department Water and Sanitation in Developing Countries (Sandec). Figure from Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph. and Zurbrügg, C., 2014. Compendium of Sanitation Systems and Technologies. 2nd Revised Edition. Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland.

Figure 3. Upflow anaerobic sludge blanket (UASB) reactors used for different population ranges: left: hundreds of inhabitants (Belo Horizonte, Brazil, followed by maturation ponds); middle: thousands of inhabitants (Sololá, Guatemala, followed by a trickling filter with biogas storage tanks); right: one million inhabitants (Belo Horizonte, Brazil, also followed by trickling filters) (middle photo reproduced with permission of Stewart Oakley; left and right photos reproduced with permission of Marcos von Sperling).

Figure 4. A nine compartment anaerobic baffled reactor (ABR) in operation, Dunnigan, California, USA (photo reproduced with permission of Stewart Oakley).

The removal of pathogens and several water quality constituents is not particularly high in UASBs and ABRs; therefore, they require post-treatment, which can be readily accomplished using technologies described in other chapters such as: Media Filters, Waste Stabilization Ponds, and Constructed Wetlands, or other technologies in combination with disinfection. Anaerobic sludge blanket reactors produce from 0.1 to 0.2 kg of dry sludge per m^3 of treated wastewater. Sludge granules and flocs that remain suspended in the blanket should be retained in the system, as they provide a surface for the growth of beneficial microbial communities. A fraction of the sludge in the blanket must be withdrawn at specified intervals depending on the solids retention time (SRT) design, and this sludge must be dewatered and treated before reuse or land application. Dewatering is most commonly accomplished using sludge drying beds (Figure 5) in small to medium-size communities, or mechanical dewatering, in medium to large-size communities. Detailed information on the design and operation of anaerobic sludge blanket reactors can be found in Chernicharo (2007), Metcalf & Eddy and AECOM (2014), and Foxon et al. (2006).

Figure 5. Sludge drying beds for the wasted upflow anaerobic sludge blanket (UASB) sludge at Sololá, Guatemala. The sludge is well digested and dried and is currently provided to the public in bags as a soil conditioner and fertilizer. This practice should be prohibited until there is sufficient removal of pathogens in the sludge. Dewatered sludge should be treated for pathogen removal prior to reuse (see Sludge Management Chapter) (photos reproduced with permission of Stewart Oakley).

2.0 Inputs and Outputs for Anaerobic Sludge Blanket Reactors

Figure 6 presents the typical inputs and outputs of anaerobic sludge blanket reactors. Anaerobic sludge blanket reactors can be used to treat a variety of waste streams, and the inputs may vary from system to system. These reactors are most commonly used to treat industrial wastewater, domestic wastewater, or a mixture of the two. Some systems may also receive landfill leachate. Manure and other agricultural waste are sometimes added to anaerobic reactors in rural areas. Anaerobic sludge blanket reactors are used in place of primary and secondary wastewater treatment and anaerobic sludge digestion, so they receive wastewater that has only gone through screening and grit removal; their effluents, however, still have relatively high BOD_5 concentrations as compared with conventional secondary treatment (50-70% removal as compared with 85-95% removal for trickling filters or activated sludge) and require post-treatment, typically with aerobic processes and disinfection, to meet discharge or reuse requirements (Chernicharo, 2007). Typical concentrations for pathogens in common input waste streams are provided in the Introduction Chapter. The outputs from anaerobic sludge blanket reactors include treated effluent (liquid), digested sludge (biosolids), and biogas (which can be captured and can be used as a fuel for cooking or heating in small plants, and electricity generation in large ones). Treated effluent is continuously discharged from these reactors, biogas is continuously produced, and digested sludge must be withdrawn periodically.

