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Characterisation of blackwater from human transportation systems equipped with vacuum toilets and controlled emissions tanks and its impact on solid/liquid separation technologies

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ABSTRACT

The first ever detailed characterisation of blackwater from human transportation systems equipped with vacuum toilets and Controlled Emissions Tanks (CET) revealed a stream that is very concentrated in salts and nutrients when compared to other blackwater sources. *Escherichia Coli (E. coli)* levels in the blackwater characterised were comparatively lower than the range reported for septic tanks, for example. Suspended solids were significantly lower than the levels found in pit latrines, but closely comparable to those reported for gravity toilets. The average COD of 3566 ± 2049 mg/L was typically lower than in pit latrines and gravity flush toilets. These findings then show that the characteristics of the blackwater from human transportation systems are directly impacted by a combination of the low flush vacuum toilets, storage in the CET, and different behaviour for passengers with increased usage for urination over defecation when compared to common uses of toilets. Such factors collectively dictate the nature of the blackwater and require that a solid/liquid separation technology for further processing is fundamentally robust in operation. The greater solids pulverisation, largely resulting from vacuum flushing combined with the storage environment, reduces the suitability of centrifugal and settling technologies whilst making filtration the most suitable option.

1. Introduction

Vacuum flush toilets are preferred for on-board (train, aircraft, ships) sanitation purposes due to space savings and low water use ($\leq$ 1 L per flush). The low flush volume delivers a significant reduction in the volume of waste produced and hence reduces the frequency for emptying the controlled emissions tanks (CET), in which the waste is stored [1]. However, if the passenger services demand is at its peak, the CET run the risk of not getting emptied regularly enough which can lead to the toilets being locked out of use, thereby leading to system failure and eventually producing inconvenience to the passengers [2]. Regular maintenance of the CET is then required. A study of original and modified versions of the CET by Hunt et al. [3] highlighted that there is a risk of solids accumulation in the CET tanks which may eventually cause problems during the emptying process at the depots. The study also highlighted a bacteriological risk for the workers, associated with the maintenance of CET. Management of the blackwater from human transportation systems then remains a major challenge for the operators. An alternative approach is then needed to provide a more sustainable practice. Recent progress has focused on the application of treatment technologies so that the blackwater produced can be treated onboard to sufficient standard for safe disposal. This then allows to reduce the time interval between CET emptying [1]. However, this approach addresses only one part of the problem. Indeed, regular stops will still be required to replenish the freshwater tanks. It has then been proposed to not only treat but also recycle the water for applications such as toilet flushing, thus ultimately limiting/eliminating blackwater storage and the related health hazards with handling/emptying the CET, while also reducing the frequency for freshwater replenishment. However, there is a significant gap in knowledge of the quality of the blackwater produced on human transportation systems. Indeed, detailed characterisation and studies of blackwater from human transportation systems are very scarce with only a limited number of studies available on ships [4–6] and railway rolling stocks [7]. For the studies on ships, the blackwater is

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often mixed with greywater and possibly also other sources from kitchen and laundry facilities [4,5]. This was also true for studies on vacuum toilets as blackwater was mixed with kitchen waste when treated in an anaerobic system [8]. As such only very limited sets of data are available for blackwater produced from vacuum toilets [9] and more specifically from railway rolling stocks [7]. Other studies have highlighted that blackwater collected from different sanitation systems (e.g., conventional, dual and vacuum flush toilets) present different characteristics. Separately collected blackwater combined with vacuum toilets results in a concentrated stream which is <30 % of the typical household volumes, thereby leading to an increase of the concentrations of the contaminants, (i.e., >50 % of organic matter and up to 80–95 % of nutrients in the stream) [10]. It is therefore very difficult to predict the characteristics of blackwater from human transportation systems and hence the treatment required for reuse.

This paper then aims to deliver the first detailed characterisation of vacuum flushed blackwater from human transportation systems equipped Controlled Emissions Tanks and determine the specific prerequisite for its treatment, in particular from a solid/liquid separation point of view. The study reported in this manuscript then contributes new knowledge on blackwater produced from vacuum toilets on human transportation systems which will in turn help inform the design of treatment systems. Specifically, the following objectives were addressed: (i) To determine the physical, chemical, and microbiological characteristics of real blackwater collected from the CET and compare with blackwater from other systems to establish if waste processing on human transportation systems can build on existing knowledge from other applications: (ii) To evaluate the suitability of different solid/liquid separation options as an initial step for treatment for reuse.

