A downflow hanging sponge (DHS) reactor for faecal coliform removal from an upflow anaerobic sludge blanket (UASB) effluent

Rosa Elena Yaya Beas, Katarzyna Kujawa-Roeleveld, Jules B. van Lier and Grietje Zeeman

ABSTRACT

This research was conducted to study the faecal coliforms removal capacity of downflow hanging sponge (DHS) reactors as a post-treatment for an upflow anaerobic sludge blanket (UASB) reactor. Three long-term continuous laboratory-scale DHS reactors, i.e. a reactor with cube type sponges without recirculation, a similar one with recirculation and a reactor with curtain type sponges, were studied. The porosities of the applied medium were 91%, 87% and 47% respectively. The organic loading rates were 0.86 kgCOD m^{-3} d^{-1}, 0.53 kgCOD m^{-3} d^{-1} and 0.24 kgCOD m^{-3} d^{-1} correspondingly at hydraulic loading rates of 1.92 m^3 m^{-2} d^{-1}, 2.97 m^3 m^{-2} d^{-1} and 1.32 m^3 m^{-2} d^{-1}, respectively (COD: chemical oxygen demand). The corresponding averages for faecal coliform removal were 99.997%, 99.919% and 92.121% respectively. The 1989 WHO guidelines standards, in terms of faecal coliform content for unrestricted irrigation (category A), was achieved with the effluent of the cube type DHS (G1) without recirculation. Restricted irrigation, category B and C, is assigned to the effluent of the cube type with recirculation and the curtain type, respectively. Particularly for organic compounds, the effluent of evaluated DHS reactors complies with USEPA standards for irrigation of so called non-food crops like pasture for milking animals, fodder, fibre, and seed crops.

Key words | biochemical oxygen demand, COD, DHS reactor, domestic wastewater, faecal coliforms, UASB

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INTRODUCTION

Proper concepts and technologies for attaining a sustainable, robust and socio-economically affordable protection of the environment need to be applied for wastewater treatment (Chernicharo *et al.* 2015). Use of treated wastewater, particularly in agriculture, is driven by the interest in increasing water availability and recycling nutrients in soils with poor fertility (van Lier & Huibers 2010). Insufficiently treated wastewater for agricultural water reuse, may create human and environmental health risks especially when water reuse is becoming a more practised activity as a result of water scarcity (van Lier & Huibers 2010). Health constraints become critical in developing countries, where helminth infections are endemic (WHO 2006). Thus, the monitoring of waterborne pathogens indicators are crucial when treated wastewater is used for agricultural irrigation. Waterborne coliforms, which are generally detected in higher concentrations than pathogenic bacteria, are used as a critical indicator for the potential presence of entero-pathogens in water (von Sperling *et al.* 2005; Uemura & Harada 2010).

The regulatory limits for the use of reclaimed wastewater for irrigation are best illustrated by the guidelines of the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) (WHO 1989, 2006; USEPA 2004).

The 2006 WHO guideline does not provide limits for viral pathogens, bacterial, protozoan and organic matter (WHO 2006), but contains sanitary measures for public health based on risk assessment. The 1989 WHO guideline considers the control of helminth eggs and faecal coliform

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content (WHO 1989). It distinguishes three categories of water reuse: unrestricted (A), restricted (B) and restricted localised irrigation (C) (see Table 1). The USEPA standard, differentiates three types of agricultural reuse: (1) non-commercially processed food crops (non-CPFC); (2) CPFC; and (3) non-food crops (USEPA 2004).

Standards for the two presented guidelines are given in Tables 1 and 2. The 1989 WHO guideline has been applied in Ecuador, Argentina, Brazil and Peru (Jiménez & Asano 2008). Moreover, most developing countries prefer to use the 1989 WHO guideline and USEPA because of their financial constraints to perform requested analysis and assessments in the new WHO (2006) guideline (Angelakis *et al.* 1999; Jiménez & Asano 2008).

Within wastewater treatment, anaerobic treatment offers advantages over other conventional processes, such as the activated sludge process for biochemical oxygen demand (BOD_5) removal. These advantages include lower energy consumption, lower excess sludge production and simple operation and maintenance (van Lier *et al.* 2010; Chernicharo *et al.* 2015). Among the anaerobic reactors, the upflow anaerobic sludge blanket (UASB) reactor has been found most suitable for domestic wastewater treatment because of its simplicity in construction and compactness. In addition, it requires neither mechanical mixing nor effluent recirculation (von Sperling *et al.* 2005). UASB reactors alone are, however, not able to meet the wastewater reuse standards particularly when treated effluents are used for agricultural purposes (Chong *et al.* 2012; Chernicharo *et al.* 2015). The limitation of UASB reactors regarding the agricultural use of treated wastewater is expressed mainly by an insufficient or negligible faecal coliforms removal (van Lier *et al.* 2010; Chernicharo *et al.* 2015). Furthermore, the helminth eggs concentration usually exceeds 1 egg L^{-1} in the effluent (von Sperling *et al.* 2005). Consequently, the effluent does not comply with the WHO and USEPA guidelines for the use of treated wastewater in irrigated agriculture with exposure to workers and public.

