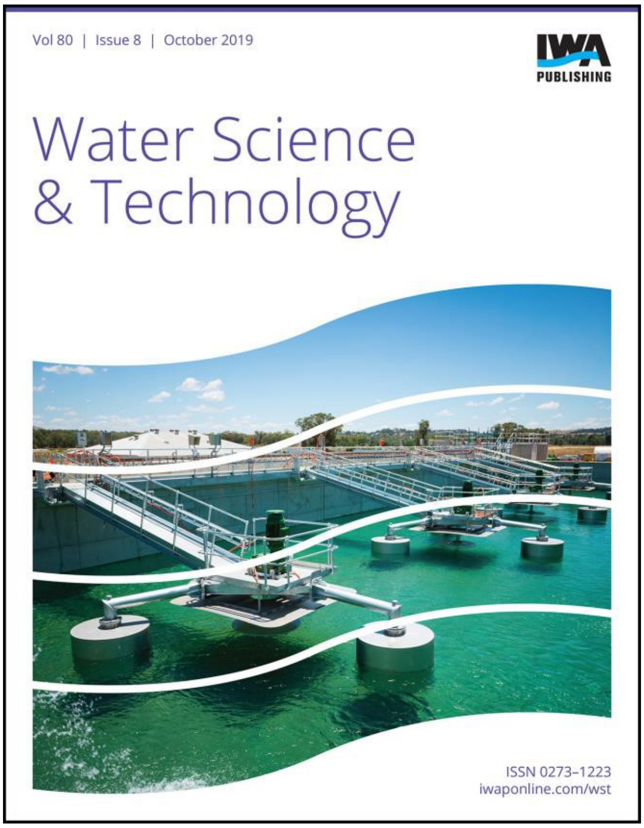

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Black water treatment by an upflow anaerobic sludge blanket (UASB) reactor: a pilot study

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ABSTRACT

Decentralized sanitary wastewater treatment has become a viable and sustainable alternative, especially for developing countries and small communities. Besides, effluents may present variations in chemical oxygen demand (COD), biochemical oxygen demand (BOD) and total nitrogen values. This study describes the feasibility of using a pilot upflow anaerobic sludge blanket (UASB) reactor to treat wastewater with different organic loads (COD), using black water (BW) and sanitary wastewater, in addition to its potential for preserving nutrients for later recovery and/or reuse. The UASB reactor was operated continuously for 95 weeks, with a hydraulic retention time of 3 days. In Phase 1, the reactor treated simulated BW and achieved 77% COD_{total} removal. In Phase 2, treating only sanitary wastewater, the COD_{total} removal efficiency was 60%. Phase 3 treated simulated BW again, and COD_{total} removal efficiency was somewhat higher than in Phase 1, reaching 81%. In Phase 3, the removal of pathogens was also evaluated: the efficiency was 1.96 log for *Escherichia coli* and 2.13 log for total coliforms. The UASB reactor was able to withstand large variations in the organic loading rate (0.09–1.49 kg COD m^{-3} d^{-1}), in continuous operation mode, maintaining a stable organic matter removal.

Key words | COD concentration, decentralized system, organic loading rate, simulated black water, stability reactor, UASB

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INTRODUCTION

A new concept of sanitation, based on maximum recovery of energy and nutrient resources and reduced use of drinking water, has gained worldwide prominence in the search for a more sustainable scenario in wastewater management (Poortvliet *et al.* 2018; Wielemaker *et al.* 2018). For new sanitation systems to operate efficiently, it is necessary to reduce collection and transport costs, i.e. to implement decentralized treatment systems (close to the source of wastewater), as well as to keep the resources (the nutrients contained in the wastewater) concentrated in order to favor their treatment and maximize their recovery (Kujawa 2005; Kujawa-Roeleveld & Zeeman 2006; Poortvliet *et al.* 2018).