2. Materials and methods

2.1. Collection and characterisation of real blackwater from CET

Blackwater samples were collected from CET at two maintenance depots, Norwich Crown Point Rail Depot (Norwich, UK) and Wembley Light Maintenance Depot, Chiltern Railways (Wembley, UK). A total of 50 raw blackwater samples were analysed in triplicates over a period of 8 months (between February and September). The samples were collected in 25 L carboys. The blackwater samples were transported to the university campus, stored in the laboratory cold room at a temperature of 4 °C, and analysed within 48 h of collection. Turbidity (NTU) (0–4000 NTU), pH, and Electrical Conductivity EC (μS/cm) (1 μS/cm to 2 S/cm) were measured using a Hach 2100 N turbidimeter, a Jenway 3450 pH meter and a Jenway 4310 Conductivity meter, respectively. COD (500–10,000 mg/L), Total Nitrogen (10–150 mg/L), Total Phosphorous (0.5–25 mg/L), and Ammonium (NH_4^+-N) (4–80 mg/L) were measured by spectrophotometry (Spectroquant® cell tests, Merck Millipore, Watford, UK). Ion chromatography was performed using a Dionex ICS-900 for cations Mg^{2+}, NH_4^+, K^+, and Ca^{2+} and Dionex IC/S600 for anions NO_3, NO_2, PO_4^{3-}, SO_4^{2-}, and Cl^- (Thermo Fisher Scientific, UK). Heavy metals were analysed using ICP-MS NexION 350D (Perkin Elmer, Canada). *E*-coli and Total Coliform were measured using Colilert-18/Quanti-tray method IDEXX Colilert detection 1 organism/100 mL.

2.2. Preparation of synthetic faeces

Simulant faeces were prepared for some of the solid/liquid separation trials in controlled conditions [11] (Table S1 in Supporting Information). All the components used in developing the simulants were sourced from Sigma- Aldrich (Merck Group) except for Psyllium husk (Wholefood Earth Organic Psyllium Husk) and miso paste was sourced locally.

In the present study the corresponding simulants were modified in structure into a faecal paste form and was shaped as needed. The effects of solid-liquid separation were studied by demonstrating the faeces mostly into lumpy, sausage like stool and completely mixed type (Fig. S1). The simulant faeces were directly placed into the toilet bowl with the corresponding volume of urine (as water) and paper (Fig. S1), with the solid/liquid separated fractions collected separately. Trials were performed in triplicates.

2.3. Experimental setup of vacuum toilet

The experimental setup of the frontend system used in this study consisted of a real vacuum pressure system by Glova Rail Vacuum toilets (Denmark) with a 0.5 L flush (Fig. 1). No chemicals were used in the operation of the vacuum toilet. Using a real vacuum toilet allowed to simulate the equivalent environment to the one in which the sampled blackwater would have been generated and then apply solid/liquid separation techniques.

2.4. Separation trials

2.4.1. Filtration based approach

Particle size fractionation of suspended solids was achieved by coarse filtration of real and synthetic blackwater through laboratory steel mesh sieves with pore sizes of 4000, 2000, 1000, 500, 250, 125, and 63 μm. Suspended solids (g/L) present in the raw samples and each filtered fraction were measured using the standard 2540D method on 1.2 μm filter paper (Whatman Glass Microfiber Filters GF/A diameter 70 mm). Samples sieved to the smallest fraction were then analysed for particle size distribution through a Mastersizer Malvern 2000 Laser Diffraction. The filtration trials were carried out with both the real and synthetic blackwater to help clarify the impact of storage in the real system during which alteration of the blackwater characteristics may have occurred.

Fig. 1. Vacuum toilet set-up.

2.4.2. Settling based approach

Settling of the real blackwater was measured in measuring cylinders and was calculated using the Sludge Volume Index (SVI) method:

$$SVI = \frac{SV\,30}{X_{TSS}}$$

SV30 = Volume occupied by sludge from the graduated cylinder in mL/L after 30 min of settling.X_{TSS} = Measured concentration of the sample in g/L.

The SVI method is commonly applied to evaluate the settleability of mixed liquor suspended solids from biological treatment processes such as activated sludge. The method was applied here in a different context but remains relevant in the assessment of the settleability of solids in water. The test duration had to be extended to 24 h due to generally very low settleability of the blackwater solids.

