Consolidated Report on Technical, Social, and Economic Evaluation of the Product for Foundation's approval for Go/No-Go Decision for Phase 2

Duke Output #4, WASHi Output #5

Prepared jointly by WASHi and Marc Deshusses and Aaron Forbis-Stokes, Duke University

March 30, 2018 – Updated June 8, 2018

1. Introduction & Background

The Mobile Treatment Unit (MTU) is an onsite fecal sludge treatment technology developed by the Water, Sanitation and Hygiene Institute (WASHi) in 2016. The MTU is a membrane-based treatment system installed on the bed of a truck and is used to treat the contents of septic tanks. The MTU is an alternative to traditional septic trucks which empty tanks and transport contents to a centralized sewage treatment plant. Due to various barriers, mostly financial and logistical, septic tank contents are often not emptied before they overflow into waterways, not emptied in a hygienic manner, or not transported to treatment facilities and instead dumped offsite. The MTU attempts to address each of these barriers so that septic tanks are emptied when needed and contents are properly treated before being discharged into the environment.

The 2011 India census found that 38.2% of urban households with toilets are connected to septic tanks. This percentage goes up to greater than 62% for cities with less than one million residents. Under the Swachh Bharat Mission, 21% of already constructed toilets in rural households are connected to septic tanks, and 24% of those under construction will be connected to septic tanks (Water Aid, 2017). Based upon these findings, India has a great need for septic tank services. The traditional practice is that septic truck operators are hired to empty these tanks once full, with the purpose of transporting contents to tipping stations or sewage treatment plants. However, it is often found that septic contents do not arrive at these treatment stations. The distance to travel, fuel cost, time demand and expenses all motivate emptiers to dump their contents in alternative, nearby locations. Often these do not provide sanitary treatment of the septic truck contents.

The primary goals for the MTU are to (1) empty septic waste and treat its contents onsite to meet India's treatment standards for discharge, (2) treat the waste at a fast rate (between 2,000 and 3,000 L h^{-1}) so that multiple tanks can be treated each day, and (3) meet the first two goals using materials and methods that require a minimal level of capital and operational expenditure so that the MTU can be operated in a for-profit model, which would enable the technology to have the greatest opportunity for uptake at a large scale and greatest potential for positive impact on sanitation in India.

2. Materials & Methods

The MTU was evaluated in two study periods hereafter referred to as Phase I and Phase II. Phase I provided baseline knowledge of MTU's capabilities and evaluated one MTU from October 2017 to February 2018. Findings from Phase I provided improved design considerations which informed system modifications made in Phase II. During Phase II, three MTUs were evaluated in different locations.

2.1. System materials

The MTU system was built on the bed of 2-ton truck (Mahindra "Bolero Maxi-Truck," Mumbai, India). Total weight of the truck after additional equipment was 3.08 tons. Figure 1 displays a process flow diagram for the MTU. During operation, the truck is driven as close as accessible to the septic tank being emptied. A ½ HP mono-block centrifugal pump (Texon Engineering, Coimbatore, India) draws waste from the septic tank using a hose pipe inserted through one of the tank's risers. This liquid is sent into a 500 L holding tank. The middle of the holding tank contains a 25 cm I.D. PVC pipe, 90 cm in height, with 10 mm diameter holes drilled into the top 75 cm of the pipe (exact number of holes is unknown, but the many holes are distributed through this section with 10 mm spacing between each) to allow septic tank supernatant to fill the pipe. The outside wall is wrapped with a #250 mesh to pre-filter the septic waste before pumping. The purpose of this mesh is to remove the larger particles and thereby extend the life of the succeeding filters by using a low-cost and easy to clean material. From the center of this pipe, liquid is pumped using a 1 HP mono-block, double capacitor centrifugal pump (CRI Pumps, Coimbatore, India). The first filter is a dual-media (D-M) filter housed in a 190 L (166 cm height, 41.2 cm diameter) fiber-reinforced plastic (FRP) container. Flow enters the FRP container at the bottom and exits from the top. The bottom 60 cm is filled with large pebbles (30-60 mm dia.), the next 45 cm is filled with small pebbles (4-30 mm dia.), and the top 15 cm was filled with coarse sand (0.5-1.0 mm dia.). The remaining volume is left empty. D-M filtrate then enters a granulated activated carbon (GAC) (Krishna Industrial, Chennai, India) filter housed in a FRP container with the same dimensions as the D-M filter, containing approximately 85 kg of GAC of #4x8 mesh size with 1,200-1,800 $m^2\ g^{-1}$ surface area. GAC filtrate enters two microfilter (MF) polypropylene wound filter cartridges (Filtcare Technology, Ahmedabad, India) in series, both of 50 cm length and 11.4 cm diameter. The membranes have a nominal pore size of 10 and 5 µm, respectively. MF effluent is treated with an ultrafiltration (UF) membrane (Vens Marketing, VM-200/1650 "The Way", Chennai, India). The hollow fiber membranes have an outer diameter of 0.1 mm and nominal pore size of 0.02 µm and are operated as dead-end filtration with an outside-in flow direction. The bottom of the holding tank is connected to a centrifuge which serves to concentrate settled solids and return liquid back to the holding tank. Centrate (i.e., clarified liquid leaving the centrifuge) was returned to holding tank using a submersible pump.