Sanitary wastewater can be segregated into two streams, according to its origins: black water (BW – wastewater from the toilet) and grey water (GW – wastewater from the shower, bath, kitchen and laundry) (Palmquist & Hanæus 2005; De Graaff *et al.* 2010). Sanitary wastewater contains, on average, 500 mg L^{-1} of chemical oxygen demand (COD), 45 mg L^{-1} of total nitrogen (TN) and 7 mg L^{-1} of total phosphorus (TP) (Tchobanoglous *et al.* 2004). Most of these are also found in BW, and their concentrations are on average 2,260 mg L^{-1} COD, 150 mg L^{-1} TN and 42.7 mg L^{-1} TP, when referring conventional flush toilets (Tchobanoglous *et al.* 2004; Palmquist & Hanæus 2005). These solutes can be treated, producing bioenergy from the carbon, and recovering macro- and micronutrients. GW can be treated to achieve a quality that can be reused, for example, for irrigation or infiltration to the ground water. (Li *et al.* 2015).

Among treatment systems, anaerobic reactors are considered to be the best technology for resource recovery, since they convert organic matter into biogas (mostly CH_4), while nutrients are preserved for later recovery and/or reuse (Zeeman & Lettinga 1999; Zeeman *et al.* 2008; De Graaff *et al.* 2010). In addition, anaerobic systems are considered sustainable and suitable for decentralized treatment (Zeeman & Lettinga 1999).

The upflow anaerobic sludge blanket (UASB) reactor is the most widely used anaerobic system in the tropics

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(Lettinga 2001). Despite the high rates of use, UASB reactor capacity for treating BW has been poorly investigated (Zeeman *et al.* 2008; De Graaff *et al.* 2010; Cunha *et al.* 2018). Those investigations were carried out with similar organic loads under mesophilic conditions.

However, no study had investigated the ability to treat both sanitary wastewater and BW, with their different organic loads, in a single UASB reactor. This study describes the feasibility of using a pilot UASB reactor to treat wastewater with different organic loads (COD), in addition to its potential to preserve nutrients for later recovery and/or reuse.

METHODS

UASB reactor

A UASB reactor was operated continuously for 95 weeks, with a flow rate of 216 L d^{-1} and hydraulic retention time (HRT) of approximately 3 days. The reactor was made of fiberglass-structured resin with an effective volume of 640 L (inner diameter: 0.45 m; height: 4.0 m). The effluent outlet spout was located 0.20 m from the top of the reactor. Due to the low upflow velocity, the biomass was not well mixed; therefore, the reactor had stainless steel blades for continuous mechanized rotation (11 rpm). The reactor had four sampling points at different heights (0.5, 1.0, 2.0 and 2.5 m from the bottom), and was operated at ambient temperature, which varied between 19 and 27 °C. The HRT to be applied in the UASB reactor was calculated according to the equation suggested by Zeeman & Lettinga (1999).

Experimental setup of the UASB reactor

For the initial start-up, the reactor used in this study was inoculated with 320 L of sludge from the full-scale UASB reactor and fed with sanitary wastewater coming from the Monjolinho Wastewater Treatment Plant (WWTP) of the city of São Carlos, São Paulo state, Brazil. The reactor was fed only sanitary wastewater for two weeks to adapt its bacteria. Then, sanitary wastewater was gradually mixed with wastewater from a pig farm each week, until the COD concentration of the influent increased to values that resembled BW. This UASB reactor start-up period lasted thirteen weeks, and the details are described in the study by Valdez (2017).

The present study began after the reactor start-up and was divided into three phases, as shown in Table 1. The UASB reactor operation was not interrupted between the phases, and there was no change in its operational conditions, apart from the loading rate.