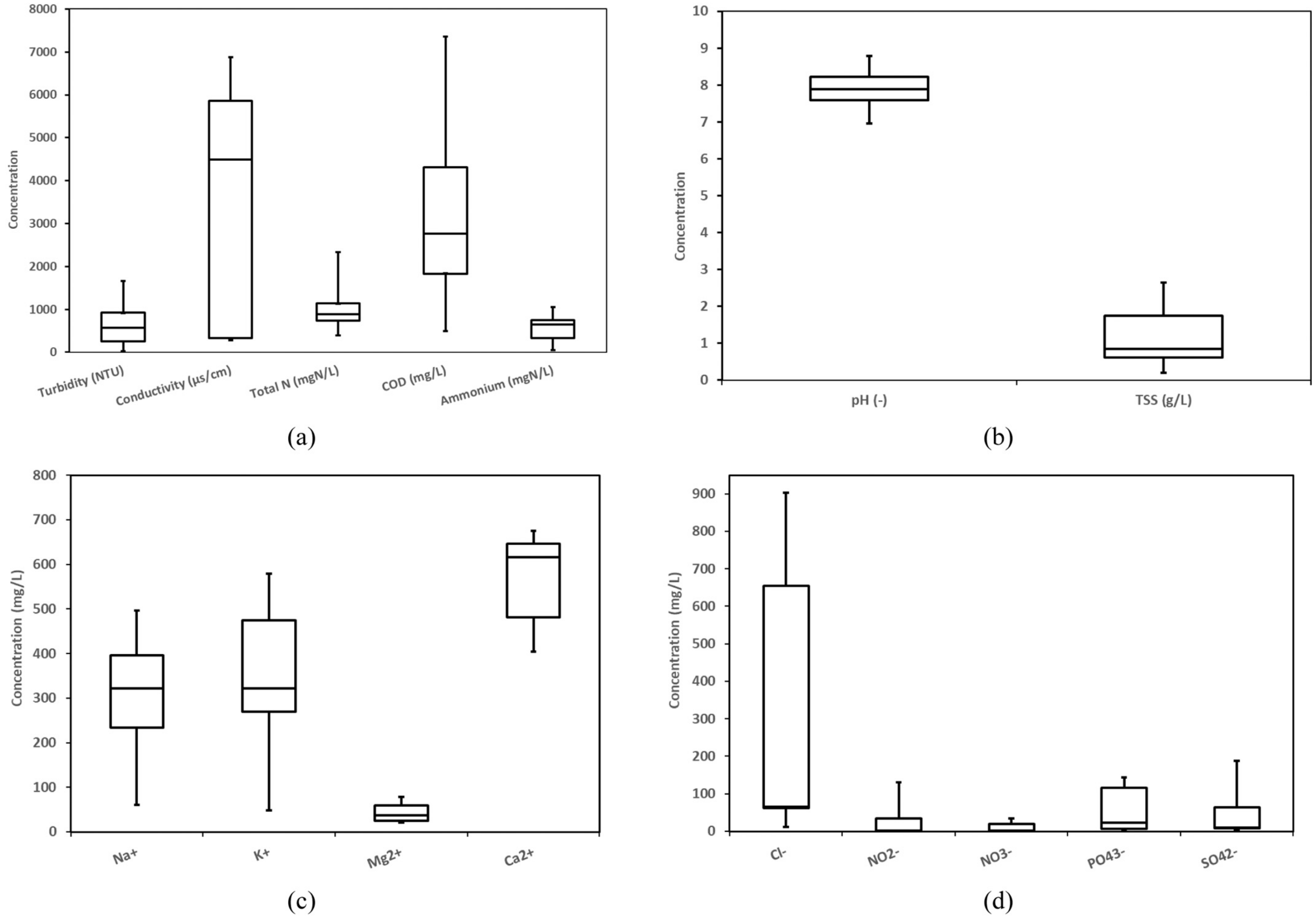
2.4.3. Vortex based approach

As part of the solid/liquid separation tests, a system using the commercially available solid-liquid separator Aquatron 90 (Aquatron, UK) was tested (Fig. S2). The separator combines multiple techniques to separate the flushed contents in two fractions as solid and liquid in which the liquid flows sideways through the outer surface of a vertical, hourglass-shaped separator and develops into a vortex or centrifuge pattern across the mid-section further expanding along the lower section, whilst the greater density solids fraction drops directly down the middle, assisted by gravity. For the trials, different solids (faeces and paper) quantities were tested with the 0.5 L flush with masses of simulant faeces of 50 g, 170 g, and 350 g simulating typical low, medium, and high masses of faeces. To this, toilet paper was added with 0, 10, and 40 sheets. The outlet of the vacuum toilet was connected using an inclined PVC pipe that was then connected to the inlet of the separator (Fig. S2). Separation of the solid-liquid fractions was explored by measuring the quantity of suspended solids (g/L) in the liquid fraction. The trials with the vortex based system were carried only with the synthetic blackwater as it was established in the filtration trials that the characteristics of the real blackwater collected had been altered during storage in the CET with in particular a significant breakdown of the solids to smaller particles and hence would not be representative of the mixture coming directly out of a vacuum toilet.

3. Results and discussion

3.1. Physicochemical characteristics

The characterisation of the blackwater showed a maximum concentration for conductivity and Total N, at 6870 μS/cm and 2340 mg/L, respectively (Fig. 2a). These values are particularly high when compared with other raw blackwater sources such as pit latrine and gravity flush toilets. For example, the conductivity of blackwater from gravity flush (8 L) toilets has been reported to range between 1606 and 2046 μS/cm [12] which is over 3 times lower than the blackwater studied here. While, Total N concentrations in gravity flush toilet blackwater has been reported at 410 mg/L and 190 mg/L [13], which represents up to 4 and 8 times less when compared to the present study. An average pH of 7.97 is comparable to other blackwater sources. The average ammonium content was 717.6 mgN/L, which is again significantly higher (nearly 27



(a) (b)

(c) (d)

Fig. 2. Characteristics of the blackwater: (a) physical and chemical, (b) pH and TSS, (c) cations and (d) anions.