In order to polish the UASB reactors effluent, several low-cost aerobic technologies based on suspended or attached growth systems without power consumption for aeration, are proposed in the literature (Agrawal *et al.* 1997; Machdar *et al.* 1997; Tandukar *et al.* 2005; von Sperling *et al.* 2005). The proposed technologies are the downflow hanging sponge (DHS) reactor, conventional trickling filter, subsurface flow constructed wetlands, rotating biological contactors, and polishing ponds.

The combined UASB-DHS reactor can remove faecal coliforms between 79.0 and 99.98% (Tandukar *et al.* 2005; Tawfik *et al.* 2006a; Tandukar *et al.* 2007; Uemura & Harada 2010; Onodera *et al.* 2014). DHS reactors are characterised by little material and energy requirement, whereas systems are very compact, having a hydraulic retention time (HRT) of less than 3 hours (Agrawal *et al.* 1997; Mahmoud *et al.* 2011). Another advantage is that the DHS reactor only requires little maintenance, since clogging of filter media does not occur. The latter is attributed to the prevailing hydraulic shear stress that dislodges parts of the attached material when growth reaches a saturated level (von Sperling *et al.* 2005). Subsequently, the excess sludge should be removed by sedimentation.

Within the DHS reactor, the influent percolates down through the sponge medium. During passage, the water gets almost saturated with oxygen without the need of mechanical aeration. Originally the DHS reactor was constructed by using cube-shaped polyurethane foam sponges that hang

Table 1 | WHO microbiological quality guidelines (1989) for water use in agriculture

Category	Reuse conditions[a]	Exposed group	Helminth eggs indicator[b] (egg L^{-1})	Faecal coliforms indicator[c] (in number per 100 mL)
A	Unrestricted irrigation: crops to be eaten uncooked, sport fields, public parks[d]	Workers, consumers, public	≤ 1	$\leq$1000
B	Restricted irrigation. Cereal, industrial fodder crops, pasture or trees[e]	Workers	≤ 1	Not standard recommended
C	Restricted irrigation: localised irrigation of crops in category B, if exposure of workers and the public does not occur	None	Not applicable	Not applicable

[a]In specific cases, local, epidemiological, sociocultural and environmental factors should be taken into account and guidelines modified accordingly.
[b]Arithmetic mean for *Ascaris* and *Trichuris* species and hookworms.
[c]Geometric mean during the irrigation period.
[d]A more stringent guideline limit ($\leq$ 200 faecal coliforms/100 mL) is appropriated for public lawns, with which the public may come into direct contact.
[e]In the case of fruit trees, irrigation should cease 2 weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

Table 2 | USEPA (2004) standard for water use in agriculture

		Reclaimed water quality	
Type	**Agricultural reuse**	**Physicochemical indicators**	**Faecal coliform indicator (number per 100 mL)[b]**
1	Not CPFC[a]: surface or spray irrigation of any food crop including crops eaten raw	pH = 6–9 $BOD_5 \leq 10$ mg L^{-1} Turbidity ≤ 2 NTU Cl2 residual ≥ 1 mg L^{-1}	No detectable
2	CPFC: surface irrigation of orchards and vineyards	pH = 6–9 $BOD_5 \leq 30$ mg L^{-1} TSS ≤ 30 mg L^{-1} Cl_2 residual ≥ 1 mg L^{-1}	≤ 200
3	Non-food crops: pasture for milking animals, fodder, fibre and seed crops	pH = 6–9 $BOD_5 \leq 30$ mg L^{-1} TSS ≤ 30 mg L^{-1} Cl_2 residual ≥ 1 mg L^{-1}	≤ 200

TSS: total suspended solids.
[a]Commercially processed food crops (CPFC) are those that, prior to sale to the public or others, have undergone chemical or physical processing sufficient to destroy pathogens.
[b]Either the membrane filter or fermentation-tube technique may be used.

freely in the air (Machdar *et al.* 2000). Due to its high porosity, polyurethane sponges could retain significantly more biomass in a DHS reactor compared to the biomass hold-up in a traditional trickling filter system. The retained biomass in the DHS consists of a wide range of microbial organisms, whose composition depends on wastewater characteristics and environmental conditions (Mahmoud *et al.* 2011). The active immobilised biomass consumes organic compounds and nutrients from the wastewater for their metabolism utilising the dissolved oxygen (DO) (Mahmoud *et al.* 2011). The most important features of DHS reactors are the natural aeration by convective flows only, the short HRT, and the very long sludge retention time (SRT) (Tawfik *et al.* 2010). The mechanisms for faecal coliforms and pathogenic bacteria reduction in the DHS reactors are different than those for organics removal; adsorption to biomass and/or predation by higher organisms might play a role (Tawfik *et al.* 2006a).

The DHS reactor was developed in six different configurations, named generations (G1–G6), to test the practical applicability. The generations differ in orientation and distribution of the sponges inside the DHS reactor and, therefore, in practical applicability and dead zone volume.