Analyses and measurements

Influent and effluent were sampled separately and analyzed weekly for temperature, pH, partial alkalinity, total alkalinity, TP, TN, biochemical oxygen demand (BOD), COD, total coliforms, *Escherichia coli*, total solids (TS) and total suspended solids (TSS), following the procedures described by the Standard Methods for the Examination of Water and Wastewater (APHA 2005). Volatile fatty acids (VFAs) were determined by the Kapp method (Kapp 1984; Ribas *et al.* 2007). Total coliforms and *E. coli* were determined according to Medeiros & Daniel (2015). All the samples were analyzed immediately after collection.

The COD analyses were divided into total, suspended, soluble and colloidal COD, where: COD_{total} referred to the raw samples; $COD_{filtered}$ related to raw samples filtered through a membrane with a pore size of 1.2 μm; and $COD_{suspended}$ was the suspended fraction, calculated from the difference between the COD_{total} and the $COD_{filtered}$. $COD_{soluble}$ was the soluble fraction achieved by filtering the samples through a 1.2 μm and a 0.45 μm membrane. $COD_{colloidal}$ referred to the difference between the $COD_{filtered}$ and the $COD_{soluble}$.

RESULTS AND DISCUSSION

Performance of the UASB reactor

The performance parameters of the pilot-scale UASB reactor (for Phases 1, 2 and 3) are shown in Table 2.

Table 1 | Operational phases of the UASB reactor

Phase	Duration (weeks)	Effluent raw	Organic loads (kg COD d^{-1})
Phase 1	53	Mixture of sanitary wastewater[a] + wastewater from a pig farm[b]	0.33
Phase 2	14	Sanitary wastewater[a]	0.09
Phase 3	28	Mixture of sanitary wastewater[a] + wastewater from a pig farm[c]	0.52

[a]Sanitary wastewater from the Monjolinho WWTP (São Carlos, São Paulo, Brazil), after preliminary treatment (screen and grit chamber).
[b]Pigpen wastewater from the Big Board farm (São Carlos, São Paulo state, Brazil).
[c]Pigpen wastewater from the Santo Ignácio de Loiola farm (Brotas, São Paulo state, Brazil).

Table 2 | Key performance parameters of the UASB reactor for Phases 1, 2 and 3 (mean values and standard deviation)

		Phase 1		Phase 2		Phase 3	
Parameters	**Units**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
Temperature	°C	23.7 ± 2.1	22.5 ± 3.0	25.5 ± 1.6	25.5 ± 1.7	22.0 ± 1.6	21.0 ± 1.7
pH	–	7.2 ± 0.1	7.7 ± 0.2	7.3 ± 0.2	7.6 ± 0.2	7.1 ± 0.2	7.5 ± 0.1
Partial alkalinity	$mg\ L^{-1}$	732 ± 312	880 ± 353	114 ± 90	195 ± 60	298 ± 78	723 ± 169
Total alkalinity	$mg\ L^{-1}$	1,047 ± 424	1,150 ± 434	235 ± 214	244 ± 71	680 ± 146	968 ± 221
VFAs	$mg\ L^{-1}$	277 ± 167	119 ± 90	49 ± 26	27 ± 35	638 ± 187	110 ± 72
BOD	$mg\ L^{-1}$	719 ± 267	118 ± 38	276 ± 75	61 ± 23	1,440 ± 223	528 ± 218
COD_{total}	$mg\ L^{-1}$	1,549 ± 729	357 ± 112	434 ± 114	172 ± 67	2,405 ± 866	464 ± 343
TS	$mg\ L^{-1}$	1,631 ± 521	984 ± 203	820 ± 416	590 ± 201	1,892 ± 588	961 ± 357
TSS	$mg\ L^{-1}$	663 ± 492	125 ± 83	267 ± 199	131 ± 174	857 ± 392	125 ± 83

Although the temperature in the UASB reactor was not controlled, there was only a slight variation during the study period (19–27 °C). The temperature variation did not influence the treatment efficiency.

The pH of the effluent from the UASB remained between 6.8 and 7.8 during the anaerobic treatment. According to Speece (1996), neutral pH conditions, ranging from 6.5 to 8.2, are ideal for methanogen activity, so the levels measured reveal the stability of the reactor in this study.