times) than the average NH_4-N in domestic gravity flush blackwater (26 mgN/L) [13]. However, closely similar levels of NH_4-N have been reported for source-separated concentrated blackwater by Moges et al. [14]. This firstly indicates that in combination to the lower flush volume, the toilets on the transport systems are largely used for urination and urea hydrolysis has occurred due to holding of the flushed blackwater contents into CET tanks. Indeed, urine is found in two states, fresh and hydrolysed. After being freshly excreted from the body, nitrogen is organic and exists in the form of urea. By coming in contact with microbiological contamination, urea is biochemically hydrolysed in the presence of urease from the faeces into ammonium, bicarbonate (HCO_3^-), and hydroxide ions (OH^-), which also increases the pH [15]. Further on salts and nutrients, on average, concentration of monovalent cations, 310 mg Na^+/L, and 341.1 mg K^+/L (Fig. 2c) are significantly higher than values reported for pit latrine and gravity flush blackwaters [12]. Also, potassium and sodium ion concentrations of 75 mg K^+/L and 97.7 mg Na^+/L in domestic application using low flush blackwater collection is still lower than the current blackwater [16]. Average calcium and magnesium in the raw blackwater of 570.6 mg/L and 41.4 mg/L, respectively, are significantly higher than raw septic tank effluent with concentrations of 19.4 mg/L and 5.4 mg/L, respectively, [17]. Similarly, the concentration of monovalent anions such as Chloride Cl^- and multivalent anions such as Phosphate (PO_4^{3-}), Sulphate (SO_4^{2-}), Nitrite (NO^{2-}) and Nitrate (NO^{3-}) were also found to be higher than in other blackwater sources. Also, rolling stock blackwater was found to be very variable with concentrations of Cl^- of 11.9 to 902.8 mg/L, PO_4^{3-} 0.7 to 143.9 mg/L, and SO_4^{2-}, 1.1 to 188.1 mg/L (Fig. 2d).

The significant variation continued to be observed for all the parameters including turbidity (19.6 to 1661 NTU) and COD (500 to 7360 mg/L) (Fig. 2a). The average COD content in the present study is 3566 ± 2049.1 mg/L which is considerably lower than that of pit latrines at 12437 mg/L, septic tanks at 7607 mg/L [18] as well as gravity flush toilet at 4710 mg/L [13]. Interestingly, COD concentrations in urine alone have been reported to range between 5000 and 17,000 mg/L [19–21] highlighting the dilution of urine with flush water, even with the very low volume used in vacuum toilets. The range of suspended solids in the blackwater is observed to be low from 0.2 to 2.4 g/L (Fig. 2b). These values for solids content are significantly lower than other types of blackwater such as the pit latrines where solids typically range from 6 to 11 g/L [18] but is closely comparable to solids reported for gravity toilets with differing flushing volumes, for example, 1.556 g/L at 3 l, 3.57 g/L at 6 l and 2.3 g/L at 9 l [13,22]. Low COD and solids content, also again considering the low flush water used, suggest less faeces in this blackwater which ultimately points to the user behaviour, with more urination than defecation. Also, different vacuum flush blackwaters from diverse environments were reported to have varying suspended solids content. For example, blackwater arising from vacuum toilets in a pilot scale experiment assessing blackwater separation with organic filters and liquid fraction treatment was reported to have a TSS content ranging from 0.43 to 3.65 g/L [22]. Also, blackwater in a remote sanitation facility for tourists employing vacuum toilets typically had short user contact time, which impacted the solids load, resulting into a lower TSS, ranging from 0.72 to 1.67 g/L [22]. This range of solids is within the TSS range measured in the current study, which also has a similar condition of limited user contact time, usually, on an average between 1 and 3 min [23].

Overall, the physico-chemical characteristics of the blackwater were found to be directly impacted by the systems with low flushwater and, long retention times of up to several days in the CET tanks as well as user behaviour (high urination, low defecation). Interestingly, this may lead to further difference depending upon the type of transport as we could imagine different user behaviours on short and long journeys.

3.2. Microbial contamination

Pathogenic viruses, and bacteria are found to escape from the human body in the excreta and may be passed onto others via exposure to wastewater [24]. Total coliform is a consistent indicator to identify faecal contamination and pathogen *Escherichia Coli* (*E. coli*) is commonly found in the human intestine which produces toxin causing diarrhoea on exposure to blackwater. By examining the concentration of coliform levels in wastewater, practical information on health hazards, in this particular case during maintenance of the systems and the reuse application, can be assessed. In this study, the *E. coli* concentrations were from 2×10^4 to $>2.4 \times 10^7$ MPN/100 mL, while the total coliform concentrations ranged from 1.1×10^6 to 2.4×10^7 MPN /100 mL, as shown in Fig. 3**.** These values are similar to the ranges reported for other blackwater sources, although higher ranges are found for septic tanks ranging from 10^8 to 10^9 *E. coli* MPN/100 mL [25], and in pit latrines $8 \times 10^9 \pm 9 \times 10^9$ *E. coli*/100 mL and $3 \times 10^9 \pm 5 \times 10^9$ Faecal Coliform/100 mL [26]. On the other hand, the concentrations of microorganisms from domestic toilet blackwater is reported at $9.83 \times 10^5 \pm 5.85 \times 10^5$ MPN/100 mL [6] which is lower than the blackwater studied here. These findings again highlight the differences in toilet usage, for example, the higher levels reported in concentrated sources such as the pit latrines and septic tanks confirm the lower use for defecation in this case whereas the lower levels observed in dilute sources such as the domestic blackwater show the impact of low flush water. Indeed, vacuum toilets have a very low flush water volume (0.5 L), higher concentrations of faeces would be projected overall, however, due to low use for defecation, even with the low flush water, concentrations remain within the same range. According to the ISO 30500:2018 [27] for non-sewered sanitation systems, the liquid effluent validation thresholds for human health protection requires a maximum concentration of no >100 CFU or MPN/L which highlights the need for significant treatment before discharge or reuse.