At the start of the study period, the MTU had already treated approximately 80,000 L of waste. This period of operation was done to observe capabilities of the system and alter the design. The waste had an average concentration of 220 mg TSS L^{-1}. All materials were replaced at the start of the study except for the UF membrane.

For Phase II of the study, the process flow remained the same but filter materials underwent slight modifications. The holding tank was modified to have a conical-bottom to improve solids settling, and a baffle was installed around the feed pipe to better restrict the flow of solid particles towards the feed pipe. The D-M filter media changed to the following distribution (bottom to top): 30 cm large pebbles (30-60 mm dia.), 30 cm small pebbles (4-30 mm dia.), 30 cm coarse sand (0.5-1.0 mm dia.), 15 cm fine sand (0.125-0.250 mm dia), and 15 cm anthracite (1-2 mm dia.). The same type of GAC as in Phase I was used. The same FRP containers were used for the D-M and GAC filters as in Phase I. Larger microfilters were used and the number of them was increased to increase total surface area of the filters. The first MF was 5 wound cartridges operating in parallel with nominal pore size of 10 µm of 76 cm length and 6.4 cm diameter. The second MF was also 5 cartridges operating in parallel of 76 cm length and 6.4 cm diameter but with nominal pore size of 1 µm (Placon Filters, Chennai, India). The UF was replaced with a ZeeWeed 1500 UF (55.7 m^2 surface area, 192 cm length, 18 cm diameter, (Suez Water Technologies, Trevose, PA, USA).

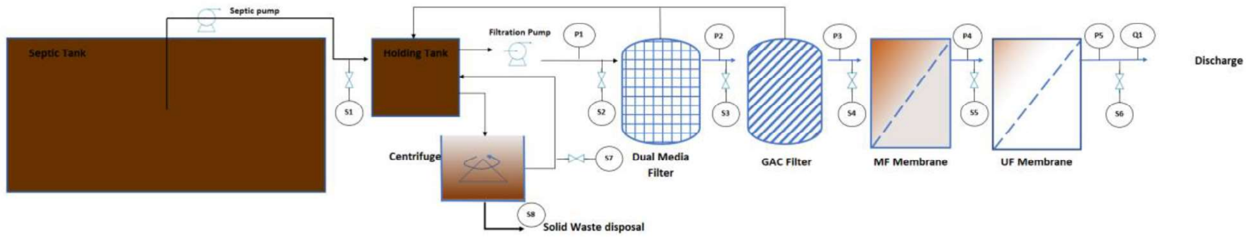

Figure 1. MTU process flow diagram.

2.2. Study location

In Phase I, the MTU was operated in the Dindigul district, located in the state of Tamil Nadu. The district covers 6,000 km^2 and has a population of 2.15 million according to the 2011 census. Of this population, 20.8% of the households are connected to septic systems. For Phase II, the study location included the Dindigul district and it was expanded into Madurai and Trichy districts. Madurai covers 3,700 km^2 with a population of 3.04 million. Trichy covers 4,500 km^2 with 2.72 million people. The additional locations were chosen due to their proximity to Dindigul.

2.3. Methods

Phase I analysis took place from October 2017 to February 2018. During this time, operational performance was analyzed by taking pressure, flow, and power readings every 15 minutes for the first hour and every 30 minutes for the remaining time of operation. Pressure readings were taken using 0-4 bar (±0.05 bar, Micro Process Controls EN 837-1, Gujarat, India) analog gauges which were located before and after each filter. The transmembrane pressure was calculated as the difference in pressure between the two gauges and was used as an indicator of filter fouling. Discrete flow was measured using a 500-5,000 L h^{-1} rotameter (ASTER Technologies F-5,000L, New Delhi, India) while total volume treated was measured using a water totalizer, 0-1.0 x 10^7 L (±0.1 L, TKT Water Meters B1214436, Coimbatore, India). Power consumption was calculated by measuring a current meter and associated to the 220 VAC power supply.

Treatment performance analysis was completed by taking samples at each step in the process after the first 30 minutes of operation and at the end of operation. These samples were analyzed in the WASHi laboratory for pH (digital meter), COD (IS 3025-58), BOD_5 (Trivedy and Goel, 1986), TSS (IS 3025-17), turbidity (IS 3025-10), NH_3 (Trivedy and Goel, 1986), NO_3 (Standard Methods 4500-NO_3-B), NO_2 (Trivedy and Goel, 1986), and PO_4 (Trivedy and Goel, 1986). Total coliform (Standard Methods 9222B) concentration was also determined but only for raw septic waste and final effluent.

