Commissioning of an emergency faecal sludge treatment plant in Imvepi, Uganda

Uppstart av nödreningsverk för fekalt slam i Imvepi, Uganda

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Abstract

This article evaluates the commissioning of an emergency faecal sludge treatment plant piloted in Imvepi refugee settlement, Uganda. The treatment plant is composed of screening and a settling tank, followed by a sequencing batch reactor (SBR) shifting between aerobic and anaerobic operation, which were evaluated in this study, and finally sand filters and chlorination. The study also explores the feasibility of adapting the units' SBR for a cold-climate crisis scenario.

During commissioning in Imvepi, several challenges were encountered, such as poorly settling sludge, high pH and accumulation of nitrite and nitrate. The addition of lime improved the settling prior to the SBR, and polymer use improved the settling in the SBR. Feeding the SBR unit with new faecal sludge right before settling facilitated denitrification and indicated that the biodegradable fraction of the organic matter was low and probably not representative for fresh faecal sludge, which would be the case in a real crisis situation. Stable treatment performance was not achieved within the first 1.5 months of plant operation, although nutrients and organic matter were reduced in the SBR. A theoretical cold-climate adaptation for a Swedish scenario (fresh sludge, an internal SBR temperature of 12°C, and strict nitrogen removal targets) would require more than 16 times the SBR volume used in Uganda.

The findings of the study demonstrate that the emergency faecal sludge treatment plant, using SBR technology, has potential for use in both tropical and cold climates if adapted to the local context, preferably with fresh faecal sludge, and accompanied by critical operational controls. However, further adaptations are needed for a reliable deployment in a humanitarian emergency setting.

Key words: Sequencing batch reactor, faecal sludge management, faecal sludge treatment plant, emergency response, cold climate sanitation

Sammanfattning

Denna artikel beskriver driftsättningen av en pilotanläggning för behandling av fekalt slam i flyktingbosättningen Imvepi, Uganda. Anläggningen består av gallerrens och sedimenteringstank, en satsvis biologisk reaktor (SBR) för växelvis aerob och anaerob behandling, vilka har utvärderats i denna studie, samt efterbehandling med sandfilter och klorering. Även möjligheter att anpassa systemets SBR till ett krisscenario i ett kallt klimat undersöktes.

Flera utmaningar uppstod under driftsättningen i Imvepi, såsom dålig sedimentering av slam, högt pH och ansamling av nitrit och nitrat. Genom att tillsätta kalk förbättrades sedimenteringen före behandling i SBR:en och polymertillsats förbättrade sedimenteringen i SBR:en. Genom att fylla på med nytt, fekalt slam strax före sedimenteringsfasen underlättades denitrifikationen, vilket indikerar att andelen bionedbrytbart organiskt material var låg och troligen inte representativ för färskt slam. Detta skulle vara fallet i en krissituation. Stabil behandling uppnåddes inte under de första 1,5 månaderna av anläggningens drift, men näringsämnen och organiskt material minskade i SBR:en. En teoretisk anpassning för ett kallt klimat baserad på ett svenskt scenario (färskt, fekalt slam, en intern SBR-temperatur på 12°C samt strikta krav på kväverening) skulle kräva mer än 16 gånger den SBR-volym som användes i Uganda.

Denna studie visar att nödreningsverket med SBR-teknik har potential att användas både i tropiska och kalla klimat om det anpassas till lokala förhållanden, företrädesvis med färskt fekalt slam och åtföljs av kritiska driftkontroller. Detta kräver dock vidare anpassning för att säkerställa en tillförlitlig insats vid en humanitär kris, d.v.s. att reningen är stabil och att det fekala slammet renas till önskad nivå.

Introduction

The common practice in urban emergency sanitation operations is to focus on provision of sanitation facilities and containment of excreta (Grange 2016). However, safe disposal of the faecal sludge, which is crucial for prevention of disease transmission, has proved to be challenging in densely populated areas during emergency responses. This became evident during the emergency response following the Haiti earthquake in 2010, when cholera spread due to inadequate management of faecal sludge (Enserink 2011; Pressl et al. 2022). The main treatment objectives are to remove or inactivate pathogens, nutrient removal and organic matter stabilisation (Niwagaba et al. 2014).