3.3. Metals

Table 1 summarises the concentrations of metals present in rolling stock blackwater in comparison with other domestic sources of blackwater collected from vacuum and gravity flush toilets, and source separated blackwater, as well as faecal sludge, sewage/wastewater sludge, and excreta. Generally, average metals concentrations of zinc (32.9 μg/L), Lead (0.4 μg/L) and Cadmium (not detected) measured here are significantly lower than in other blackwater sources. Findings from the literature suggest metals are typically found at higher concentrations in faeces. Also, metals are found to partition to the particulate with evidence in sewage [28]. This then supports the previous observations that the current blackwater contains lower levels of faeces and solids in general. However, metals such as Cd, Pb, and Zn present a threat with impacts such as acute and chronic toxicity to the organisms, ecosystem accumulation, loss of biodiversity and habitat as well as threat to human health [29]. Factually, industrial emissions are considered a major

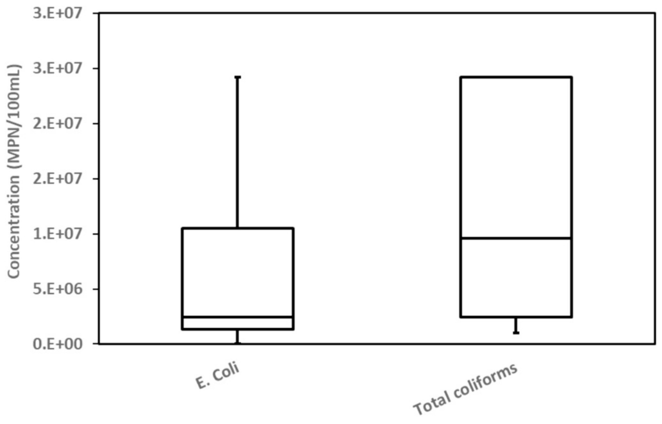
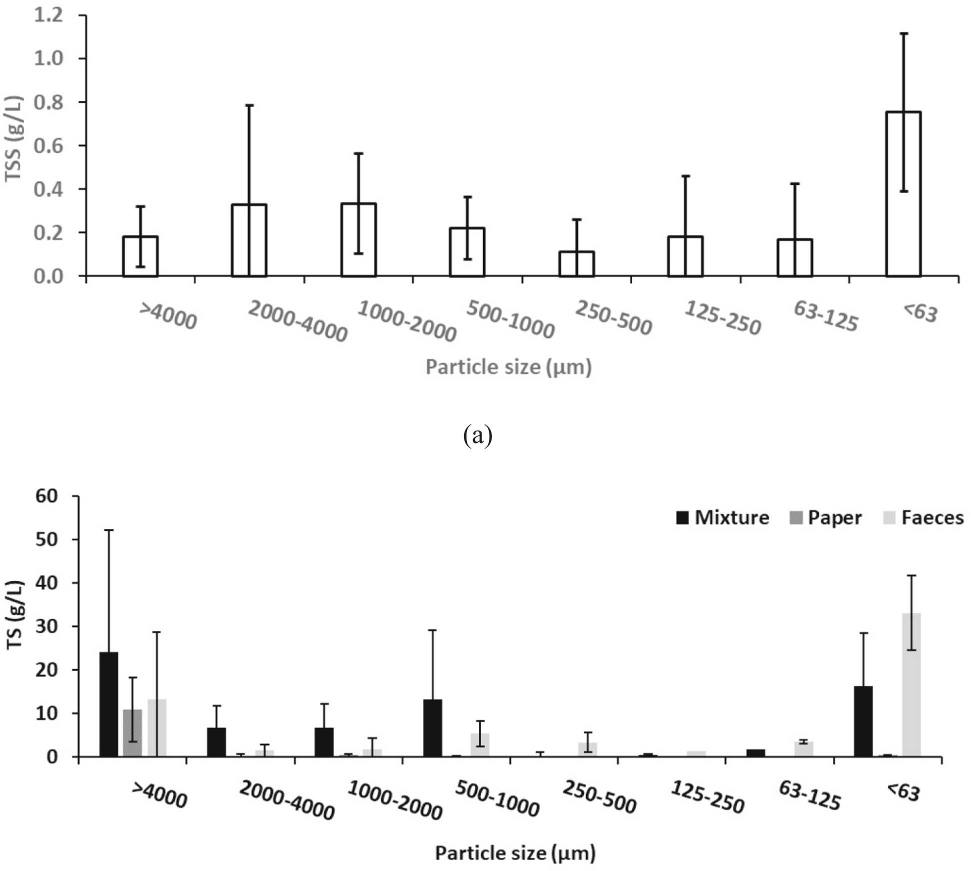


Fig. 3. *E. coli* and Total coliforms levels in the blackwater.