The system generated alkalinity and consumed volatile acids in all three phases. This behavior indicates satisfactory conditions for organic matter conversion into methane (Speece 1996). Alkalinity has a primary role in anaerobic treatment, because it maintains the buffering capacity and prevents the accumulation of volatile acids formed in the anaerobic process (Chernicharo 2007). According to Dama *et al.* (2002), high alkalinity consumption in anaerobic reactors is an indicative of possible system failure. The results indicate that the reactor recovered well from the load variations. According to Tchobanoglous *et al.* (2004), BW contains enough alkalinity to control the pH of the medium.

According to Ripley *et al.* (1986), the ratio of intermediate alkalinity/partial alkalinity (IA/PA) may indicate the occurrence of disturbances in the anaerobic digestion process when the ratio presents values higher than 0.3. The mean ratio of IA/AP in this system was 0.32, varying from 0.05 to 0.52. However, Foresti (1994) affirms that it is possible to achieve process stability even for values above 0.3, depending on the case.

In the case of the present study, the UASB reactor showed a stable operation and removed an average of 73 ± 15% of the COD_{total} and 80 ± 11% of the BOD. COD_{total} and BOD performance in the UASB reactor in all phases is shown in Figure 1.

The mean COD_{total} influent concentration of Phases 1, 2 and 3 was 1,549 ± 729 mg L^{-1}, 434 ± 114 mg L^{-1} and 2,405 ± 866 mg L^{-1}, respectively. Despite the fluctuations in influent concentration and the decrease in organic load from Phase 1 to Phase 2, and the increase from Phase 2 to Phase 3, the system achieved stable removal efficiencies for COD_{total} and BOD.

The lowest COD_{total} and BOD removal efficiencies were observed in Phase 2 (56% and 71%, respectively). After increasing the organic loads, the COD_{total} removal was reduced immediately from 78.2% to 14.7%; however, the reactor recovered its efficiency in the following weeks.

Chen *et al.* (2014) also verified increased COD removal efficiency concomitantly with increased organic loading, when evaluating the performance of a UASB reactor treating diluted pharmaceutical fermentation wastewater.

The mean COD_{total} and BOD removal efficiencies of the system were 73% and 80%, respectively. Studies such as the ones by De Graaff *et al.* (2010) and Luostarinen *et al.* (2007) also reached similar efficiencies when treating BW anaerobically by UASB reactor and UASB-septic tank, respectively.

Figure 2 shows the correlations between applied organic load rate (OLR) and organic removal rate (ORR) in the UASB reactor during the three phases.

The applied organic load rate of the system varied from 0.09 to 1.49 kg COD m^{-3} d^{-1}, with averages of 0.52, 0.14 and 0.81 kg COD m^{-3} d^{-1} for Phases 1, 2 and 3, respectively. The organic removal rate was 0.40, 0.08 and 0.66 kg COD·m^{-3}·d^{-1} for Phases 1, 2 and 3, respectively. The COD_{total} removal rate showed a linear correlation with applied organic loads, for all phases. Khan *et al.* (2015) also