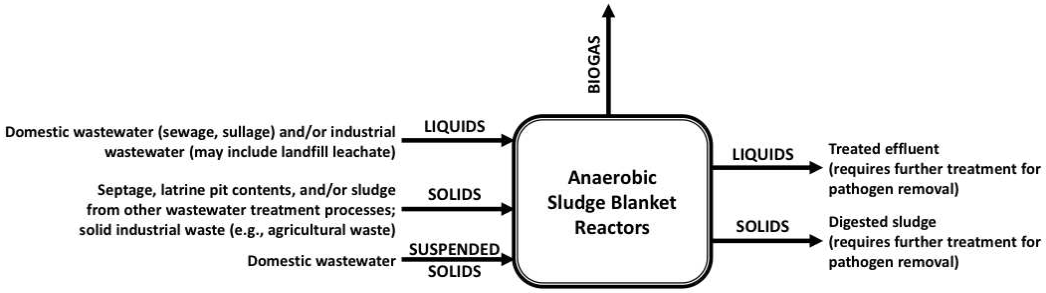

Figure 6. Typical inputs and outputs for anaerobic sludge blanket reactors

3.0 Factors Affecting Pathogens in Anaerobic Sludge Blanket Reactors

Anaerobic wastewater treatment processes are designed specifically for organic matter stabilization (i.e., reduction in BOD and COD) and methane production; therefore, any removal or inactivation of viral, bacterial, protozoan or helminth pathogens in treated effluents or sludge is incidental to the design objectives. Nevertheless, the reduction of viral, bacterial, protozoan, and helminth pathogens has been reported to range from negligible to 1.5 $\log_{10}$ units for UASBs (WHO, 2006).

A summary of the most important factors for removal of the different pathogen types is presented in Tables 1a and 1b. The principal removal mechanism for pathogens in anaerobic sludge blanket reactors is retention in the sludge and removal via sludge withdrawal, although some pathogens may also be inactivated due to physical-chemical factors (Figure 7). The retention of pathogens in the sludge may occur due to physical filtration as wastewater passes through the dense layer in the sludge blanket, or due to microbiological factors—pathogens may be retained in the sludge blanket by the same mechanisms that cause the formation of granular sludge (Chernicharo, 2007; Metcalf & Eddy AECOM, 2014). Very few studies have been performed to determine the impact of individual mechanisms for pathogen removal in UASBs and ABRs; most studies simply report the differences in influent and effluent concentrations.

Table 1a. Summary of factors and mechanisms for pathogen removal in anaerobic sludge blanket reactor effluent: Retention in the sludge

Summary of removal mechanism

Retention in the sludge is the primary mechanism responsible for the removal of pathogens from wastewater treated in anaerobic sludge blanket reactors. Helminth eggs with settling velocities much greater than 0.5 m/h (e.g., *Schistosoma* spp.) could potentially be removed by sedimentation. One mechanism that may cause pathogen retention in sludge is their attachment to microbial extracellular polymeric substances in sludge blanket granules, but this has not been well-studied.

Factors contributing to removal	Viruses	Bacteria	Protozoa	Helminths
Some important factors for the retention of pathogens in anaerobic reactor sludge include: - upflow velocities - contact time with settled sludge and sludge blanket - sludge retention time in reactor - turbulence due to biogas production	0.7 $\log_{10}$ removal of human adenovirus 0.2 $\log_{10}$ removal of norovirus GII in a UASB at a hospital in Rio de Janeiro, Brazil. No removal for rotavirus group A (Prado et al., 2011) Adenovirus qPCR copies and culturable enterovirus were more volumetrically concentrated in UASB reactor sludge than they were in the wastewater (Symonds et al., 2014; Verbyla, 2015).	1.0 $\log_{10}$ removal for *Salmonella* spp., 0.5 $\log_{10}$ removal for *Shigella* spp., 1.0 $\log_{10}$ removal for *Vibrio* spp in a UASB reactor (Pant and Mittal, 2007) 1.1 $\log_{10}$ reduction of thermotolerant coliforms in UASB reactors (Oliveira and von Sperling, 2011) 1.0 $\log_{10}$ reduction of thermotolerant coliforms in an ABR reactor (Lalbahadur et al., 2005)	0.3 $\log_{10}$ removal of *Cryptosporidium* oocysts (Morsy et al. 2007)	0.42 to 1.30 $\log_{10}$ for UASBs (Keller et al., 2004; von Sperling et al., 2003; Yaya-Beas et al., 2015). 1.66 $\log_{10}$ for an eight compartment ABR with a 42 hour hydraulic retention time (Foxon et al., 2006).