Table 1
Comparison of metal concentrations (μg/L) in the studied blackwater with other blackwater sources reported in the literature.

	CET blackwater (Present Study)			Flush toilet blackwater [29]			Source separated blackwater [16]	Faecal sludge (Pit latrine) [31]	Sewage Sludge [32–34]	Typical municipal WWTP influent [35]	Excreta (Faeces) [36]
	Min	Max	Avg ± Stdev	0.5 L	1 L	5 L	Avg	Avg ± Stdev			
Mg	445	1770	1081.8 ± 503.9	6100	14,900	21,400	17,000	–			
Al	41	113	83.6 ± 26.5	665	316	211	540	–	–	–	–
Ca	3720	6100	4848.3 ± 1079.9	58,200	53,100	50,800	68,600	–	–	–	–
Mn	3	5	4 ± 1	–	–	–	130	–	–	–	–
Fe	70	162	113.9 ± 37.1	1350	945	606	1280	21,000	–	–	–
Zn	15	97	32.9 ± 31.8	598	419	270	525	646,000 ± 56,000	1,132,000–4,900,000	100–1600	135,000–355,000
Sr	12	21	16.5 ± 3.8	–	–	–	–	–	–	–	–
Cd	<LOD	<LOD	<LOD	–	–	–	0.4	<2000	4000–10,100	0.4–75	300–400
Ba	2	4	3.1 ± 0.8	–	–	–	34.9	–	–	–	–
Pb	<LOD	1	0.4 ± 0.5	–	–	–	2.26	28,000 ± 8000	220,000–365,000	2–100	700–1200

source of entry of heavy metal in municipal wastewater however, raw sewage may contain significant concentrations of heavy metal which arise from other sources as well [30]. The heavy metals present in blackwater will primarily be from the faeces and urine excreted and originating from pharmaceuticals, pesticides and food additives [16]. However, other materials may be dumped into toilets which may contribute to the heavy metals levels in blackwater (e.g. cigarettes butts) [16]. The construction materials of the toilet and collections systems (e.g. pipes and tanks) may also contribute to the levels observed. The blackwater from the present study is of relative environmental risk, from a metals point of view, if it was to be discharged into the environment and hence removal will be essential but as stated above, as metals partition to the solids fraction, the solid/liquid separation step is expected to provide the necessary treatment.



(a)

(b)

Fig. 4. Fractionated (a) real and (b) synthetic blackwater.

3.4. Solid/liquid separation of the blackwater

3.4.1. Filtration

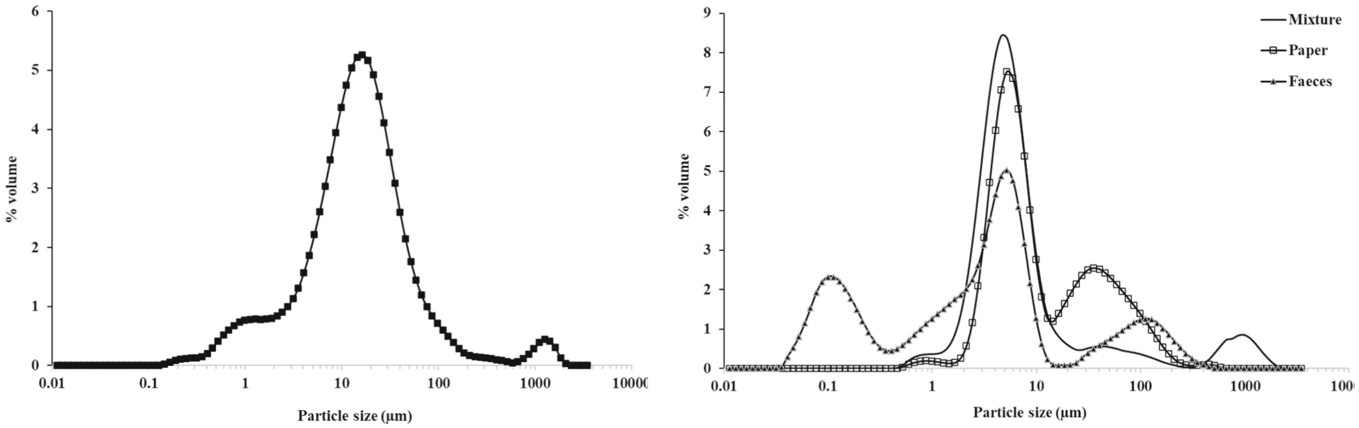
Overall, particulate matter contained within the different fractions of the blackwater is rather mixed. For example, suspended solids found in the large fractions (>4000 μm) are 0.18 ± 0.23 g/L and make 8 % of the total suspended solids, whilst fractions containing particles sized between 1000 and 2000 μm and 2000–4000 μm have TSS of 0.33 ± 0.23 g/L and 0.33 ± 0.45 g/L, respectively, and together make up to 29 % of the total suspended solids (Fig. 4a). The smaller size fractions in the range 63–500 μm make up 30 % of the suspended solids, with 0.17 ± 0.25 g/L found in 63–125 μm, 0.18 ± 0.27 g/L in 125–250 μm and 0.11 ± 0.14 g/L in 250–500 μm. Finally, the smallest particle size fraction of <63 μm actually makes up a significant fraction with 33 % and a TSS content of 0.75 ± 0.36 g/L. High variability in the TSS levels in each fraction was also observed, which indicates the variation in the blackwater collected in the CET tank system. Further study through particle size analysis (Fig. 5a) has shown that blackwater samples sieved to the smallest pore size of 63 μm mainly contain solids of about 10 μm in size. This implies that the smaller particles formed in blackwater are a result of mechanical breakdown of the solid particles from larger fractions.