A pilot for a faecal sludge management emergency response unit (FSM ERU) has been developed at BOKU University in Vienna together with the Austrian Red Cross (AutRC). The treatment unit was developed for deployment worldwide as part of the Red Cross Red Crescent (RCRC) surge services to improve health and environmental conditions during sanitation operations in densely populated regions affected by crises (Pressl 2024).

The objective of this study was to evaluate and optimise the performance of the pilot FSM ERU treatment plant during commissioning in Imvepi, Uganda. This included identifying challenges with the treatment processes and adapting the operation accordingly. The study focused on the processes in the unit's sequencing batch reactor (SBR). Considering that the FSM ERU shall have the possibility for deployment in diverse climates, the feasibility of implementing the treatment unit's SBR in colder climates was also theoretically evaluated. This is of interest for crisis preparedness in cold climates where the biological processes for nitrogen removal slow down (von Sperling 2007).

This article summarizes a Master's thesis initiated by Norconsult and carried out at and in collaboration with the Austrian Red Cross, with the academic supervision by SLU and Uppsala University. A more extensive description of methods, data (including raw data) and analysis is available in the thesis (Sternbeck, 2025).

Background

The International Federation of Red Cross and Red Crescent Societies (IFRC) has a concept called Emergency Response Unit (ERU) that can be rapidly deployed in areas experiencing disasters where the national Red Cross Society needs support (British Red Cross 2021). An ERU is composed of standardised

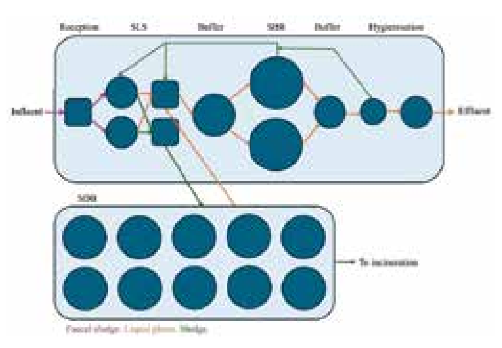

Figure 1. Treatment scheme of one line of the faecal sludge treatment plant. Two lines are needed to serve 20,000 person equivalents. Sizes of the tanks are not to scale. Purple lines represent faecal sludge, orange lines liquid phase and green lines sludge. SBR is sequencing batch reactor. SLS is solid-liquid separation. SDB is sludge drying bed.

modules and equipment, as well as trained personnel (British Red Cross 2021). The unit is non-permanent and should be able to be operated and managed manually. Ideally, the equipment and other physical material should be able to be transported even with poor infrastructure. Moreover, the unit should be space-efficient since space can be limited during crises (Pressl et al. 2022).

The faecal sludge management (FSM) ERU is an emergency response unit specifically designed to cover collection and storage, conveyance, treatment and reuse or disposal of faecal sludge (FS) from up to 20,000 person equivalents (Pressl et al. 2022). Faecal sludge is the faecal matter, and cleansing materials or water, collected from on-site sanitation technologies such as pit latrines, dry toilets or septic tanks (Strande 2014).

The treatment plant of the FSM ERU consists of several modules (Figure 1 and 2), starting with screening (into the reception tank), followed by settling (SLS tanks) to separate the supernatant from the solid material. The solid material is then directed to drying beds (SDB) while the supernatant is pumped to a buffer tank where it is stored before being pumped to the sequencing batch reactor (SBR) where the main treatment of the supernatant is undertaken. The SBR tank(s) is operated in cycles consisting of feeding, mixing, settling and decanting (Figure 3). Following each feeding, the material in the SBR is mixed with and

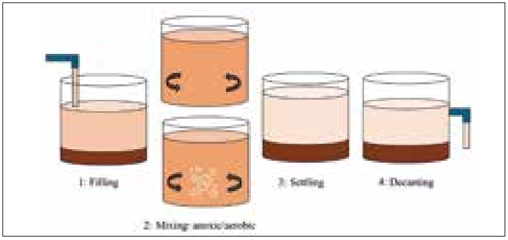

Figure 3. The schematic operation of the sequencing batch reactor (SBR) showing the four phases where the second phase of mixing alternates aerated and non-aerated mixing before settling and decanting.

Figure 2. The Feacal Sludge Management Emergency Response Unit (FSM ERU) treatment plant piloted in Imvepi, Uganda, 2025 showing from left to right the solid-liquid separation (SLS); buffer tanks holding supernatant after sedimentation; the sequencing batch reactor (SBR); buffer tank before hygienisation; and behind the SBR the sludge drying beds (SDB).