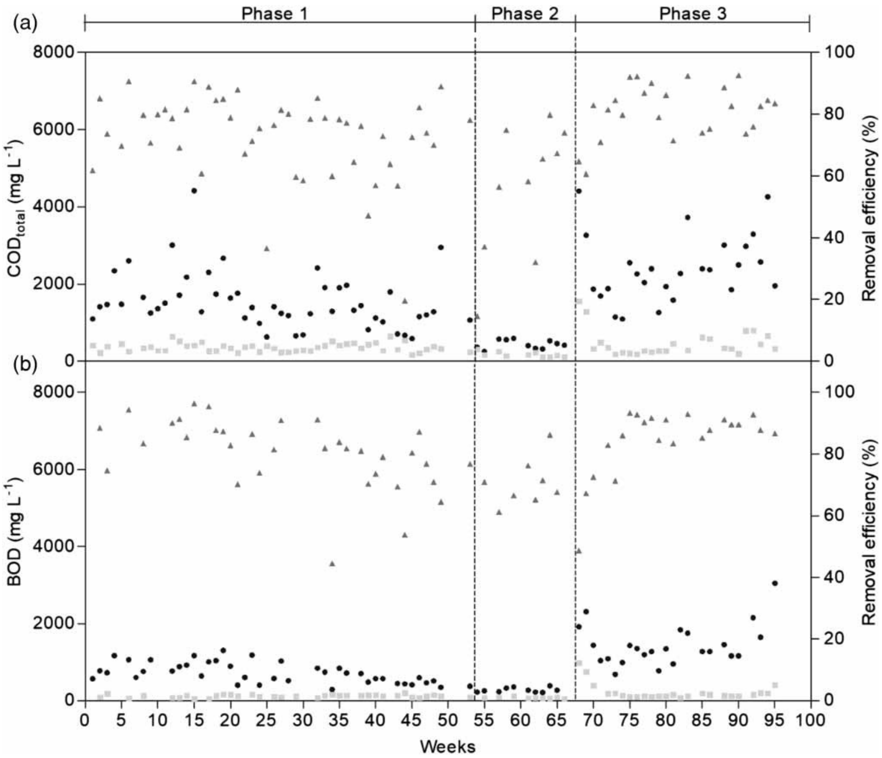

Figure 1 | (a) COD_{total} and (b) BOD concentrations in the influent (●), effluent (■) and removal efficiency (▲) in UASB reactor.

observed a correlation between removal of organic matter and applied organic loads, in a UASB reactor.

Khan *et al.* (2015) observed a reduced COD efficiency when treating wastewater at varying organic loads by means of a UASB reactor: when low organic loads were used, high variations occurred in COD reduction. The authors mentioned several factors as possible causes: shock load, gas entrapped in the blanket, short circuit and substrate availability from the particulate BOD encapsulated in the flocculent sludge blanket.

Kujawa-Roeleveld *et al.* (2005), using the UASB septic tank to treat concentrated BW with similar organic loads (0.33 and 0.42 kg COD m^{-3} L^{-1}), obtained 61 and 74% COD removal efficiency, respectively, values close to those found in this study.

The fractions corresponding to COD_{total} in the effluents are shown in Figure 3.

Figure 3 clearly shows that the $COD_{suspended}$ and $COD_{soluble}$ were the main contributors to the COD_{total}, while $COD_{colloidal}$ was relatively low. The average effluent COD fractions were 45.8% for $COD_{suspended}$, 40% for $COD_{soluble}$ and 14.2% $COD_{colloidal}$.

Phases 1 and 3 showed a better performance compared to Phase 2 regarding the $COD_{suspended}$ fraction. Phase 2 showed a measured $COD_{suspended}$ fraction of 64.8%, which corroborates the low COD removal efficiency. Sludge accumulation and escape from the previous phase may be a reason for the low efficiency in Phase 2, as well as gas entrapped in the sludge blanket (Khan *et al.* 2015).

Figure 4 shows the total solids and total suspended solids in the UASB. From Figure 4, it can be seen that TS and TSS values showed similar behaviors for all phases, with removal efficiencies around 41 and 81% for TS and TSS, respectively. Almost all suspended solids were retained in the UASB reactor. For all phases, the TSS to TS relation in the effluent was low.

Removal and nutrient recovery

The mean values of nutrients (TN and TP) in all phases in the UASB reactor are shown in Figure 5.