To better understand the impact of existing conditions in the system mixtures of synthetic faeces, urine (as water), and toilet paper were flushed down the vacuum toilet. As shown in Fig. 4b, the paper was found to mainly sit in the larger fractions with approximately 88 % of paper particles being >4000 μm. This was mainly due to the wet particles sticking to each other during the sieving process, which can be expected to occur in most separation processes. However, in contrast to paper, when simulated faeces were flushed down the toilet alone, they were mainly found to sit in the largest (21 % >4000 μm) as well as the smallest (52 % <63 μm) fractions, which demonstrates a greater degree of disintegration. This explains the very small solids found in real rolling stock blackwater. Finally, mixture of paper and faeces, similar to the real blackwater, was characterised by a broader distribution across all size fractions but with more solids (34 % >4000 μm) in the largest size fraction which suggests that further breakdown of solids occurs during the storage stage in the CET tanks and ultimately highlights the challenge faced in terms of separation of solid and liquid as part of wastewater treatment system implemented in transport systems. In this case, as solid/liquid separation occurs soon after flushing, the additional breakage of particles due to storage will be eliminated and hence provide a better separation efficiency. In parallel, Fig. 5b shows the particle size analysis for the water with the simulant faeces, paper, and the mixture, reaffirming that blackwater samples sieved to the smallest pore size of 63 μm contains solids of around 10 μm in size, as previously seen from the real blackwater samples. However, when simulant faeces and toilet paper are flushed individually, both can undergo breakdown relatively more easily than the synthetic mixture. In summary particle breakdown is due to a combined effect of solids disintegration which is mainly attributed to the low water consumption and vacuum flush toilets system, but additional breakdown is also likely to occur during storage due to the constantly mobile environment occurring in transport systems.

3.4.2. Settling

Gravity separation through settling is the most commonly applied technology for solid/liquid separation for wastewater treatment. For this, the settleability of the particles that differ in size, shape, and density must then be considered. Settling in the blackwater was evidenced through diverse ranging sludge volume index (SVI) between >30 mL/g to <700 mL/g over 24 h. The SVI is defined as the volume (in mL) occupied by 1 g of sludge after settling for 30 min [37] and typical SVI values for activated sludge can be found ranging between >50 to <400 mL/g, after settling for 30 min where 50 mL/g indicates wastewater with very good settleability, and 400 mL/g indicates poor settling characteristics [38]. The SVI values calculated for the settled blackwater between 32 and 694 mL/g over 24 h highlighted that the particles present did not settle well. In addition, even after leaving to settle for 24 h, the supernatant was still highly turbid.

Based upon the settleable and non-settleable solids theory, solids associated with settling velocity $\nu_s \geq 0.0278$ cm/s in water, reach the bottom of a tank retention time of 4 h, and are classified as "settleable solids", whereas solids associated with $\nu_s \leq 0.0278$ cm/s are classified as "poorly settleable solids" [39]. In this case, assuming the density of faeces 1060 kg/m^3 [40], and the size of particles measured in the current blackwater, based on Stokes' law, the particles' settling velocity should be mostly above 0.34 cm/s, so all particles should settle in <30 mins. Furthermore, as the density of the toilet paper reported as 250–500 kg/m^3 [41] is less than that of faeces and water (~1000 kg/m^3), it would naturally float, or if wet will remain in suspension. The same can be observed for faeces if they become full of water. Also, in practice, as seen before, the solids are broken into very small particles. Thus, the above reasons collectively indicate the limitations of settling based separation for solid/liquid separation for this type of blackwater. In addition to this, movement in transportation systems likely to results in some mixing of the water would affect the settling process.



(a)

(b)

Fig. 5. Particle size distribution of (a) real and (b) synthetic blackwater.