Table 1. Design characteristics for influent and effluent of the emergency faecal sludge treatment plant based on the results of the BOKU and AutRC pilot in 2022 (Pressl 2024).

	Influent (mg L^{-1})	**Effluent** (mg L^{-1})
Suspended solid (SS)	25,000	<200
Chemical oxygen demand (COD)	25,000	<250
Biological oxygen demand (BOD)	5,000	<100
Total nitrogen (TN)	1,500	<450
Ammonium nitrogen (NH_4^+-N)	1,000	<10
Nitrate nitrogen (NO_3^-N)	<10	<400
Total phosphorus (TP)	150	<50

without aeration so that nitrification, denitrification and biological removal of organic matter can occur. After the mixing phase of the cycle, settling is allowed so that the biomass and the treated supernatant can be separated. Lastly, the supernatant is decanted from the surface of the SBR. The decant volume equals the feeding volume. The exchange ratio as well as the time required for each phase depends on the characteristics of the incoming faecal sludge. The effluent of the SBR passes through a second buffer tank and then a sand filter before the final step, which chlorinates the supernatant (hygienisation tank) to reduce bacteria, virus and protozoa. The removal of total ammonia nitrogen (TAN) and organic matter in previous treatment steps are important for the effectiveness of the chlorination as well as for avoiding the formation of byproducts harmful for human and environmental health (Metcalf & Eddy, Inc 2014a). After chlorination the supernatant can be discharged into the environment or used for irrigation. The influent and effluent concentrations that the treatment plant has been designed for are presented in Table 1 (Pressl 2024).

Methods

In mid-January 2025, the construction of the pilot FSM ERU treatment plant began in Imvepi refugee settlement. The plant was deployed in Imvepi for the pilot study, not for an ongoing emergency; hence, there was no need to implement the two lines of treatment. The piloted units comprised one reception tank, two SLS, one buffer tank before and one after the SBR, one SBR, and two SDB (Figures 1 and 2). The plant was in operation from the 24th of April 2025, and the data for this study were collected until the 9th of June 2025.

The operation was based on treatment outcomes as well as on influent faecal sludge characteristics. Main approaches for operation were to adjust the feeding rate based on not exceeding 150 mg L^{-1} NH_4^+-N in the SBR to avoid ammonia nitrogen (NH_3) inhibition of the nitrifiers and aeration was targeting a dissolved oxygen (DO) concentration of 2 mg L^{-1}. These targets were determined based on Metcalf & Eddy 2014b. Due to time limitations not allowing for a thorough review of literature, a trial-and-error problem-solving approach was used. The changes in operation during the study included adjustments of aeration and pH, liming of faecal sludge and additions of polymer and alum, as well as the use of a pressure washer to enhance settling (Figure 4).

During the first weeks, the operation was focused on starting up the microbiological processes adding

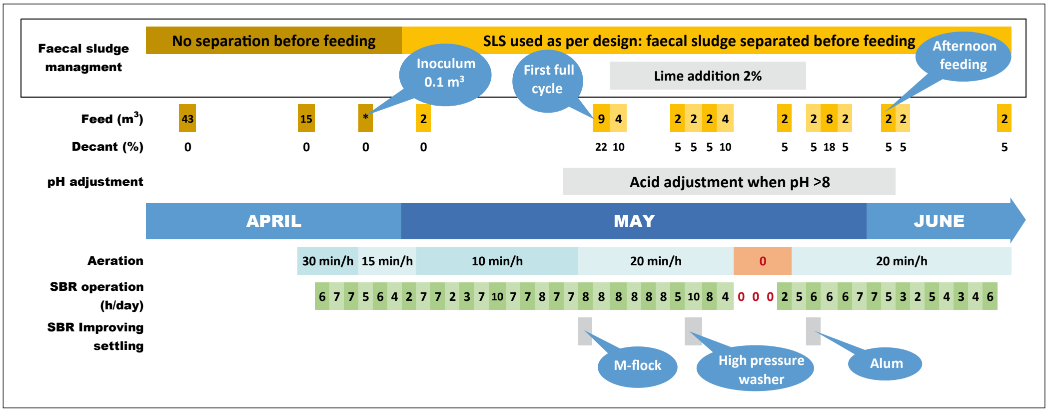

Figure 4. Timeline for the operation of the pilot plant showing approaches and changes in operation. SBR is sequencing batch reactor. SLS is solid-liquid separation.