Results of previous research (Tandukar *et al.* 2005; Tawfik *et al.* 2006b; Tandukar *et al.* 2007) demonstrated that DHS reactors type G3, G4, G5 and G6 remove between 79.032 and 99.693% faecal coliforms at an HRT between 2 and 2.7 hours. The capacity to remove faecal coliforms of DHS reactor type G1 and G2 was not studied. The G1 and G2 type has however shown their simplicity in terms of construction (Agrawal *et al.* 1997; Machdar *et al.* 1997; Machdar *et al.* 2000). Basically, investment, operation and maintenance costs and simplicity are the most important criteria when selecting a technology in developing countries (von Sperling *et al.* 2005). Therefore, the aim of the present research was to define the capacity of DHS reactors (G1 and G2) for removing faecal coliforms from domestic UASB reactor effluent for agricultural reuse in developing countries.

MATERIALS AND METHODS

Influent wastewater

The research was carried out using wastewater from two urban villages called El Angel and El Milagro located in Lima (Peru). This wastewater was fed into a pilot plant located at the Research Centre for Wastewater Treatment and Hazardous Wastes (CITRAR) at the campus of the National University of Engineering (Lima, Peru). The effluent from a 536 m^3 pilot-scale UASB reactor located at CITRAR was used as influent wastewater for the constructed DHS reactors. The main characteristics of the wastewater fed into the DHS reactors are shown in Table 3.

The wastewater was daily pumped into three 200 L independently stirred tanks (18 rpm) and from there, transported by gravity to each DHS reactor.

Table 3 | Effluent wastewater characteristics of the 536 m3 UASB reactor located at CITRAR

Parameter	Units	Average	n^a
Total coliforms	MPN·100 mL^{-1}	$2.6 \times 10^8 \pm 2.9 \times 10^8$	10
Faecal coliforms	CFU·100 mL^{-1}	$3.4 \times 10^7 \pm 9.8 \times 10^7$	45
Dissolved oxygen (DO)	mg L^{-1}	0.7 ± 0.7	160
Biochemical oxygen demand (BOD_5)	mg L^{-1}	102 ± 44.2	42
Total chemical oxygen demand (total COD)	mg L^{-1}	227.1 ± 103.1	67
Soluble chemical oxygen demand (soluble COD)	mg L^{-1}	128.9 ± 52.9	40
Turbidity	NTU	133.1 ± 82.2	638
Temperature	°C	20.9 ± 5.1	640
pH		7.4 ± 1.2	636

[a]*n*: number of grab analysed samples.

DHS reactors

Two types of DHS reactors were applied: the cube type without (G1) and with recirculation (G1), and the curtain type (G2). Different types of polyurethane sponges were used as biomass carrier media and the densities of the sponges were 18 kg m^{-3}, 12 kg m^{-3} and 20 kg m^{-3}, according to manufacturer specifications, respectively for each reactor. The sponge porosities were determined according to the water saturation method performed by Chen *et al.* (2004) with the difference that a volume of sponge (Vol) was immersed in a known volume of distilled water (V) under vacuum for 5 hours. The saturated sponge was removed, and then the remaining volume was measured (V−Vv). The porosity (*n*) was calculated by dividing the volume of pores (Vv) by the corresponding volume of the sponge (Vol). The measurement was repeated five times. The sponges were cut in small pieces as will be described for each type of reactor.

Three experiments were executed. For experiment 1, two identical cube type (G1) DHS systems were constructed and operated in parallel; each one was composed of two modules in series (01 and 02) as shown in Figure 1. Each module was made of acrylic with a total height of 0.29 m and a diameter of 0.09 m. Each module contained five columns of cube type sponges. Each column comprised six sponge cubes (Figure 1).

For experiment 2, one cube type (G1) DHS reactor, composed of two modules in series (01 and 02) was built as is indicated in Figure 1. Each module was made of glass with a total height of 0.55 m and a diameter of 0.115 m. Each module contained 12 columns of cube type sponges and each column comprised 12 sponge cubes. The side of each cube, and distance between each sponge cube were respectively, 0.030 m and 0.005 m for experiment 1, while for experiment 2 these measurements were correspondingly 0.025 m and 0.005 m. In order to allow natural aeration, the distances between module 01 and 02 were 0.10 m and 0.15 m respectively, for experiment 1 and 2. DHS reactors were operated from 6 July 2009 to 30 June 2010 for experiment 1, and from 1 July 2011 to 2 March 2012 for experiment 2.

For experiment 3 one curtain type (G2) DHS reactor, composed of two modules in series (01 and 02) was built as indicated in Figure 1. Each module consisted of one acrylic vessel containing 10 sponge rectangular parallelepipeds (sponge-columns) whose sides were 0.50 m, 0.050 m and 0.038 m for height, length and width, respectively. Each vessel had a total length of 0.59 and a height of 0.74 m. The width of the vessel was 0.09 m. The horizontal distance between each sponge strip inside each vessel was 0.002 m. A funnel was placed at the end of each sponge, to allow proper conduction of the effluent from module 01 to module 02. In order to allow natural aeration, the vertical separation between module 01 and 02 was 0.010 m. No recirculation was applied in this experiment. The DHS reactor in experiment 3 was operated from 2 April 2011 to 30 October 2011. In order to retain possibly produced sludge, in all experiments, a settler was included after the DHS reactor. The settler was cleaned every week. The volume of the settler was 0.5 L, 2.6 L and 3.6 L for experiments 1, 2 and 3 respectively.