The method of MTU operation was continued in the same manner for Phase II, although the number of parameters and samples for treatment performance analysis was reduced in Phase II. The performance of each consecutive unit was assumed to be similar as in Phase I. In Phase II only the septic tank and final effluent were analyzed for all parameters. The intermediate sampling points were only analyzed for turbidity and COD. These two parameters were then assumed to be representative of TSS and BOD removal based on relationships found in Phase I. NO_3^- and NO_2^- were no longer analyzed as these concentrations were negligible. Further, only one sampling event was performed per septic tank treated as the variation between the duplicate samples in Phase I was minimal and not associated with operation time.

During Phase I, the MTU would typically treat one septic tank of 1,000-3,000 L per day. The system was operated manually, turning the septic and filtration pumps on and off as needed. The centrifuge was typically only used at the end of the treatment period for each septic tank. Power for the system was supplied from the home being serviced. Most homes could not provide sufficient power to run both pumps and centrifuge at the same time. This is why the centrifuge was only used at the end when the septic pump was turned off. All filters were operated in dead-end mode except for the UF. The UF reject valve was partially opened to allow approximately 50% of flow to return to the initial holding tank. The system was not backwashed while in operation, but was backwashed with water at the end of the operation after treating each septic tank. The system was chemically washed with NaOCl (200 ppm) and NaOH (500 ppm), and then HCl (500 ppm) once a month.

During Phase II, treating two septic tanks per day was targeted. Operation was manual (as before during Phase I). The UF was operated without reject, but a reverse flow backwashing protocol was initiated. After every 30 minutes of operation, pumping was stopped and collected UF effluent was pumped in the reverse direction for 30 seconds. This flow went through all filters and was returned to the initial holding tank. The centrifuge was also used during this period in an attempt to achieve more solids removal with the centrifuge and allow for higher flow rates during normal operation. Backwashing filters with water and rejecting the return continued to be done at the end of each day, and chemical washing was conducted (as before) monthly with NaOCl (200 ppm) and NaOH (500 ppm).

3. Results

3.1. Wastewater characteristics

3.1.1. Phase I

Table 1 displays results for wastewater characteristics from each step in the MTU. The right side of the table references the latest effluent discharge standards for India's sewage treatment plants (Ministry of Environment Forest and Climate Change, 2017). The most recent regulations include a different set of standards for metro (Mumbai, Delhi, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad and Pune) and non-metro areas, the latter of which is shown in the table as that one better describes the target locations for the MTU. Table 2 displays the percentage removal performance of each filter stage in the MTU. The left side of the tables shows the percent removal of each parameter for that filter's effluent with respect to the raw septic waste, while the right side displays the percent removal for that filter's with respect to that filter's influent. The pH had negligible change through the process, which was expected as the processes are purely physical. The BOD (90% removal), COD (90%), TSS (76%), and TC (98.8%) all had high removal percentages from the influent to the final effluent. The average values of BOD and TSS began to increase after January 10, 2018 (i.e., after 102 h operation) (Figure 2). At this point, the UF had treated 63,500 L of waste in Phase I and 80,000 L of waste previously, and probably surpassed its capacity. The average BOD and TSS concentrations from October 2017 to January 10, 2018, were 19 mg_{BOD} L^{-1} and 37 mg L^{-1}, which results in 92% and 86% removal from the influent, respectively. TN (30% removal) and TP (57%) removal percentages were not as high.

The individual step removal listed in Table 2 show that the fabric filter was one of the most effective filters. It had the highest step removal of COD, BOD, and TP, and it was second only to the UF in TSS removal. The GAC was the least effective filter in the majority of parameters, but it did have a more significant removal of BOD.

Table 1. Summary of average concentrations from each step of the MTU process (N = 83).

	Septic		Fabric filter		Dual-Media		GAC		MF		UF		Discharge
Parameter	**Avg.**	**St.Dev.**	**Avg.**	**St.Dev.**	**Avg.**	**St.Dev.**	**Avg.**	**St.Dev.**	**Avg.**	**St.Dev.**	**Avg.**	**St.Dev.**	**India Std.**
pH	7.6	*0.5*	7.7	*0.4*	7.7	*0.5*	7.7	*0.5*	7.7	*0.4*	**7.6**	*0.4*	**6.5-9**
BOD (mg/L)	226	*102*	91	*54*	60	*31*	44	*26*	33	*22*	**22**	*18*	**30**
COD (mg/L)	469	*183*	112	*110*	83	*70*	76	*65*	65	*57*	**47**	*35*	**N/A**
TSS (mg/L)	258	*198*	175	*150*	168	*151*	159	*150*	147	*144*	**61**	*88*	**100**
Turbidity (NTU)	72.2	*41.9*	50.0	*30.7*	47.9	*29.4*	43.7	*28.6*	39.8	*27.4*	**14.8**	*18.1*	**N/A**
TN (mg/L)	32.3	*15.9*	15.0	*8.6*	13.8	*8.5*	13.3	*8.2*	12.5	*7.7*	**22.7**	*12.4*	**N/A**
TP (mg/L)	4.7	*2.2*	3.5	*1.6*	3.1	*1.6*	2.7	*1.4*	2.5	*1.4*	**2.0**	*1.5*	**N/A**
TC (CFU/100 mL)	5,736	*6,366*									**66**	*31*	**1,000**

Table 2. Percent removal for each filter for its effluent in reference to the raw septic (left) and the inlet to that filter (right).