a microbial inoculum and a smaller amount of feed without any decanting. Hence, the first cycle was 21 days (Figure 4). After that (14th of May), shorter decanting/feeding cycles were conducted. Cycles were normally 1 (on weekdays) or 3 days (over weekends), but occasionally, when not possible to decant, 2–7 days. Decanting and feeding took place in the morning, except on the 2nd of June, when the SBR was fed in the afternoon. The exchange ratio per cycle, based on keeping the ammonium nitrogen (NH_4^+-N) ≤ 150 mg L^{-1}, was never greater than 25% and during poor settling, it was 5% (Figure 4).

Daytime, including weekends, the SBR was mixed alternating between mixing with and without aeration (Figure 4 for SBR operation), and for the remaining time, the SBR content was left to settle. The ratio between the time for aerated and non-aerated mixing was adjusted, aiming for a dissolved oxygen (DO) concentration of 2 mg L^{-1} during the non-aerated mixing. The aim was to have a pH between 7.5–8.0 in the SBR for the nitrifiers to thrive (Metcalf & Eddy, Inc 2014b), so when monitoring showed that pH exceeded 8 it was adjusted with acid.

Some management strategies were tested on the pilot plant to optimise the settling in the SLS and the SBR (Figure 4). Lime equal to 2% of the volume was added to the barrels of influent faecal sludge with the aim of improving settling in the SLS. To improve settling in the SBR, a polymer, M-flock (E-20B), was added once (23.3 mg L^{-1}), and on another occasion, alum was added (30 mg L^{-1}). Both the polymer and the alum were added after the mixing phase on the day before decanting. To sink the floating sludge in the SBR after settling, water was sprayed over the surface using a pressure washer. Furthermore, an experiment was performed in a separate tank by adding table sugar (1 g L^{-1}) to faecal sludge supernatant to enhance denitrification.

Influent and samples from the treatment plant were analysed for chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), nitrite (NO_2^-), nitrate (NO_3^-), pH, temperature, dissolved oxygen (DO), sludge volume (SV) and total solids (TS). See Sternbeck (2025) for analysis methods. Influent faecal sludge collected from the same location was sampled and pooled, while the buffer tank and the SBR (during mixing and after settling) were sampled as a grab sample from the surface. Analyses were always performed directly after sampling.

To estimate total ammonia nitrogen (TAN) in the samples, the pH and temperature-dependent equilibrium between NH_4^+-N and NH_3-N was used (Nordin 2010) based on measured NH_4^+-N, pH and temperature. Stability of TAN removal was defined as a variation in reduction ≤ 20% within one hydraulic retention time (HRT). The fluctuations in reduction during the last hydraulic of the monitoring period were calculated to evaluate whether or not stability had been reached.

To determine the SBR volume required in a cold climate, volume requirements were calculated based on the following four factors: nitrification, denitrification, solid retention time (SRT) and to avoid NH_3 inhibition of the nitrifiers. Equations for these four factors were applied with assumptions of a Swedish scenario where the influent faecal sludge would be fresh and kept at a minimum of 12°C and that complete nitrification and denitrification would be crucial. The equations are presented in Sternbeck 2025. The largest volume out of these four calculated volumes was the SBR volume needed for the cold climate FSM ERU treatment plant. It was then evaluated whether SBR would meet the revised wastewater directive (EU) 2024/3019 in terms of total nitrogen (TN) and phosphorus (TP) removal. Further, was the amount of aluminium (Al) or iron (Fe) required for phosphorus precipitation calculated in order to meet the (EU) 2024/3019 directive.

Results

The influent faecal sludge was collected mainly from lined pit latrines (11 of 16 pooled samples) and a few from septic tanks (4) and 1 from an unlined pit latrine. Only total solids (TS) were significantly different (p 0.036), with lower TS of faecal sludge from septic tanks (average 1.4 g L^{-1}) compared to lined pit latrines (average 12 g L^{-1}). For other parameters there was no significant difference between sanitation systems and there was a large variation for many of the analysed parameters with coefficients of variation ranging from 88–180% with an average COD of 2,197 (131–7,250) mg L^{-1}, NH_4^+-N of 680 (96–2,370) mg L^{-1} and TS of

9.1 (0.9–24) g L^{-1}. The pH of the influent averaged 8.0 (7.4–9.7).