Table 1b. Summary of factors and mechanisms for pathogen removal in anaerobic sludge blanket reactor effluent: Other potential physical-chemical factors

Other Factors	Evidence of Pathogen Vulnerabilty
Other potential physical-chemical factors include temperature, reaction times, NH_3 toxicity, and volatile fatty acid toxicity. • Higher temperatures in reactors increase the rate of other pathogen inactivation mechanisms; UASBs and ABRs, however, are mostly operated at ambient temperatures, thus minimizing temperature effects • Short hydraulic retention times limit reaction times for pathogen inactivation • Uncharged aqueous ammonia (NH3) has microbiocidal effects, especially at high pH values (when this form of ammonia is present in high concentrations); however, the pH levels encountered in anaerobic sludge blanket reactors are typically much more neutral, supporting the formation of NH4+. • Volatile fatty acids have microbiocidal effects at low pH values; however, the pH levels encountered in anaerobic sludge blanket reactors are typically near neutral, potentially minimizing these effects.	There are no supporting data for these possible removal mechanisms for viruses, bacteria, protozoa or helminths

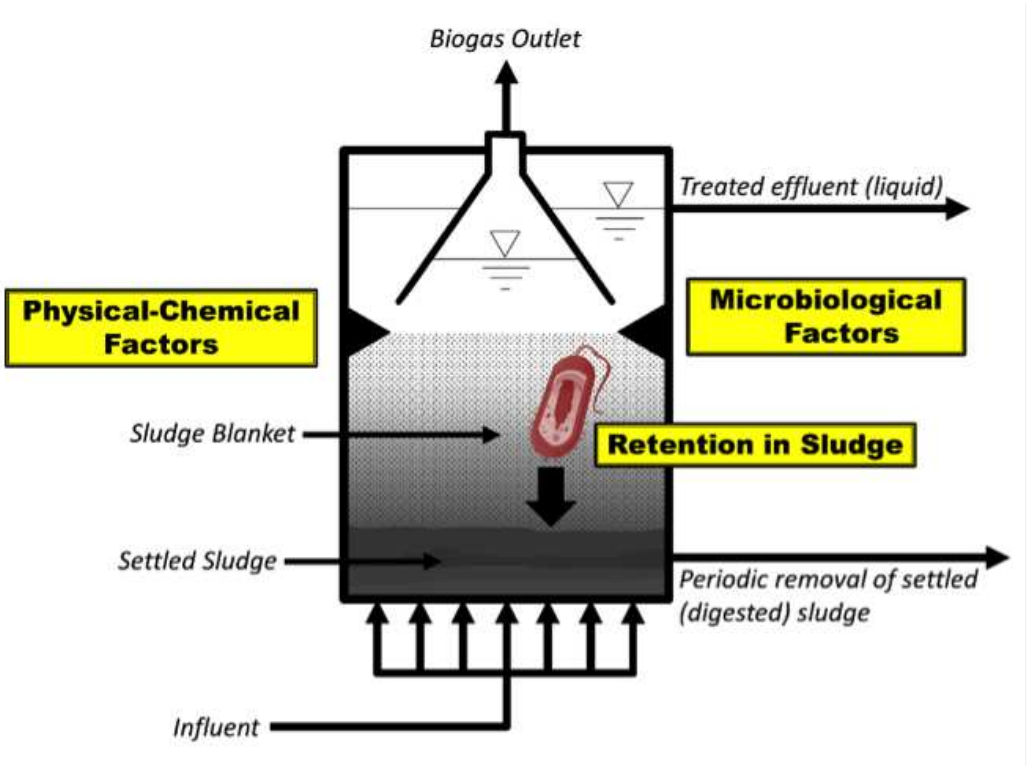

Figure 7. Major factors affecting pathogen fate in anaerobic sludge blanket reactors