Operational conditions

Feeding of DHS reactors was obtained by using equal distribution of influent wastewater over the sponges via the influent inlet (Figure 1). Flow distributors were calibrated three times a day in all experiments in order to guarantee the established flow indicated in Table 5. The flow

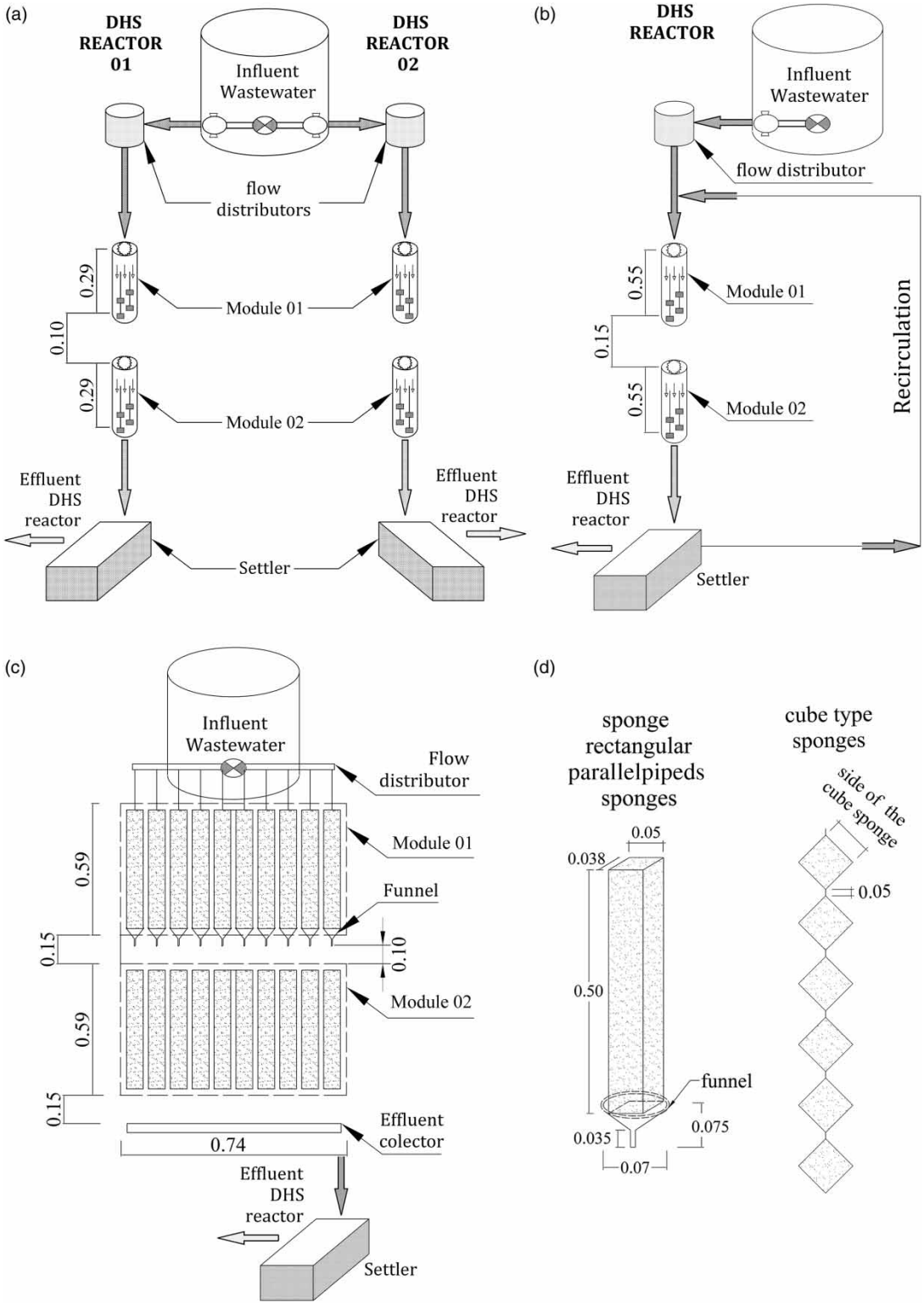

Figure 1 | Set up of experiments in the laboratory-scale DHS reactors as a post-treatment for a UASB reactor effluent with special emphasis on faecal coliforms removal: (a) experiment 1 using two cube-type DHS (G1) reactors; (b) experiment 2 using one cube-type DHS reactor (G1) with recirculation; (c) experiment 3 using one laboratory-scale curtain type DHS (G2) reactor; (d) details of sponge-columns.

distributors were replaced by new and clean ones every 2 weeks. No inoculation was applied in any of the reactors.