The influent faecal sludge did not settle in the SLS, and separation of sludge and supernatant was only accomplished (visual observation) when lime was added to the faecal sludge. However, the lime increased the pH and alkalinity, which further increased the acid demand to maintain a pH below 8.0 in the SBR. As the treatment plant was located in a remote area of Uganda, it proved challenging to procure enough quantities of acids for pH adjustment, hence the liming was discontinued on the 27th of May.

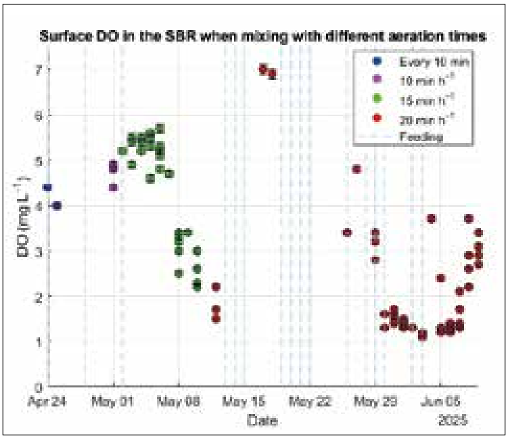

Figure 5: Dissolved oxygen (DO) in the sequencing batch reactor (SBR) while mixing with different aeration times. Note that the DO was measured during the mixing phase, but it was never noted how long after the aeration was turned off it was measured. Error bars of 1.5% due to measurement uncertainty of the DO probe. Vertical blue lines show dates when the SBR was fed.

The initial aeration approach of alternating between aeration and mixing every 10 minutes resulted in a DO twice as high as the target. Adjustment of the aeration time and interval resulted in DO below 2 mg L^{-1} first at an aeration of 10 min h^{-1} (Figure 5). The aeration was increased to 20 min h^{-1} on the 13th of May and remained at this level due to other more critical tasks to prioritise, despite sometimes being higher or lower than desired. The daily runtime of the SBR did not seem to have affected the DO concentrations.

When the TAN concentration of the SBR after feeding (mixed SBR) was compared with the TAN concentration when decanting (settled SBR) (Figure 6) it was lower at the end of most cycles compared to the beginning, with the greatest reduction during the first cycle. Stability in terms of TAN removal in the SBR was not reached within the monitoring period, as the daily TAN reduction fluctuated more than 20% over one HRT. Further was there no significant correlation between the daily TAN reduction (%) and the daily mixing/aeration time, COD, pH, NH_3, DO, NO_2^- and NO_3^- (significance level of 0.05 used).

COD was not sampled as frequently as intended due to limitations in the capacity of the field lab. The COD in the SBR was never lower than 400 mg L^{-1} and the reduction within a cycle was ≤ 74 mg L^{-1} when comparing the same type of sample (Figure 7).

Both NO_2^- and NO_3^- concentrations increased over time until the 1st and 3rd of June (Figure 8). On the 3rd of June, a sludge blanket had formed on

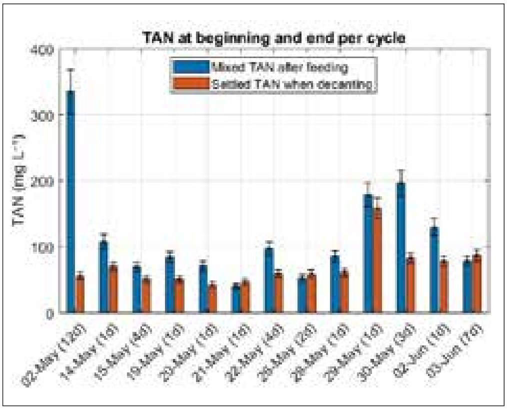

Figure 6. Comparison between mixed and settled total ammonia nitrogen (TAN) samples on days with no feeding or decanting with the cycle length given in parenthesis. Error bars showing the 10% accuracy of the NH_4^+-N probe.