Nutrients in the effluent were slightly lower than in the influent and were similar for all phases. Nitrogen and phosphorus were conserved on average at more than 78% in the liquid effluent. The portion of removed phosphorus was partially due to precipitation

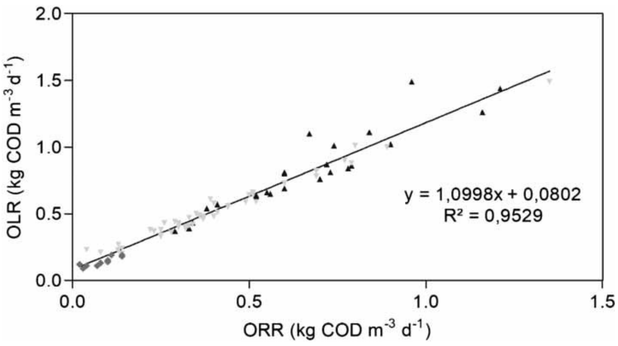

Figure 2 | Variation of applied load organic rate and organic removal rate in Phase 1 (▼), Phase 2 (◆) and Phase 3 (▲).

(Kujawa-Roeleveld *et al.* 2005). These values demonstrate the possibility of using this effluent to recover nutrients, either by physicochemical methods or by biological methods, such as the use of microalgae (Cuellar-Bermudez *et al.* 2017; Kim *et al.* 2017).

De Graaff *et al.* (2010) conserved about 91% of nitrogen and 61% of phosphorus in the effluent of a UASB reactor treating concentrated (vacuum-collected) BW.

Removal of pathogens

Microbiological analysis was carried out only during Phase 3. Thirteen samples were collected and analyzed in thirteen random weeks during Phase 3 to determine indicator microorganisms (Table 3).

The UASB reactor removed 1.96 log of *E. coli* and 2.13 log of total coliforms. This removal was larger than expected for a UASB reactor, which, according to the literature, removes only 1 log, so its removal was twice as much

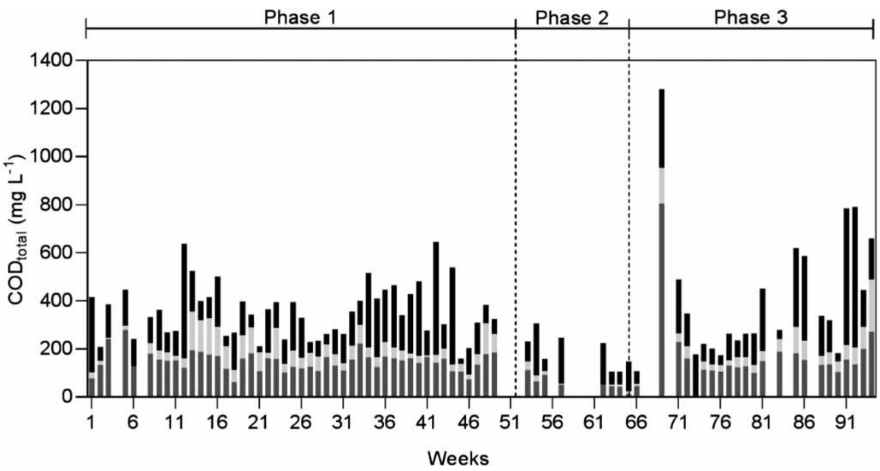

Figure 3 | COD_{total} in soluble (■), colloidal (■) and suspended (■) fractions in the effluent.