The influent flows were 12.2 L d^{-1} for experiment 1, and 30.9 L d^{-1} for experiment 2. Only for experiment 2, a recirculation was introduced from the settler back to the first module. Recirculation of settled wastewater was applied in order to guarantee (i) a homogeneous hydraulic load, (ii) an increase of dissolved oxygen in the influent through the contact of the effluent, and (iii) probably less dead zones than reactors without recirculation (von Sperling *et al.* 2005). The recirculation (R) flow of 30.9 L d^{-1} was equal to the influent flow (Figure 1). The recirculation flow was calibrated three times a day. For experiment 3, the flow was 86.4 L d^{-1} and 10 pipes were installed in order to equally divide the wastewater over the whole sponge area.

The end of the start-up period was considered to be achieved when a stable turbidity content was reached, which was 30 ± 24, 17 ± 8 and 19 ± 2 NTU for experiments 1, 2 and 3, respectively, in the previous 10 weeks. In order to research the performance of the three DHS reactors, grab samples of 1 L were taken from each experiment after 90 days, 70 days and 57 days of the start-up of the reactors, respectively. The sampling frequency was determined based on the laboratory facilities and is indicated in Table 4.

Experiments 1, 2 and 3 were performed during 269 days, 175 days and 154 days respectively after the end of the start-up period. The experimental duration was influenced by the availability of laboratory facilities. Faecal coliform content was selected as the main microbiological quality indicator. BOD_5 and chemical oxygen demand (COD) were selected as physicochemical quality indicators for organic compounds.

The effluent quality in terms of faecal coliform content of the evaluated reactors was then compared with the WHO (1989) standards. Regarding BOD_5 content, turbidity and pH, the effluent quality was compared to USEPA standards since the 1989 WHO guideline does not include these parameters. A summary of the main operational conditions for each DHS experiment is given in Table 5.

Table 4 | Frequency of sampling and performed analysis for the three experiments. The pH and temperature was analysed daily

Parameter	Experiment 1	Experiment 2	Experiment 3
DO	twice a week	twice a week	daily
Turbidity	daily	daily	once a week
BOD_5	every 3 weeks	every 4 weeks	BOD_5
COD total	COD total	every 2 weeks	COD total
COD soluble	COD soluble	COD soluble	COD soluble
Faecal coliforms	Faecal coliforms	Faecal coliforms	Faecal coliforms

Physicochemical and bacteriological analysis

Total and faecal coliforms, COD, BOD_5, and DO analysis were determined following *Standard Methods* (APHA 2005). Faecal coliforms were measured by the membrane filtration technique using m-FC agar base as the medium. The agar was prepared in accordance with manufacturer specifications (Criterion, Hardy Diagnostics, Santa Maria, CA). The mixture of agar and appropriately diluted wastewater sample on the petri dishes was uniformly spread to avoid trapping air bubbles. The cultured Petri dishes were inverted and incubated at 44.5 °C for 24 hours. The produced colonies by faecal coliforms were then counted and reported in colony forming units per 100 mL (CFU·100 mL^{-1}) of wastewater sample having a level of detection of 1 CFU·100 mL^{-1}. Total COD was determined from unfiltered samples. Soluble COD was measured after filtering the sample through a 0.45 μm Millipore membrane filter. COD analysis was executed using high range Hach COD digestion vials high range (20–1500 mg L^{-1}) and low range (0–150 mg L^{-1}) as well as a digester reactor DR 200, and programme 17 from colorimeter DR 890. Nephelometric and electrometric method were applied for turbidity and DO determination. BOD_5 was determined as a difference of DO content at the beginning of the experiment and after 5 days of incubation at 20 °C (bottle method). The pH and temperature were measured with a Hach HQ411d laboratory meter.

RESULTS AND DISCUSSION

The water saturation method showed that the porosities of sponges were 91 ± 0.5%, 87 ± 0.25% and 47 ± 0.45% respectively for experiments 1, 2 and 3. Effluent faecal coliform content was approximately 100 smaller when operating the cube type DHS reactor without recirculation ($2.1 \times 10^2 \pm 4.1 \times 10^2$ vs $3.4 \times 10^4 \pm 5.1 \times 10^4$). However, the mean BOD_5 content was reduced from 19 to 6 mg L^{-1} by using recirculation for the cube-type DHS reactor. Soluble COD also decreased from 62 to 47 mg L^{-1}. A total COD, soluble COD and BOD_5 removal of respectively 67.2 ± 3.1%, 53.5 ± 1.1% and 80.9 ± 2.0% was achieved for experiment 1. Somewhat, higher removal efficiencies were accomplished in experiment 2: 74.6% ± 8.2, 71.1% ± 10.6 and 93.6 ± 3.4% for total COD, soluble COD and BOD_5, correspondingly. The removal of total COD, soluble COD

Table 5 | Main operating characteristics of the DHS reactors

Experiment[a]	Units	1	2	3
Reactors				
DHS type		cubes	cubes with recirculation	curtain
Generation		G1	G1	G2
Flow	$L\ d^{-1}$	12.2	30.9	86.4
R[b]		0	1	0
Surface area[c]	m^2	0.0064	0.0104	0.0657
DHS volume[d]	m^3	0.0037	0.0114	0.0775
HRT[e]	h	2.90	1.52	2.49
HLR[f]	$m^3\ m^{-2}\ d^{-1}$	1.92	2.97	1.32
OLR[g]	$kgCOD\ m^{-3}\ d^{-1}$	0.86	0.53	0.24
Settler				
HRT	h	1	2	1
Volume	m^3	0.0005	0.0026	0.0036
Data of the medium				
Total volume of the medium	m^3	0.0016	0.0023	0.0191
OLRm[h]	$kgCOD\ m^{-3}\ d^{-1}$	1.96	2.69	0.97