3.1 Retention in Sludge

There is a scarcity of data in the literature on the mechanisms of pathogen retention in sludge from anaerobic sludge blanket reactors. As a result, it is assumed that pathogen retention in sludge is similar to the processes retaining biomass in anaerobic sludge blanket reactors. These processes include Chernicharo, 2007; Metcalf & Eddy AECOM, 2014):

- Attachment of microorganisms to other cells or organic solids
- Flocculation due to bacterial growth
- Interstitial retention of bacteria passing through sludge blanket
- Adsorption of microorganisms or colloidal particles by reversible physiochemical forces
- Irreversible attachment of microorganisms by microbial extracellular polymers
- Granulation and multiplication of bacterial cells by substrate diffusion into the granular structure

Verbyla (2015) measured the quantities of human adenovirus using qPCR in samples collected from the influent, effluent, sludge blanket, and settled sludge of a full-scale UASB reactor in Brazil, separating samples into a

pellet (larger, settleable solids) and a supernatant (liquid and non-settleable solids) by centrifugation for 10 min. at 1,157×*g*. The concentrations of adenovirus in the liquid supernatant were similar in samples collected at the effluent and from the sludge blanket; however, concentrations per dry mass in the pellet from the sludge blanket samples were more than an order of magnitude greater than they were in the pellet of the treated effluent, indicating that the viruses were volumetrically concentrated in the sludge. Verbyla (2015) also found that the concentrations of adenovirus per dry weight of solids in the sludge blanket and in the settled sludge were similar, which indicated that retention in the sludge and removal of settled sludge might be one mechanism for the removal of adenovirus in UASB reactors.

3.2 Physical-Chemical and Microbiological Factors

There has been limited research into the specific impact of physical-chemical and microbiological factors on the inactivation of pathogens retained in UASB and ABR reactors. Therefore, it is assumed that the factors that are most relevant for pathogen removal and inactivation in these systems are similar to the factors responsible for pathogen removal in anaerobic reactors (i.e., digesters) used to treat primary and biological sludge from other wastewater treatment systems (see Chapter on *Sludge Management*). In particular, pathogens may be vulnerable to toxicity from metabolites naturally present in wastewater and its sludge, such as NH_3, amines, aldehydes, ketones, volatile fatty acids (Acquisto et al., 2006). This may cause pathogens to be present in the treated effluent, but in non-viable forms. For example, Foxon (2009) found no difference in the overall concentration of *Ascaris* eggs in pilot-scale ABR with 8 compartments and 20 hour hydraulic retention time, but the percentage of viable eggs was reduced from 36% at the influent to only 2% in the treated effluent. Higher temperatures can also accelerate the natural die-off of pathogens in anaerobic reactors, especially if they are retained in the system for a long time. Compared to other pathogen types, helminth eggs are very resistant to high temperatures, and may enter a dormancy stage to maintain viability in anaerobic environments. Authors of one study found that *Ascaris* eggs became dormant (remained unembryonated) when exposed to the anaerobic environment in a 35°C lab-scale anaerobic digester and 65% maintained viability for up to 16 days (Manser et al., 2015). The authors reported that of the *Ascaris* eggs that were initially exposed to aerobic conditions (to trigger their initial stages of development), only 35% maintained viability after 16 days once they entered the anaerobic digester.