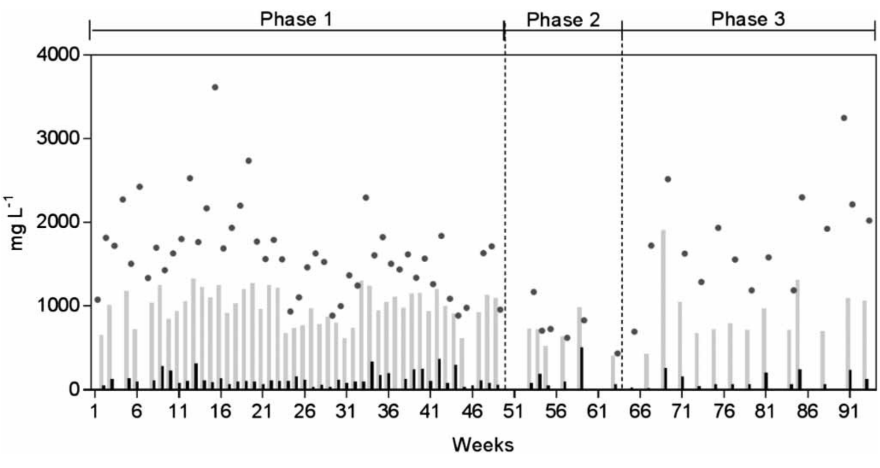

Figure 4 | Total solids (TS) in the influent (●) and effluent (■), and total suspended solids (TSS) in the effluent (■).

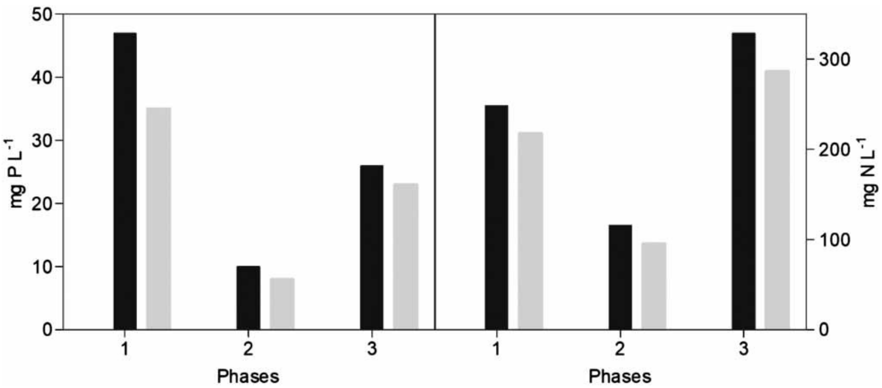

Figure 5 | Average values of nutrients in the influent (■) and effluent (■) in the UASB reactor.

Table 3 | Removal of indicator microorganisms by the UASB reactor during Phase 3 (mean values and standard deviation)

Microorganism	Influent	Effluent	Log inactivation
E. coli (CFU/100 mL)	$1.87 \times 10^7 \pm 2.23 \times 10^7$	$2.03 \times 10^5 \pm 1.42 \times 10^5$	1.96
Total coliform (CFU/100 mL)	$1.40 \times 10^8 \pm 3.00 \times 10^6$	$1.03 \times 10^6 \pm 9.87 \times 10^5$	2.13

as expected, but not sufficient for safe reuse. This higher removal can be attributed to the long HRT (3 days).

Therefore in the case of not choosing to recover the nutrients in the liquid, but rather to directly reuse them in agriculture, it is necessary to add a disinfection step to ensure safety in use. The same behavior was observed by Kujawa-Roeleveld *et al.* (2005) when treating vacuum-collected BW in a UASB reactor: the effluent still did not comply with the standard for unrestricted irrigation (WHO 1989), and, from this point of view, an additional treatment is needed.

Santos & Daniel (2017) and WHO (1989) also recommend analyzing the effluent for protozoa, such as helminth eggs (HE). Yaya-Beas *et al.* (2015) show the positive effect of a decreased upflow velocity on the removal of HE in the sludge bed. In addition, the infecting dose of protozoa is extremely small (1–10 individuals), and their cysts are highly resistant to environmental conditions.

CONCLUSIONS

Anaerobic treatment of concentrated BW in a UASB reactor was successfully achieved at an HRT of 3 days. The UASB reactor is able to withstand large variations of organic load in a continuous operation mode, maintaining a relatively stable organic matter removal, as demonstrated by the COD and BOD removals. However, the effluent of the UASB reactor needs further treatment to remove and/or recover nutrients such as nitrogen and phosphorus, as well as a specific disinfection step to ensure safety in use.

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