		Cumulative removal with respect to septage (%)					Removal in each individual filter with respect to its influent (%)				
Parameter	Septic	Fabric	D-M	GAC	MF	UF	Fabric	D-M	GAC	MF	UF
pH	7.6	-1%	-1%	-1%	-1%	0%	-1%	0%	0%	0%	1%
BOD (mg/L)	226	60%	73%	80%	85%	90%	60%	33%	27%	26%	34%
COD (mg/L)	469	76%	82%	84%	86%	90%	76%	26%	9%	14%	28%
TSS (mg/L)	258	32%	35%	38%	43%	76%	32%	4%	6%	7%	58%
TN (mg/L)	32.3	54%	57%	59%	61%	30%	54%	8%	4%	6%	-82%
TP (mg/L)	4.7	26%	35%	42%	46%	57%	26%	12%	10%	8%	20%

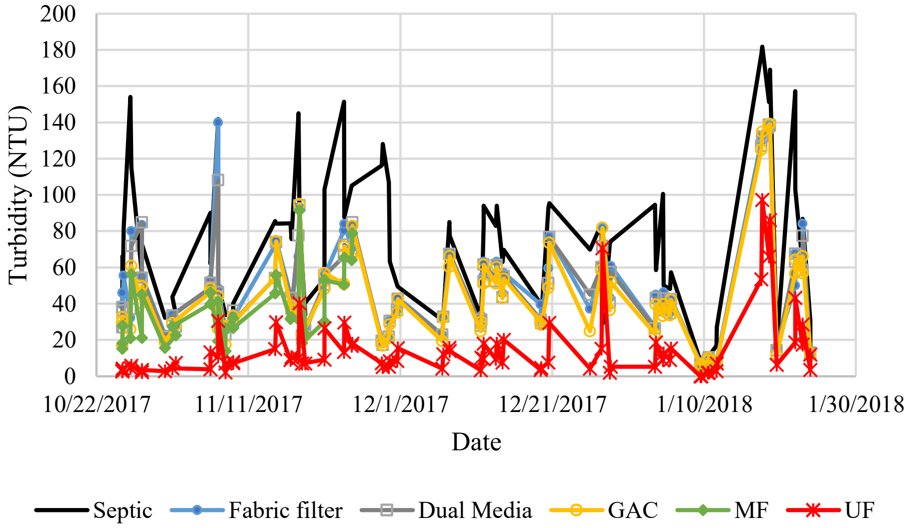

Figure 2. Turbidity at each step of MTU process during Phase I study.

Nitrogen speciation testing from Phase I experienced some challenges. Though results were fairly consistent, the concentrations determined did not match measurements from an outside laboratory (T.Stanes & Company, Coimbatore, India). For the sample, the outside lab found a Total Kjeldahl Nitrogen (TKN) and NH_4^+ raw septic waste concentrations of 234 mg TKN L^{-1} and 191 mg NH_4^+-N L^{-1} compared to 6.2 mg TKN L^{-1} and 5.3 mg NH_4^+-N L^{-1} in the WASHi lab. Both labs reported negligible concentrations of NO_3-N and NO_2-N, meaning that TKN is well representative of TN. At this time, the reason for the difference is best believed to be due to an issue in the development of the calibration curve used to calculate TN and NH_4^+-N concentrations at the WASHi lab, but this hypothesis is yet to be confirmed. The outside lab reported a final effluent concentrations of 145 mg TKN L^{-1} and 118 mg NH_4^+-N L^{-1}, 38% removal for each. This sample was taken on January 17, 2018, when the MTU had treated 70,200 L of waste.

3.2. Operational characteristics

3.2.1. Phase I

The MTU in Phase I was operated for a total of 170 hours. Transmembrane pressure (TMP) values for each filter are shown in Figure 3. The D-M and GAC TMP values remained low for the majority of the study, as expected. The rise of TMP for the MFs was quite rapid, as seen from 0-26 h, 26-58 h, 58-79 h, and 97-125 h (around Feb 5). During some of this increased pressure periods for the MF, the TMP was greater than the TMP for the UF. The TMP of a MF membrane is expected to be about one tenth of a UF membrane indicating that the MF had severe fouling issues during these periods.