The sedimentation of pathogens not retained in sludge particles from anaerobic sludge blanket reactors has not been specifically studied, but may be minor. The experimentally measured settling velocity for helminth eggs in tap water was found to average 0.22 m/h for *Ascaris* and 0.54 m/h for *Trichuris* (Sengupta et al., 2011); and settling velocities for protozoa, and especially bacteria and viruses, would be much lower (Cizek et al., 2008; David and Lindquist, 1982; Kulkarni et al., 2004; Medema et al., 1998). Design guidelines for liquid upflow velocities in UASB reactors indicate that they should be 0.5 – 0.7 m/h during average flow conditions and no more than 1.5 m/h during peak flow conditions (Chernicharo, 2007). Furthermore, the design upflow velocity is calculated using the interior reactor diameter and the flow rate. In reality, the volume occupied by sludge blanket granules acts as hydraulic dead space, meaning that the actual velocity of the liquid moving through the reactor can be slightly greater (Bolle et al., 1986). Therefore, it is likely that "free floating" helminths would exit the reactor in the liquid effluent, reinforcing that the major mechanism is retention in sludge blanket or attachment to sludge granules with sedimentation playing a minor role.

Tables 1a and 1b present summaries of what is known about the mechanisms associated with pathogen removal in anaerobic sludge blanket reactors.

4.0 Design, Operation, and Maintenance Guidelines for Pathogen Removal

From a design perspective, not much can be done to enhance the removal of pathogens in anaerobic sludge blanket reactors, as they are primarily designed to remove soluble and suspended organic matter (i.e., BOD and COD). The design engineer should ensure that systems using these reactors are equipped with appropriate post-treatment technologies and sludge treatment systems to remove pathogens from effluent and sludge to the extent necessary for safe reuse. Shallow (< 1 m) and/or baffled polishing ponds have been reported to be effective post-treatment technologies for the removal of helminth eggs and fecal indicator bacteria from UASB reactor effluent (Cavalcanti et al., 2001; Dias et al., 2014; Khan et al., 2011; von Sperling and Mascarenhas, 2005; von Sperling et al., 2005, 2003, 2002). The depth of the polishing pond is important for enhancing pathogen removal. For example, a community-managed wastewater treatment system in Bolivia with a UASB reactor and deeper (unbaffled) polishing ponds showed limited removal of helminth eggs, *Giardia*, and viruses (Symonds et al., 2014; Verbyla et al., 2013). Khan et al. (2011) also reported good removal of helminth eggs in an overland flow system treating UASB reactor effluent.

There are several operational concerns that can lead to reduced pathogen removal in well-designed anaerobic sludge blanket reactors. Hydraulic overloading, high upflow velocities, excessive sludge accumulation, and solids loss due to gas production can result in the discharge of solids and retained pathogens in the treated effluents. The most important way to maximize pathogen removal and minimize microbial risks for wastewater treatment systems with UASBs, EGSBs and ABRs is to ensure proper design, operation, maintenance, and the safe treatment and management of sludge. Due to their small volumes and short retention times, UASBs, EGSBs, and ABRs are not very robust to short-term fluctuations in wastewater flow and quality. Changing conditions may cause sludge granules to spontaneously disintegrate (Liu et al., 2004), potentially releasing pathogens retained in the sludge.

Trained and experienced operators are required to ensure that the systems perform well; in one study, it was reported that 15 different anaerobic sludge blanket reactor systems in India failed their discharge standards despite the fact that they were well-designed and had been in operation for less than 7 years (Sato et al., 2006).

Table 2 presents a summary of key factors associated with the removal of the four major groups of pathogenic organisms in anaerobic sludge blanket reactors, indicating whether the factor enhances or reduces removal. Considering that sludge drying beds are widely used for dewatering the sludge removed from anaerobic reactors, the key factors associated with pathogen removal in the sludge treatment unit are described in Table 3 and in further depth in Chapter on *Sludge Management*.