3.4.3. Vortex

Interestingly, a system is commercially available for solid/liquid separation specifically applied to blackwater. The Aquatron separator has been tested, and is commercialised, for applications with gravity flush toilets [42–45]. To our knowledge, this work is the first evaluation of the technology with a low volume vacuum flush toilet. First, an increase in the TSS levels in the liquid fraction was observed when the faecal solids quantity per flush was increased, irrespectively of the toilet paper quantity (Fig. 6). This can be specifically observed in the case of faeces as the only input constituent. To illustrate, the TSS levels from flushing a minimum of 50 g faeces is lower with on an average 1.2 ± 0.5 g/L, which then rises to 59.4 ± 0.5 g/L and 70.6 ± 33.7 g/L when the faeces inputs increased to 170 g and 350 g. When compared to the average TSS levels in the real blackwater (1.07 g/L), the above TSS levels are significantly higher indicating that the real blackwater contains proportionally much lower levels of faeces and paper inclusive flushes, with some of the solids having undergone degradation during the blackwater storage in the tank.

When the concentration of faeces is fixed and the number of toilet paper sheets per flush is varied, different trends can be observed depending on the level of faeces. At 50 g of faeces, a slight increase in solids in the water fraction can be observed the amount of paper is increased (Fig. 6). This shows that some of the paper, known to have a lighter density, was not as well removed. Interestingly, at 170 g of faces, a revere trend was observed as the levels of solids in the water fraction decrease as the paper was increased. This suggests a better interaction and possible aggregation of the faeces and paper which help the separation mechanisms. Finally, with 350 g of faces, the solids levels in the water fraction remains relatively stable and high. This demonstrates that the separation was not effective in these conditions. The difference in the TSS levels is mainly attributed to the difference in shear rheological properties of the two solids. For instance, faeces when flushed as a separate constituent are likely to undergo more disintegration mainly due to its generally thixotropic nature [46]. In other words, faeces are thick and viscous under static conditions, however, when shaken or agitated they can become thin and eventually less viscous thus making it possible for faeces to flow. On the other hand, toilet paper is developed to dissolve in water and has a relatively low density [40,47,48]. In practice, once flushed, all the blackwater components such as urine, flush water, faeces and paper rapidly mix with each other. Because of the limited difference in densities of the liquid and solid components, when merged, the particles do not move in different phases during the low water flushing which is further exacerbated by additional breakdown under the effect of the vacuum pressure. Overall, the conditions observed in a system with a low flush volume and vacuum flush are not suitable for this type of technologies to ensure good separation of liquid and solids.

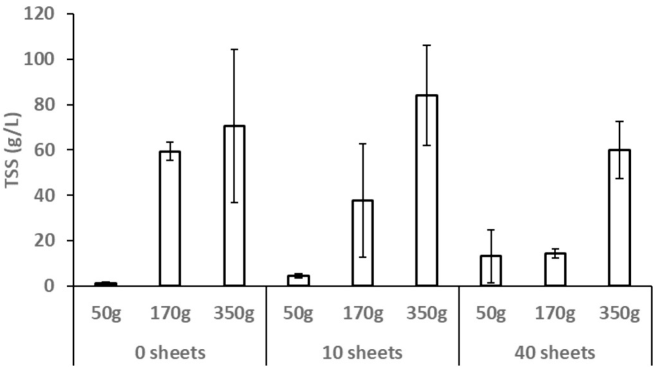


Fig. 6. Average TSS (g/L) in liquid fraction from the Aquatron system.

4. Conclusions

The current study has delivered the first detailed characterisation of blackwater from human transportation systems equipped with vacuum toilets and CET while also testing solid/liquid separation technology as the primary step for its treatment. The work presented here then contributes new knowledge on the specificities of blackwater produced on human transportation systems which ultimately helps inform the design of treatment systems. To illustrate, the characteristics of the blackwater, with for example high levels of ions and nutrients and low levels of organics and solids, evidenced the significant contribution of low water flushing through the vacuum toilets coupled with characteristically high onboard urination and low defecation. Furthermore, as highlighted by the high pH and ammonia levels indicative of urea hydrolysis and the breakdown of solids (faces and paper) to very small particle sizes due most probably to the constant mobile environment, storage in the CET has a significant impact on the blackwater characteristics. From an application point of view, these results suggest that rapid processing of the blackwater, as it is flushed, will help maximise the solid/liquid separation and then facilitate the subsequent treatment of the liquid phase. In addition, because of the vacuum flush toilets used in human transportation systems leading to the formation of small non-settleable particles, filtration was identified as the most viable option for solid/liquid separation. Finally, the significant variations in parameters such as COD and turbidity observed which can be explained by the variability in occupancy of the transport systems for different journeys will be a major challenge for the application of treatment technologies in this context, potentially impacting treatment performance and maintenance requirements. This will then influence the choice of treatment technologies to be implemented for options less susceptible to feed water variations and shock loads.

CRediT authorship contribution statement

N. Jadhav: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **T. Brown:** Writing – review & editing, Funding acquisition, Conceptualization. **L. Williams:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **M. Pidou:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2024.106083.

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