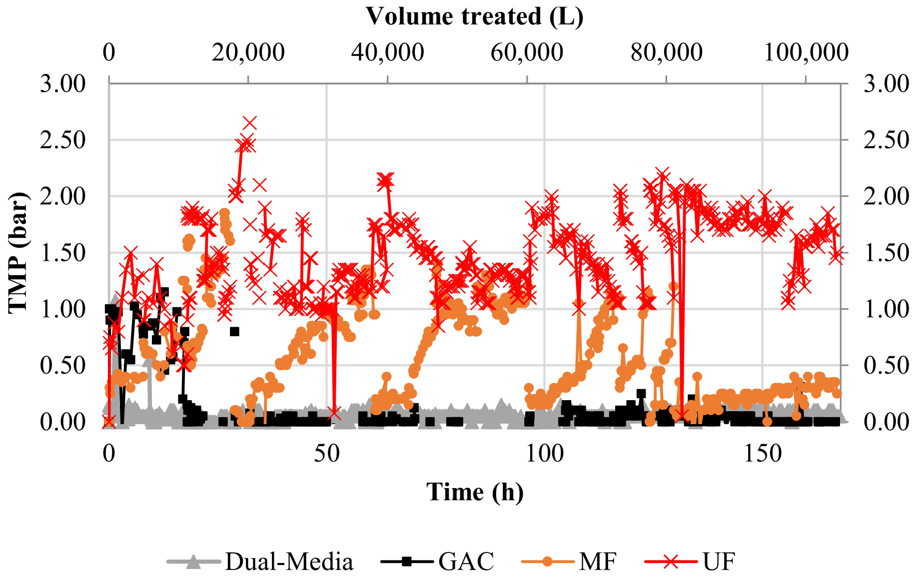

Figure 3. Transmembrane pressure (TMP) of each filter vs. the total MTU operating time.

MFs were replaced on November 14, 2017, (after 25.6 h operation; 18,000 L treated), December 6 (58.3 h; 38,300 L), January 9, 2018, (96.9 h: 60,300 L), January 22 (118.0 h; 73,300 L), February 5 (127.0 h; 77,600 L), and February 7 (131.0 h; 79,600 L). The MFs treated 18,000; 20,300; 22,000; 13,000; 4,300; and 2,000 L of waste, respectively. The last 3 replacements were not due to necessity but for trial. The MF capacity based on this study was on average 20,000 L with 258 mg TSS L^{-1}, or a total of 5.16 kg TSS.

A bag filter added on December 27, 2017, (79.4 h; 50,700 L) to help increase the life of the MFs. Starting from February 5 (122.4 h) the MFs were chemically washed after each day of use. The filter bag did not appear to greatly improve performance as the TMP did not decrease from 79.4 to 96.9 h, and the rate of TMP increase with the new MF after 96.9 h did not decrease. The daily chemical washing that began after 122.4 h, however, did significantly impact MF performance. The TMP rate of increase was only 0.4 bar over 40 hours, compared to 1.0 bar within 20 hours without the washing.

Flow measured at the outlet during the operation time of Phase I is shown in Figure 4. The average flow was 716 L h^{-1} (with a standard deviation of 234 L h^{-1}). Because the filters were backwashed at the end of the day after each day of operation, the flow values can be seen to decrease quickly for a few hours before shooting back up. The general trend of flow decreased rapidly from approximately 1,700 to 600 L h^{-1} after 20 hours of operation. The MF TMP increased rapidly over this same time period (Figure 3), and the flow increased back up to 1,500 L h^{-1} when the filter was replaced. Again, the flow quickly decreased until the MF was replaced another time after 58.3 h of operation, after which the flow increased to 1,300 L h^{-1}. The combined results from TMP and flow suggest that the MF was the primary factor restricting the operational flow in the MTU system for the first 60 hours of operation. The MF was replaced three more times after the 60 hour mark, but the flow did not increase a significant amount after these replacements. At the same time the general trend of the UF TMP was increasing. It may be interpreted, then, that the UF membrane was the primary component restricting after 60 hours of operation.

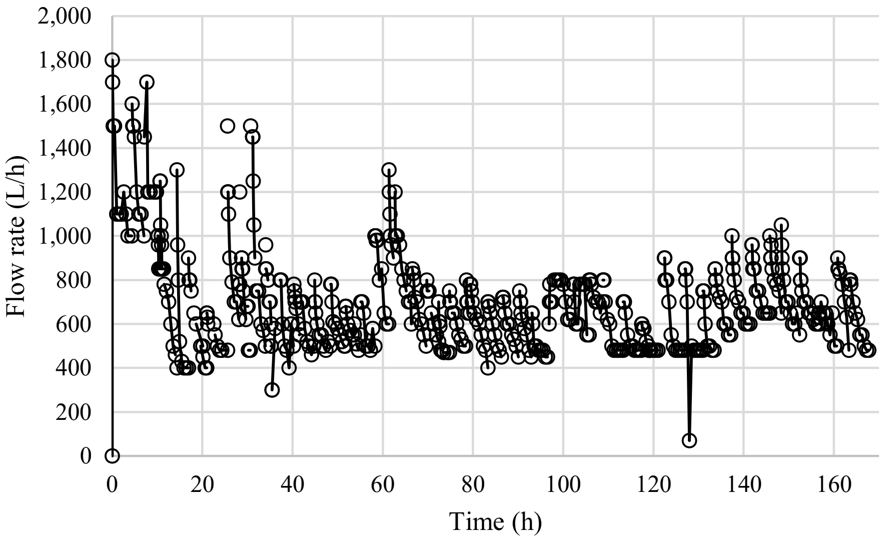

Figure 4. MTU flowrate over the total operational time of Phase I.