Table 2. Summary of key factors for pathogen removal in anaerobic sludge blanket reactors

Factor	Pathogen removal is potentially ↑ enhanced or ↓ reduced under the following conditions:
Upflow Velocity (for UASBs and EGSBs)	Lower upflow velocities = ↑ Pathogen Removal
Baffle Configuration (for ABRs)	Proper Baffle Configuration = Minimized Solids Loss = ↑ Pathogen Removal
Temperature	Higher Temperature = ↑ Pathogen Removal
Retention in Sludge Blanket and Periodic Sludge Removal	Well-Developed Sludge Bed = ↑ Pathogen Retention Removal of Sludge = ↑ Pathogen Removal
Hydraulic Overloading	Hydraulic Overloading = ↓ Pathogen Removal
Excessive Sludge Accumulation (causing loss of solids)	Excessive Sludge = ↓ Pathogen Removal
Gas Production (causing loss of solids)	More Solids Loss = ↓ Pathogen Removal
Post-Treatment	UASBs, EGSBs, or ABRs without post treatment do not provide sufficient pathogen removal

Table 3. Summary of key strategies to reduce microbial risk from sludge drying beds used with anaerobic sludge blanket reactors (See also Chapter on Sludge Management)

Factor	Pathogen Removal is Potentially ↑ Enhanced or ↓ Reduced Under the Following Conditions:
Temperature	Higher Temperature = ↑ Pathogen Removal
pH	Higher pH (lime application) = ↑ Pathogen Removal
Humidity	Roofed Drying Bed = ↑ Pathogen Removal
Time	Longer Time in Drying Bed = ↑ Pathogen Removal
Inappropriate Use	Sludge removed from drying beds should be monitored for helminth eggs and other pathogens prior to reuse

5.0 Data on Fecal Indicator and Pathogen Removal in Anaerobic Reactors

The range of pathogen reduction reported in the literature for UASB reactors is generally between zero and 2 $\log_{10}$ units for bacteria, and less than 1 $\log_{10}$ unit for other pathogens (Figure 8). The most commonly reported pathogen removed in UASB and ABR systems has been helminth eggs, principally those of *Ascaris*. Studies from Brazil have reported helminth egg removals ranging from 0.42 to 0.92 $\log_{10}$ units in UASB reactors from full scale wastewater treatment plants (von Sperling et al., 2005), with influent concentrations ranging from 17 to 254 eggs/L and effluent concentrations ranging from 3 to 37 eggs/L (Keller et al., 2004; von Sperling et al., 2003). A laboratory study on UASB reactor operation at low temperature (11-14 °C) in Peru reported helminth egg removals ranging from 0.96 to 1.30 $\log_{10}$ units, with effluent concentrations ranging from 5 to 35 eggs/L, and found that removal was independent of upflow velocities in the reactor for velocities between 0.12 – 0.41 m/h (Yaya-Beas et al., 2016). The removal of helminth eggs in UASB reactors with hydraulic retention times between 6 – 8 hours was equal to or greater than the removal of helminth eggs with retention times between 4 – 6 hours (Figure 8).