[a]Experiment: number of the experiment.
[b]R: recirculation factor expressed as the relation Q_r/Q_i, where Q_r and Q_i are the recirculation and influent flow respectively.
[c]Surface area of the reactor: it corresponds to the surface area of module 01 and is also equal to the cross sectional area of the acrylic modules.
[d]DHS volume: DHS reactor volume which corresponds to the volume of module 01 plus module 02 excluding the separation between modules.
[e]HRT: hydraulic retention time of the reactor which implies the HRT of module 01 plus module 2. Both modules have the same HRT.
[f]HLR: hydraulic surface loading rate of the reactor, based on the flow rate over the surface area of the reactor.
[g]OLR: organic loading rate, based on the average COD mass flow over DHS volume.
[h]OLRm: medium organic loading rate, based on the flow rate, average COD and total volume of the medium.

and BOD_5 for experiment 3 was respectively $68.8 \pm 8.2\%$, $84.9 \pm 5.3\%$ and $84.9 \pm 5.3\%$. A summary of the results for all experiments, after the start-up period, is presented in Table 6.

The DHS reactor capacity for removing faecal coliforms

The main emphasis of this research was to study the removal efficiency of three types of DHS systems for faecal coliforms. The pathogenic indicator, faecal coliforms, showed a significant reduction in all experiments and the best results were obtained for the cube type DHS reactor. The highest faecal coliforms reduction of $99.997 \pm 0.000\%$ was obtained in experiment 1. A lower removal efficiency of $99.919 \pm 0.117\%$ was achieved in experiment 2. Experiment 3 showed the lowest faecal coliforms reduction, with a value of $92.121 \pm 6.210\%$.

Despite the relatively long HRT of 2.49 hours, the curtain type DHS reactor showed the lowest average faecal coliform removal (1.25 $\log_{10}$) compared with that in the cube type configuration with (3.42 $\log_{10}$) and without recirculation (4.74 $\log_{10}$). This significantly lower removal efficiency could be associated with a much lower porosity and possible occurrence of dead zones and short circuiting compared with experiments 1 and 2. The latter might be attributed to the experimental set-up and must be further investigated. Results indicate that it is necessary to analyse the flow distribution in the studied DHS reactors. The porosity of the medium characterises the available adsorption sites of the carrier material as previously reported (Tawfik *et al.* 2010; Tawfik *et al.* 2011). A low porosity implies low biomass adsorption. It also implies low substrate conversion rates because of the non-optimised contact between wastewater pollutants and the low amount of biomass. Consequently, a low porosity will lead to a low biomass yield and low substrate conversion capacity. The sponge porosity may affect the type of biomass, the permissible hydraulic loading rate and the degree of clogging of the surface area of the carrier material. Clogging of the sponge surface area could result in dead zones during the filtration