Operational experience showed that the flow of incoming septic waste was often higher than the filtration flow due to fouling of membrane surfaces. Fouling of the fabric filter around the filtration feed tube would cause the inner portion of the tube to empty more quickly than the incoming septic waste could enter. Therefore, the septic pump was turned off and on frequently during the treatment period. The fouling rate of the fabric filter was magnified when treating septic tanks with higher solids content which led to the feed tube lifting out of holding tank. Under this condition, the filter pump was turned off temporarily in order for the septic waste to reenter the feed tube. Based upon this experience, the holding tank was redesigned for Phase II to improve solids separation in the septic waste before reaching the fabric filter. The standard water tank was replaced with a conical-shaped tank (locally fabricated as industrial versions difficult to access) to improve solids settling, and a baffle wall was wrapped around the feed pipe to increase the flow path of incoming waste to the fabric filter.

The average current draw for MTU operation was 9.0 A at 220 VAC (single-phase). Assuming power factor of 1, the operating power is 1.98 kW. The average operation time was 3.49 h (with a stdev. of 0.93), resulting in 6.9 kWh power demand per septic tank treated. It was discovered that grid power outages are frequent in the test region, especially during daytime in summer months. The MTU operates on power supplied by the home being serviced, so these power outages stopped MTU operation, causing delays of up to 30 minutes per outage. Additionally, periodic power shut-downs scheduled by local governments for daytime hours will prevent the MTU from operating during those days.

3.3. Cost considerations

In Phase I of the study, the costs of the components were as follows: ₹600 for fabric filter mesh, replaced monthly over 4 months at ₹150 each; ₹3,500 for D-M filter (media) and ₹9,400 container; ₹14,000 for GAC filter and ₹9,400 container, ₹650 for MF filter cartridges and housing, and ₹97,350 for UF filters and housing.

In Phase II of the study, the costs of the components were as follows: ₹150 for fabric filter mesh; ₹15,800 for D-M filter and container; ₹29,400 for GAC filter and container; ₹45,900 for MF filters and housing with each replacement cartridge at ₹190; and ₹141,600 for UF filters and housing.

4. Discussion

4.1. Treatment effectiveness and discharge levels

Based on these results, the MTU met India Discharge standards for all parameters. Under the newest regulations for discharge standards, Metro areas have more strict standards for BOD and TSS (20 vs. 30 mg_{BOD} L^{-1} and 50 vs. 100 mg_{TSS} L^{-1}). As discussed in Section 3.1 of the results, if analysis was stopped at January 10, 2018, the average concentrations of BOD and TSS in the effluent would have been 19 mg_{BOD} $L^{-1}$and 37 mg_{TSS} L^{-1}. The MTU effluent would then have met effluent standards even under the strictest conditions of the current standards. The current standards do not consider COD, turbidity, TN, or TP. However, past standards under consideration included limits of 100 mg_{COD} L^{-1} and 10 mg_{TN} L^{-1}. These targets were removed due to the difficulty to achieve them. Even so, maintaining a high level of treatment is desired in case any future regulations include more strict limits. The MTU effluent was well below 100 mg_{COD} L^{-1}. The total nitrogen concentration did decrease from inlet to outlet, but not sufficiently enough to meet the older strict standards. The TN removal is assumed to be mostly the organic fraction of N removed by filtration of organic particles. The MTU has no provision for other forms of N removal, typically achieved through biological processes. Though consistent and reliable ammonia analysis has been a challenge, it appears that the majority of total nitrogen is in the form of NH_4^+ which is expected for aged septic waste. NH_4^+ removal through adsorption in GAC is potential method of TN reduction in the existing MTU, but there is lacking evidence that adsorption is occurring (no significant difference of TN concentration between inlet and outlet of GAC filter). GAC has a potential ammonia adsorption capacity of about 17 mg g^{-1} (Long et al., 2008). Based on this capacity, the MTU with 85 kg of GAC could have removed 1.46 kg of NH_3. If 90% of the average concentration of 32.3 mg TN L^{-1} (i.e. the concentration measured by WASHi's lab) in the raw septic was total ammoniacal nitrogen (TAN) (29 mg TAN L^{-1}), the MTU could have removed TAN from 50,000 L. However, if the outside laboratory's results for NH_4^+-N were those trusted for the inlet TAN (191 mg NH_4^+-N L^{-1}), the MTU could have removed TAN from only 7,600 L of septic waste. This volume could result in a requirement of replacing the GAC every two days if two tanks are treated per day, which is clearly not a realistic option for MTU operation. Depending on the true amount of NH_4^+ in the septic waste, and what, if any, nutrient limit is imposed upon the MTU effluent, additional nitrogen management solutions may be necessary.