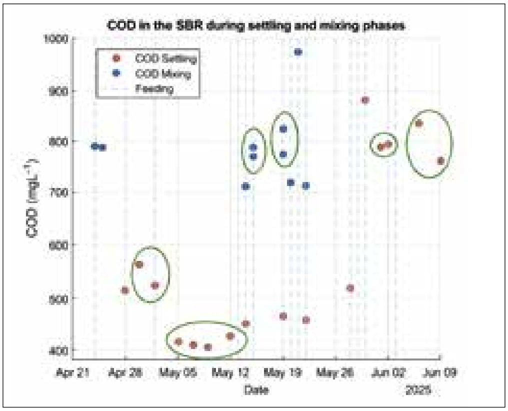

Figure 7. Chemical oxygen demand (COD) in the SBR with values in circles being within the same cycle and the same type of sample (mixed or settled). Error from measurement not shown. Broken lines show days on which the SBR was fed.

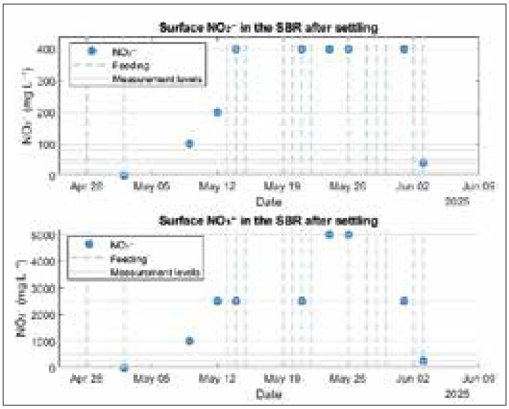

Figure 8. Concentration of NO_2^- (upper) and NO_3^- (lower) in the sequencing batch reactor (SBR) after settling with horizontal lines showing the levels for the methods resolution.

top of the SBR (Figure 9), and both NO_2^- and NO_3^- had been reduced by 10 times (Figure 8). A decrease of NO_2^- and NO_3^- down to non-detectable levels (<1 mg L^{-1} for NO_2^- and <10 mg L^{-1} for NO_3^-) was only observed in the denitrification experiment, where sugar had been added.

The settling in the SBR was poor, with tiny flocks being colloidal. Polymer addition improved settling and flock formation in the SBR but was only used once, as long-term use of the polymer could lead to its accumulation within the unit and cause pumping issues (Gårdefors, pers. ref. 2025). During the remaining monitoring period after polymer use, biomass flocculation occurred. Some of the biomass settled while some stayed afloat on the SBR (especially on the 3rd of June, as described above). Alum improved the settling to some extent, but not as much as the polymer. Floating sludge would not sink when sprayed with a pressure washer. The generally poor settling of sludge in the SBR limited the exchange ratio of the SBR cycles and hence the SBR could not treat the quantities of sludge as it had been designed for. Over the whole monitoring period, TS ranged from 2.5 to 4.1 g L^{-1} in the mixed SBR content and from 2 to 4.1 g L^{-1} in the SBR supernatant after settling.

To implement the FSM ERU in a cold climate, using Sweden as a case, assuming heating to 12°C during the cold months, a 16 times larger SBR volume will be needed. The required volume can be decreased by increasing the internal SBR temperature. Despite full nitrification and denitrification, the revised wastewater directive (EU 2024/3019) cannot be met for total nitrogen removal due to the high concentration of non-biodegradable nitrogen in faecal sludge. The requirements for total phosphorus removal can be met

Figure 9. Sludge blanket on top of the sequencing batch reactor (SBR) on the morning of the 3rd of June.

by precipitating phosphorus with either 28.8 kg Al d^{-1} or 38.7 kg Fe d^{-1}.

Discussion

The start-up of the faecal sludge treatment plant, according to initial assumptions, was problematic, and it was challenging to get the processes into desired performance. Challenges included poor settling, poor COD removal and accumulation of NO_2^- and NO_3^- (Figure 8).