Table 6 | Experimental results obtained using DHS reactors

Parameter	Units	n[a]	Influent	Effluent[b]	Efficiency	
A. Experiment 1: cube type DHS reactor without recirculation						
Temperature	°C	266	20.9 ± 2.3	20.5 ± 3.1		
pH		266	7.4 ± 0.3	7.7 ± 0.4		
DO	mg L^{-1}	134	0.8 ± 0.7	5.6 ± 1		
Turbidity	NTU	266	145.3 ± 50.1	47.1 ± 35.3	67.2 ± 1%	
BOD_5	mg L^{-1}	12	104.4 ± 13.7	19.5 ± 6.5	80.9 ± 2%	
COD total	mg L^{-1}	26	260.8 ± 77.7	85.9 ± 62.6	67.2 ± 3.1%	
COD soluble	mg L^{-1}	26	133.3 ± 31.5	62 ± 38.1	53.5 ± 1.1%	
Faecal coliforms	CFU·100 mL	10	$6.1\times10^6 \pm 3.4\times10^6$	$2.1\times10^2 \pm 4.1\times10^2$	99.997 ± 0.000%	
Parameter	**Units**	**n**	**Influent**	**Effluent 1[c]**	**Effluent 2[d]**	**Efficiency**
B. Experiment 2: cube type DHS reactor with recirculation						
Temperature	°C	130	23.3 ± 4.3	23.4 ± 4.3	23.2 ± 4.2	
pH		126	7.6 ± 0.3	7.7 ± 0.3	7.5 ± 0.5	
DO	mg L^{-1}	26	0.4 ± 0.3	5.9 ± 1.1	6.1 ± 0.9	
Turbidity	NTU	9	144.1 ± 63.7	26.1 ± 17.9	10.3 ± 4.7	92 ± 4.3%
BOD_5	mg L^{-1}	8	107.4 ± 39.1	20.4 ± 5.2	6.2 ± 2.8	93.6 ± 3.4%
Total COD	mg L^{-1}	19	196.2 ± 51.3	68.8 ± 33.8	47.3 ± 15.2	74.6 ± 8.2%
Soluble COD	mg L^{-1}	12	113.2 ± 25.8	43 ± 7.9	31.4 ± 9.3	71.1 ± 10.6%
Faecal coliforms	CFU·100 mL	11	$1.1\times10^8 \pm 2\times10^8$	$5\times10^6 \pm 3.1\times10^6$	$3.4\times10^4 \pm 5.1\times10^4$	99.919 ± 0.117%
Parameter	**Units**	**n**	**Influent**	**Effluent 1[c]**	**Effluent 2[d]**	**Efficiency**
C. Experiment 3: curtain type DHS reactor						
Temperature	°C	154	18.8 ± 1.4	18.9 ± 1.2	18.9 ± 1.1	
pH		154	7.3 ± 1.1	7.5 ± 0.4	6.6 ± 0.5	
DO	mg L^{-1}	154	2.3 ± 0.4	4.2 ± 0.7	4.9 ± 0.7	
Turbidity	NTU	154	104.1 ± 13.8	30.8 ± 12.3	18.9 ± 4.8	81.8 ± 4.4%
BOD_5	mg L^{-1}	22	98.8 ± 15.5	23.4 ± 5.3	14.9 ± 5.8	84.9 ± 5.3%
Total COD	mg L^{-1}	22	214.1 ± 44.2	N. M.[e]	77.6 ± 18.6	62.8 ± 9.9%
Soluble COD	mg L^{-1}	22	136.2 ± 33.7	N. M.	59.3 ± 14.1	55 ± 10.9%
Faecal coliforms	CFU·100 mL^{-1}	22	$7.2\times10^6 \pm 5.6\times10^6$	$1.7\times10^6 \pm 1.7\times10^6$	$5.9\times10^5 \pm 7.5\times10^5$	92.121 ± 6.210%

[a]*n* means number of grab samples.
[b]Results show the average values for the effluent of the two DHS reactors.
[c]Results show the average values for the effluent after the module 01.
[d]Results correspond to the effluent of the DHS reactor.
[e]N.M. means not measured.

process since no biomass will grow in the sponge interior areas (Tawfik *et al.* 2011).

A significant difference in faecal coliforms removal is shown between the cube type DHS reactors without recirculation among experiments 2 and 3. The best performance in experiment 1 could be ascribed to the longer HRT in the cube type DHS reactor compared with the other two experiments (Figure 2).

The compliance with water reuse guidelines

Following the 1989 WHO guideline, the effluent with a faecal coliform content of 2.1×10^2 CFU·100 mL^{-1}, produced in experiment 1 can be used for unrestricted irrigation (category A). For restricted irrigation, category B and C is assigned to the effluent of experiment 2 with a faecal coliform content of $3.4\times10^4 \pm 5.1\times10^4$ CFU·100 mL^{-1} and the effluent of