It is also worth considering the soluble COD removal capacity of the GAC. The fabric filter and dual-media filter provided the bulk of COD removal (82% of total influent COD removed at this point). The majority of COD remaining could be considered mostly soluble (based on the definition of what passes a 0.45 µm filter which is smaller than the fabric and finest portion of D-M). If the GAC has a COD adsorption capacity of 400 mg_{COD} g_{GAC}^{-1} and 83 mg_{COD} L^{-1} average D-M effluent, the 85 kg of GAC could then remove COD from 409,000 L of waste. However, based upon results from this study, an average of only 7.9 mg_{COD} L^{-1} was removed from the total flow of 104,500 L, a removal capacity of only 9.7 mg_{COD} g_{GAC}^{-1}. The BOD removal, though, was higher. An average of 16.1 mg_{BOD} L^{-1} was removed in the GAC filter, a removal capacity of 19.8 mg_{BOD} g_{GAC}^{-1}. Both of these removal capacities are much lower than expected.

Both the GAC and MF did not exhibit a high removal. At this point in the treatment process, the filtrate has passed through a #250 mesh (58 µm) and a dual-media filter. Remaining particles are therefore small and various species are dissolved. One reason for low removal for these in the GAC filter could potentially be due to lower quality GAC than assumed. Another reason could be that particles were still large enough to foul the outer surfaces of the GAC, limiting the availability of the internal porous structure. With the still fairly polluted GAC effluent entering the MF and relatively small membrane surface area, the MF fouled quickly and caused the most operational and maintenance burden. Based on rapid MF fouling, increasing the membrane surface area of the MF was recommended for Phase II of the study. Another approach that could be considered is switching the MF and GAC in the treatment process. If the GAC provides little pre-treatment for the MF, then moving the MF downstream should have minimal detrimental impact on MF performance. In return, the GAC would be assured to only received dissolved materials which may improve its treatment capacity. Still, even if their efficacies were less than expected, the GAC and MF likely expanded the lifetime of the UF (treating 143,500 L before exceeding discharge standards).

The centrifuge did not provide a noticeable difference from the raw septic waste in terms of wastewater characteristics. However, experience found that the centrifuge did remove suspended material, and that using the centrifuge while working with thick sludge decreased the clogging of the fabric filter. Additionally, solids were retained in the centrifuge bag. Two sampling events were used in an attempt to achieve representative sampling and to capture the heterogeneity of the septic waste, but it is possible that some of the thicker sludge was not fully represented in the sampling. The final result for average raw septic waste characteristics was still assumed to be accurate as the thick sludge section only made up less than 5% of the septic tank volume, but this was the section were the centrifuge was most needed.

The solids retained in the centrifuge were removed approximately once a month. WASHi used the solids at their own facilities to make fuel briquettes. The solids can also be used for composting. Fabric centrifuge bags were used in this study, but biodegradable centrifuge bags (if such bags were available) could eliminate the need for any handling hazardous material by composting the entire bag.

4.2. Lifespan, cost, and efficiency

The cost effectiveness of removing COD was evaluated. In doing so, one must remember that large particulate COD will be easier to remove than colloidal or dissolved COD. Still, the comparison is warranted. The fabric filter was the most effective filter in the system and at the lowest cost. It had the highest step removal of COD, BOD, and TP, and it was second only to the UF in TSS removal while being only ₹600. The fabric filter removed 356 mg_{COD} L^{-1} from 104,500 L, or 37.2 kg_{COD} for ₹600. COD removal, then, for the fabric filter was 62 g_{COD} ₹$^{-1}$. The D-M filter was more effective than the GAC and MF filters at removing COD, BOD, and TP. By removing 29 mg_{COD} L^{-1}, the treatment cost was 0.23 g_{COD} ₹$^{-1}$. The GAC and MF filters were not as effective and still high cost at ₹22,300 for GAC and ₹650 for MF. Removing 7.9 and 10.5 mg_{COD} L^{-1}, respectively, the treatment costs were 37 mg_{COD} ₹$^{-1}$ and 1,688 mg_{COD} ₹$^{-1}$. The UF was the most expensive component, but the second-most effective filter. It removed 18.2 mg_{COD} L^{-1} at ₹97,350, or 19.5 mg_{COD} ₹$^{-1}$, which is the highest cost for amount of COD removal. Though the UF was the greatest cost, it was necessary in order to achieve discharge standards, removing the most difficult contaminants from the treatment stream.