Despite the influent COD concentration in the SBR being lower than expected, the effluent concentration exceeded the design value (Table 1 and Figure 7). The small reduction in COD over time for both mixed and settled samples from the SBR (see green ovals in Figure 7) indicates that the readily biodegradable COD (rbCOD) constituted only a small fraction of the total COD. Other results confirming that the COD in the influent had low biodegradability was the rapid decrease in both NO_2^- and NO_3^- (Figure 8) observed first when the SBR was fed in the afternoon instead of in the morning. The decrease in NO_2^- and NO_3^- as well as formation of a thick sludge blanket on top of the SBR (Figure 9) indicated that denitrification had occurred overnight since N_2 gas from the denitrification can attach to flocks, changing their buoyancy and hence lifting them to the surface (Svenskt Vatten 2021). A theory is that the feeding at the end of the mixing/aeration phase in the afternoon provided enough biodegradable organic matter to both create anoxic conditions when consumed by heterotrophs during the settling phase as well as providing organic matter as energy source for denitrifiers to convert NO_2^- or NO_3^- to N_2 gas. It is possible that the requirement of biodegradable matter to create anoxic conditions could be decreased by regulating the DO to better meet the targeted 2 g L^{-1} (Figure 5).

In this pilot study, faecal sludge of unknown age from onsite systems was used, while the biologically degradable COD fraction of the total COD is likely larger in fresh sludge (Lopez-Vazquez et al. 2014). Achieving conditions in favour of the denitrifiers should be more feasible with fresh faecal sludge, which would be the case in a humanitarian crisis, in particular when the FSM ERU is connected to a Mass Sanitation Module 20 unit which provides sanitation for 20,000 persons as commonly used by the The International Federation of Red Cross and Red Crescent Societies (IFRC) disaster response. In a situation where the influent rbCOD concentration is low, feeding of the SBR could be done in the afternoon, or an external carbon source could be added, like during the experiment where sugar was added. A high COD in the effluent of the SBR would, during an implementation of the full treatment plant, cause issues during chlorination, increasing the chlorine demand and potentially forming harmful by-products, threatening human health (Metcalf & Eddy, Inc 2014a). The use of a coagulant for organic matter removal could be explored (Sand & Zaki 2020) to precipitate COD concentrations in the influent to the chlorination unit.

A lot of effort was made to improve the solids separation, which, if functional, could have contributed to COD reduction. The poor settling in the SLS could be a result of the solids concentration of the influent being low, on average 9,100 mg L^{-1}, compared to what the plant had been designed for (Table 1). Lime additions promoted settling but increased the need to adjust the pH. Alternative practices to improve settling in the SLS could be to use polymer in the SLS instead of in the SBR. The SLS should be less sensitive to polymer accumulation than the SBR which has aerator pumps.

The observed poor settling in the SBR, also confirmed by similar TS in samples after mixing and after settling, was likely due to microbial flocks being colloidal, caused by shear stress from the high velocity of the aerator (Thomas, pers. ref. 2025). Occasionally, flock accumulation on the surface could be observed after a night of settling, likely due to denitrification but this could not be confirmed by a substantial decrease in NO_2^- and NO_3^- concentration apart from on the 3rd of June. To increase settling during future deployments of the SBR, polymer may be used only occasionally to keep accumulation down. Alum could also be further explored investigating higher doses as the 30 mg L^{-1} used in Imvepi was not sufficient. Using a high-pressure washer did not solve the issue of floating sludge, as was observed during the pilot.

The settling in the SBR is also of importance to achieve control of the sludge age, crucial for maintaining the microbial activity needed for the biological treatment of faecal sludge. Typically, the sludge age is controlled by regular removal of flocks from the middle of the SBR using the sludge wasting outlet requiring settling.

The varied TAN reduction could not be explained by how the plant had been operated or by the other analysed parameters. A source of error for the TAN is that it was not directly measured but calculated from NH_4^+-N measured after a dilution, but using pH value before dilution. Not knowing the effect of dilution on pH makes the actual TAN concentration uncertain, but the error should be similar for samples diluted the same way so that TAN concentration could be used for comparison between measurements. For future implementations of the plant and the field lab, the pH of the samples should be lowered to shift all TAN into the form of NH_4^+-N before measuring. Having a functioning denitrification taking place, as achieved in the late part of the study, could probably affect the performance in TAN removal, as the nitrogen conversion steps rely on each other. Due to the study ending this could not be confirmed.

Stable treatment performance was not reached for TAN removal in the SBR within the monitoring period of the treatment plant. For COD, NO_3^- and NO_2^-, stability could not be evaluated due to the limited data collected. Since stable treatment performance was never achieved, it is not possible to evaluate how effective the SBR of the FSM ERU is. Despite stability not being reached, it can be observed that the SBR did remove TAN, NO_2^-, NO_3^- and COD throughout the 1.5 months the pilot plant was monitored (Figures 6, 7 and 8), but not to the effluent concentrations the plant had been designed for (Table 1). More analyses would have been desirable to evaluate treatment performance of the SBR but this was not possible due to limited capacity in the lab.