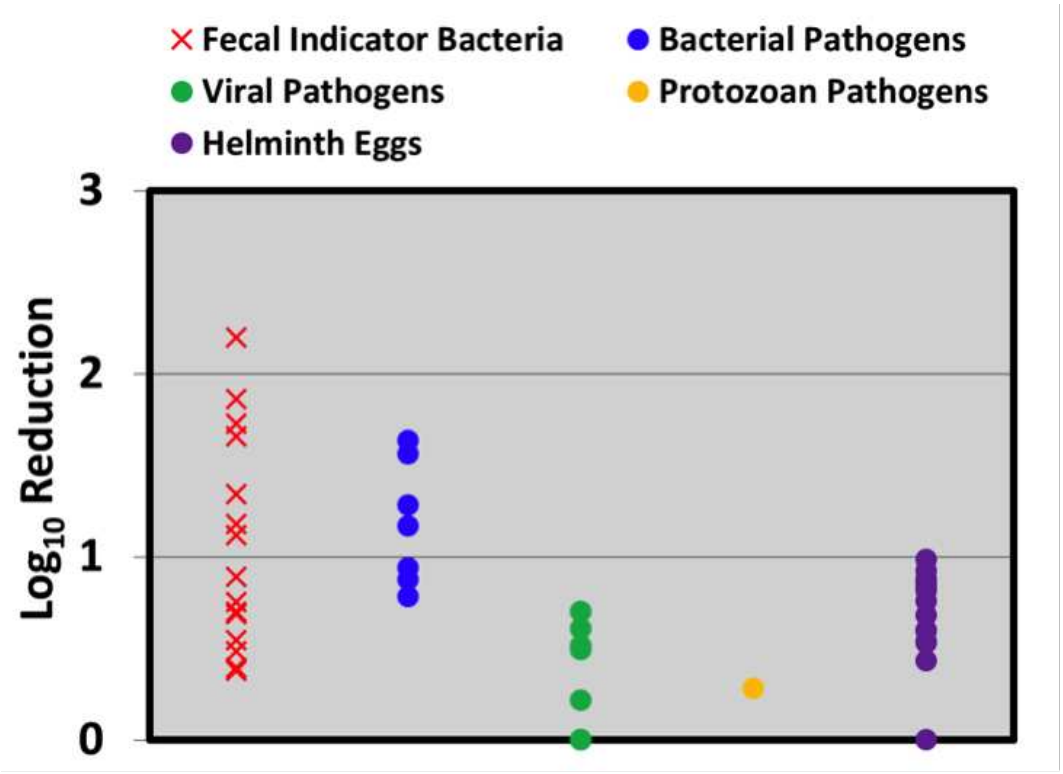

Figure 8. Log10 reduction values for pathogens and fecal bacteria (including E. coli and fecal streptococci) in UASB reactors. Data sources: (Chernicharo et al. 2001; Dixo et al. 1995; Prado et al. 2011; Soares et al. 2000; von Sperling et al. 2002; 2003; 2005; Keller et al. 2004; Ribeiro et al. 2015; El-Khateeb et al. 2009; Morsy et al. 2007; Trein et al. 2015; Gonçalves et al. 2009; Dias 2016; Verbyla 2015; Symonds et al. 2014; Pant and Mittal 2007).

In one of the few studies reporting pathogen removal in ABRs, Foxon et al. (2006) reported a 1.66 $\log_{10}$ removal of *Ascaris* spp. from treated effluent for an eight compartment pilot scale ABR, with mean influent and effluent concentrations of 772 and 17 eggs/L, respectively. This is the highest removal for helminths reported in the literature for sludge blanket reactors. It may be attributed to enhanced liquid phase contact with the sludge blanket by passing through multiple upflow/downflow compartments coupled with a long hydraulic retention time (44 hours) (Foxon et al., 2006).

Pathogen removal in UASB reactors has also been published in very few studies, but the findings to date indicate that reduction is below 1 $\log_{10}$ for all pathogens, perhaps with the exception of bacterial pathogens and other fecal bacteria. Prado et al. (2011) reported a 0.7 $\log_{10}$ removal for human adenovirus, a 0.2 $\log_{10}$ removal for norovirus GII, and no removal for rotavirus group A. Symonds et al. (2014) reported negligible removal of rotavirus and norovirus GI for a UASB reactor in the remote Yungas region of Bolivia (based on only two 24-hour composite samples, measured using RT-qPCR); they reported a 0.5 $\log_{10}$ reduction of culturable enteric viruses (on BGMK cells) in the same system (based on only a single pair of 24-hour composite samples). Verbyla (2015) found up to 0.6 $\log_{10}$ removal of human adenovirus (using qPCR) for three different UASB reactors in Brazil, based on 4 – 6 samples collected biweekly. Only one study was found regarding the removal of protozoan pathogens in UASB reactors; Morsy et al. (2007) reported 0.3-$\log_{10}$ reduction of *Cryptosporidium* oocysts.