The lifespan of most filters was beyond the length of the study period. Only the fabric filter and MF membranes were replaced during Phase I. The fabric filter was replaced monthly as it was found that it began to tear due to fouling, but low cost of the fabric makes this replacement a minor issue. The MF membranes were replaced approximately every 20,000 L. As the MTU is intended to treat high volumes of wastewater per day during Phase II and actual commercial deployment (possibly up to 4,000-6,000 L d^{-1}), the lifespan of the MF is much shorter than desired. Based upon this finding, it was determined that MF surface area needed to be increased for Phase II. MF cartridges were both of 50 cm length and 11.4 cm diameter. The manufacturer was not able to provide the total membrane surface area for filters used during both Phase I and II, but the outer surface area for each MF apparatus in Phase I was 1,790 cm^2. For Phase II, each MF apparatus was replaced with 5 wound cartridges operating in parallel of 76 cm length and 6.4 cm diameter. Each cartridge had an outer surface area of 1,530 cm^2, thus the total surface area of the 5 cartridges in parallel was 7,640 cm^2. The second MF was also 5 cartridges of 76 cm length and 6.4 cm diameter operating in parallel. Because the MF required the greatest amount of maintenance and appeared to cause the greatest restriction of flow, the expanded MF surface area was expected to reduce maintenance requirements and allow for a greater flow rate.

Working with thick septic sludge was rare during the five months of Phase I operation. The low solids and organic concentrations found are typical for Indian septic tanks due to high water usage. However, very thick sludge in two tanks was encountered while piloting the Phase II system, which could not be successfully handled. One was a well-drained leach pit, and the other was a septic tank that allowed liquid to overflow and had not been emptied in maybe 15 years. One tank had a TSS concentration of 26,200 mg_{TSS} L^{-1}. Normally, these tanks would be outside of the scope of application of the MTU system, but the home owners were not aware of their tank characteristics. Not being able to handle the high concentration of solids was not a concern because this concentrated sludge is not typical, and a great need for emptying and treatment exists for many septic tanks with much lower solids concentrations. However, some design considerations are being made so that any tanks or pits, even those with very think sludge, may be serviced by the MTU.

No formal social acceptability studies have been performed at this time. The primary concerns for social acceptance are odors associated with the treatment process and the aesthetics of the discharge liquid. Based on observation, odors were only noticeable within 1-3 meters downwind of the truck. This odor can be classified as a noticeable fecal odor that is bearable to unpleasant, but rarely intense enough to encourage a bystander to move away. The odor source was the holding tank that the raw septic waste is pumped into. Air gaps in this tank allowed odors to escape. A preliminary test in which the air openings were covered with a compost-biochar mixture removed noticeable odors from the system. Regarding effluent aesthetics, the flowing discharge liquid appeared clear with no detectable odor. Slight foaming did appear, however, which is likely from detergents coming from the household into the septic tank. Collected effluent typically had a slight-yellow tint. Odor was only noticeable when sniffing within 10-20 cm of collected effluent. This odor had an earthy, musty scent that was not unpleasant.

5. Conclusion

The primary goals for the MTU are to (1) empty septic waste and treat it onsite to meet India's treatment standards for discharge, (2) treat the waste at a fast rate so that multiple tanks can be treated each day, and (3) meet the first two goals using materials and methods that require a minimal level of capital and operational expenditure so that the MTU can be operated in a for-profit model, which would enable the technology to have the greatest opportunity for uptake at a large scale and greatest potential for positive impact on sanitation in India.

Based upon the findings from Phase I of the study, the MTU met the first goal for India sewage treatment plant discharge standards. If more strict standards were applied, the greatest barrier would be nutrient removal, particularly nitrogen. The second goal is the focus of Phase II. The primary barriers to maintaining a high flow rate were fouling of the fabric filter and MF. For Phase II, better solids separation has been implemented into the waste holding tank which should reduce the fabric filter fouling rate. Secondly, the MF has been replaced by multiple MFs of much greater surface area which should lower the fouling frequency. Finally, a new backwashing protocol has been developed and will be implemented. No backwashing was used during Phase I while the MTU was in use. During Phase II, the UF effluent will be used to backwash the filtration series every 30 minutes for 30 seconds by using an additional pump to send the liquid in the reverse direction back to the holding tank. The downtime required for this backwashing is minimal in reference to normal operation time, and the procedure is simple. The implementation of this reverse flow backwashing is to clear any buildup on filter surfaces while in operation and to expand the life of the filters by preventing particles from imbedding themselves deep into the membrane structures, particularly the MF and UF.

The results from Phase II will demonstrate how these modifications bring the MTU closer to its goals. The costs of the changes were low compared to the total MTU cost, so that the third goal is still within reach. Phase II is expected to be from April to June 2018. A near-complete MTU design which meets all goals is expected at the end of this time which will be ready for collaboration with a commercial partner for final product design.

References

Ministry of Environment Forest and Climate Change, 2017. Sewage Treatment Plants Effluent Discharge Standards, The Gazette of India.

Trivedy, R.K., Goel, P.K., 1986. Chemical and Biological Methods for Water Pollution Studies. Environmental Publications.

Water Aid, 2017. Quality and sustainability of toilets: A rapid assessment of technologies under Swachh Bharat Mission - Gramin 24.