The nitrification is temperature-dependent, with optimal efficiency between 25 and 36°C (von Sperling 2007), and below optimal temperatures the growth rate of nitrifiers halves with a temperature decrease of 7°C (von Sperling 2007). It should also be mentioned that the nitrification process is not only affected by temperature but also by sudden changes in temperature, as this may cause a temperature shock to the nitrifiers (Champagne et al. 2017). With Imvepi having a warm and rather stable climate with temperatures within the optimal nitrification range, the climate is ideal for nitrification. For an implementation of the FSM ERU SBR in a colder climate, such as Sweden, a volume increase will be necessary as the process of nitrogen removal is slower in colder climates. Therefore, the SBR volume would need to be increased by 16 times for use in Sweden if the internal temperature is kept at a minimum of 12°C. The volume required can be reduced further by increasing the internal temperature; however, this increases the expenses related to energy and heating. In the case of Sweden, where large, open areas of land are easily available, the SBR volume should not be a constraint regarding area availability. Even in the larger cities, the area should be available as the treatment plant unit would fit on a large parking lot or a football field. Further research should look at a broader perspective of implementing the SBR in other cold-climate countries. Further studies should also assess how to insulate and heat the unit and how the other treatment steps of the FSM ERU plant can be implemented and adapted for a reliable treatment of faecal sludge in cold climates. The cold climate SBR should also be piloted to evaluate the feasibility of transporting, constructing and running the unit.

Conclusion

The commissioning in Imvepi provided insight into key challenges and operational constraints of the FSM ERU treatment plant while exploring optimisation strategies. Lime proved successful in improving settling in the SLS but resulted in an increased acid demand to maintain the desired pH in the SBR. For future implementations, it is therefore important to have sufficient acid available on site to be able to regulate the pH when needed, especially if the influent faecal sludge will be limed. The possibility of using a polymer instead of lime to improve settling in the SLS could be explored. Poor settling was also an issue in the SBR, which limited the exchange ratio per cycle and also made it difficult to control the sludge age. Polymer addition improved settling, but should not be used regularly in the SBR; instead, the use of alum could be further explored. Another challenge was to achieve conditions to favour denitrification, likely due to low rbCOD of the influent faecal sludge. Feeding in the afternoon and the addition of an external carbon source were both approaches which favoured denitrification, and these strategies could be applied during a future implementation. However, in a real crisis, the faecal sludge will be fresher than during the pilot, and therefore, the concentration of rbCOD will likely be higher. The FSM ERU should be operated using fresh faecal sludge in order to evaluate and optimise the treatment plant for the sludge characteristics that would be expected in a humanitarian crisis.

Under the current conditions, 1.5 months were not sufficient to reach a stable treatment performance. With stability not being reached, the effectiveness of the SBR could not be evaluated. Nonetheless, biological activity was initiated in the SBR, and TAN, NO_2^-, NO_3^- and COD were partially removed.

The theoretical study on cold climate implementation showed that the SBR volume would have to be increased by 16 times to be applicable in a Swedish crisis scenario where the unit is insulated and heated up to a minimum of 12°C. Further studies are needed to cover how the remaining treatment steps of the FSM ERU could be implemented in a cold setting.

While the pilot study revealed the complexities of the FSM ERU treatment plant, it also demonstrated its potential for faecal sludge treatment in remote areas during challenging conditions. The lessons learned regarding commissioning should be considered for future implementations of the plant. With some adjustments, the SBR of the treatment plant could be adapted for colder climates, expanding the applicability of the treatment plant.

Acknowledgement

Warmest gratitude goes to the Austrian Red Cross for funding this study and hosting Maja in Uganda for nearly 5 months, with a special thanks to Debora Falk, the head of the Uganda FSM team, always being supportive and offering a sense of home in Yumbe and Imvepi. Gratitudes also to staff at the National Red Cross Societies of Austria, Uganda, Germany, the United Kingdom and Sweden for supporting the study and generously sharing expertise. Thanks also to Sören Säf (Norconsult), supervising Maja's thesis work, for continuous support during the project.

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