There are several studies on the removal of fecal indicator bacteria (mostly coliforms) in UASBs but very few on the removal of actual bacterial pathogens. In general, the removal of fecal bacteria appears to be a bit greater than the removal of viral, protozoan, and helminth pathogens. Pant and Mittal (2007) found a 0.94 $\log_{10}$ removal for *Salmonella* spp., a 0.78 $\log_{10}$ for *Shigella* spp., and a 0.87 $\log_{10}$ for *Vibrio* spp.; they also reported a 0.69 $\log_{10}$ removal for thermotolerant coliforms and a 0.75 $\log_{10}$ for fecal streptococci. El-Khateeb et al. (2009) reported more efficient reduction of fecal bacteria in a UASB reactor in Egypt, with removals of more than 1 $\log_{10}$ for total and thermotolerant coliforms, fecal streptococci, *Pseudomonas aeruginosa*, *Listeria monocytogenes*, salmonella, and staphylococci.

6.0 Data on Pathogens in Sludge from Anaerobic Reactors

UASB reactors produce sludge at a rate of 0.1 – 0.2 kg/m^3 (dry mass solids) of domestic wastewater treated, and this sludge must be removed from the reactor every few weeks to maintain proper operating conditions. Prior to reuse, the sludge must be dewatered and treated, as it still contains high concentrations of pathogens (Chernicharo, 2007).

7.0 Conclusions

Anaerobic sludge blanket reactors are designed with the main objective of removing organic matter and providing some digestion of sludge, therefore the removal of pathogens in these reactor is not particularly high. The wastewater and sludge outputs from these reactors require some type of additional treatment to reduce the concentrations of pathogens prior to their discharge or reuse for beneficial purposes. Table 4 presents a summary of the removal of three types of pathogens from wastewater in anaerobic sludge blanket reactors, derived from the literature (no literature data were found for removal of protozoan pathogens in these systems). Table 5 presents concentrations of pathogens in the sludge.

Table 4. Summary of indicators and pathogen removal from wastewater in anaerobic reactors

Type of Reactor	Average Reported Pathogen and Fecal Indicator $\log_{10}$ Removal Values[a] (Ranges Shown in Parentheses)				
	Bacterial Pathogens	**Viruses**	**Protozoa**	**Helminth Eggs**	**Fecal Indicator Bacteria (including *E. coli*)**
UASB Reactor	1.2 (0.8 to 1.6)	0.3 (negligible to 0.7)	0.3	0.7 (negligible to 1)	1.1 (0.4 to 2.2)
Anaerobic Baffled Reactor	ND[b]	ND	ND	1.7	~ 1

[a] Sources: (Chernicharo et al. 2001; Dixo et al. 1995; Prado et al. 2011; Soares et al. 2000; von Sperling et al. 2002, 2003, 2005; Keller et al. 2004; Ribeiro et al. 2015; El-Khateeb et al. 2009; Morsy et al. 2007; Trein et al. 2015; Gonçalves et al. 2009; Dias 2016; Verbyla 2015; Symonds et al. 2014; Pant and Mittal 2007; Foxon 2009; Foxon et al. 2006; Lalbahadur et al., 2005; Oliveira and von Sperling, 2011; von Sperling and Mascarenhas, 2005; Yaya-Beas et al., 2015)

[b] ND = No data

Table 5. Concentrations of pathogens found in anaerobic reactor sludge

Pathogen[a]	Country	Concentration/g TS[b]	Type of Sludge	References
Helminths				
Ascaris (total eggs)	Brazil	48 eggs	UASB reactor	Keller et al., 2004
	Mexico	62.9 eggs	UASB reactor	Rojas Oropeza et al., 2001
Ascaris (viable eggs)	Mexico	2.9 eggs	UASB reactor	Rojas Oropeza et al., 2001
Viruses				
Culturable enteroviruses	Bolivia	500 iu	UASB reactor	Symonds et al., 2014
Human adenovirus	Brazil	1.6E+06 to 3.4E+07 gene copies	UASB reactor	Authors' own unpublished data

[a] No data were found for bacterial and protozoan pathogens; [b] TS is total solids

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