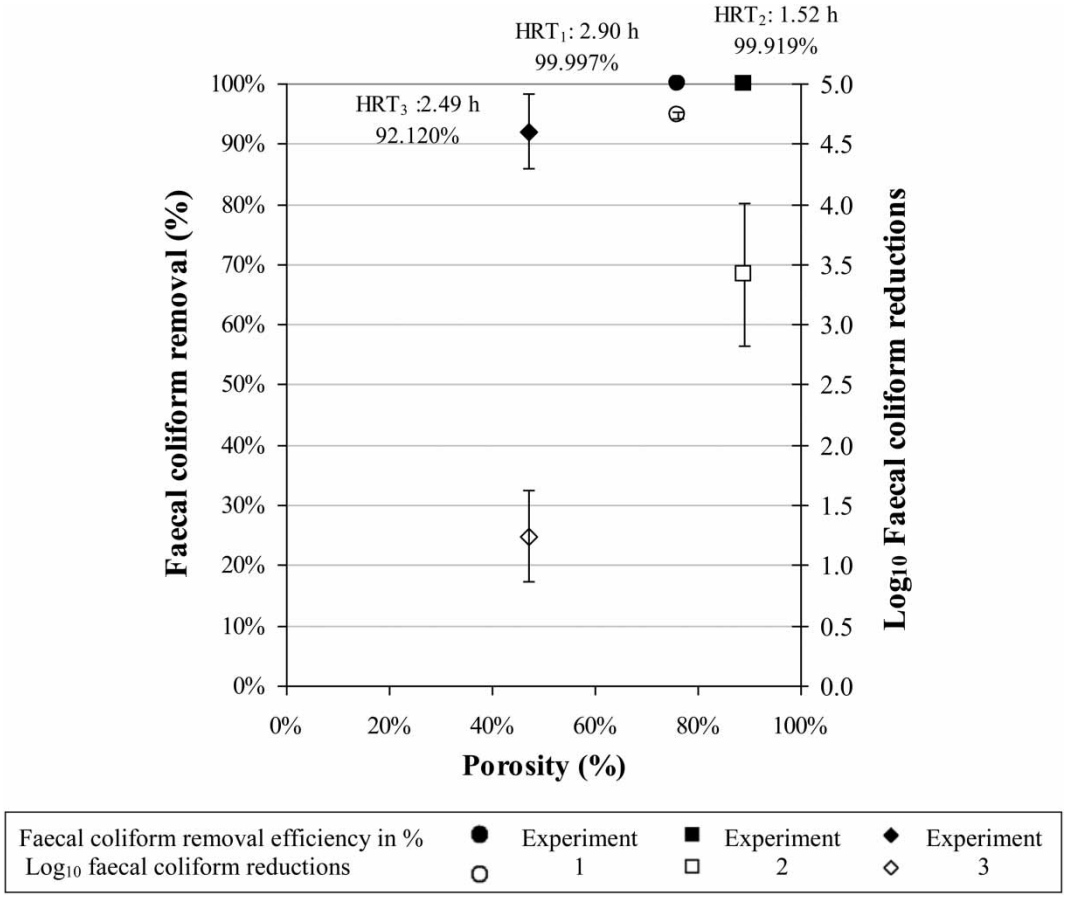

Figure 2 | Faecal coliform removal expressed in terms of percentage and $\log_{10}$ reductions versus porosity. Log_{10} reductions were determined by dividing faecal coliform content in the influent between faecal coliform in the effluent.

experiment 3 with a faecal coliform content of $5.9 \times 10^5 \pm 7.5 \times 10^5$ CFU·100 mL^{-1}, respectively.

Average BOD_5 content in the effluent of the evaluated DHS reactors, varied between 6.2 and 19.5 mg L^{-1}, which is lower than the USEPA standard of 30 mg L^{-1} for treated effluents applied for CPFC and non-food crops (types 2 and 3). The average pH variation between 6.6 and 7.7, complies with USEPA standards for each type of agricultural use. Average turbidity variation between 10.3 and 47.1 NTU in all evaluated DHS reactors, exceeds significantly the limit of 2 NTU for irrigation of food crops (type 1). Therefore, in terms of BOD_5, turbidity and pH, the effluents meet the USEPA standard for agricultural reuse, type 2 and 3.

The performance of DHS reactors with respect to organic matter removal

Generally, the DHS is a good polishing step in terms of total COD, soluble COD and BOD_5 removal. No significant differences were found regarding total and soluble COD removal between the three experiments. The average BOD_5 of 80.9 to 93.6% and total COD removal efficiency of 67.2 to 74.6%, observed in the DHS G1 reactors were in close proximity to the results of Agrawal *et al.* (1997) and Machdar *et al.* (1997). The latter were 97% and 78% for the BOD_5 and total COD removal efficiency, respectively. The total COD removal efficiency of 62.8%, obtained in DHS G2 reactor was similar to the 59% reported by Machdar *et al.* (2000).

The turbidity, a measure for the suspended solids content, was reduced by 67.2 ± 1%, 92.0% ± 4.3% and 81.8% ± 4.4% in experiments 1, 2 and 3, respectively. Results illustrate a significant increase in average DO in the effluent of the DHS reactors: 0.8–5.6 mg L^{-1}, 0.4–6.1 mg L^{-1} and 2.3–4.9 mg L^{-1} for experiments 1, 2 and 3, respectively (see Table 6). The latter can be attributed to convective flow natural aeration.

The lowest BOD_5 and turbidity removal was obtained in experiment 1. BOD_5 removal in experiment 2 was 12.7%

higher compared with the value obtained in experiment 1. BOD_5 removal in experiment 2 was slightly higher than for experiment 3. The highest BOD_5 removal efficiency was observed in experiment 2, which could be attributed to the recirculation of the settled wastewater. Recirculation enhances the contact between organic mater and microorganisms present in the biofilm (von Sperling *et al.* 2005). Additionally, turbidity removal in experiment 2 was higher than that in experiment 3, with a significant difference of 10% (see Table 6). No correlation was found between BOD_5 and faecal coliform removal.

The pH in the effluent of experiment 2 is slightly lower compared to the pH of the influent. This reduction could be associated with some degree of nitrification as observed in the lowest part of trickling filters when the BOD_5 concentration is near 15 mg L^{-1} (Agrawal *et al.* 1997; von Sperling *et al.* 2005).

During the experimental trials, the operation and maintenance activities of the laboratory-scale DHS reactors were relatively simple and consisted of cleaning pipelines to maintain a constant flow and to prevent clogging. Sponges remained in good condition (no visual damage observed) during the research period.

CONCLUSIONS

Cube type (G1) DHS reactors showed the best capacity for faecal coliform removal. The cube type system without recirculation complies with WHO (1989) standards for unrestricted irrigation (category A). Restricted irrigation, categories B and C, is assigned to the effluent of the cube type DHS reactor with recirculation and the curtain type DHS reactor, respectively. Regarding organic compounds, the effluent of the evaluated DHS reactors complies with USEPA standards in terms of BOD_5, pH and turbidity for irrigation of only non-food crops, like pasture for milking animals, fodder, fibre, and seed crops. Results did not show a correlation between BOD_5 removal and faecal coliform removal.

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