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EVALUATION OF AN INNOVATIVE ANAEROBIC BIOREACTOR WITH FIXED-STRUCTURED BED (ABFSB) FOR BREWERY WASTEWATER TREATMENT

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Abstract - The aim of this study was to evaluate the application of the anaerobic bioreactor with fixed-structured bed (ABFSB) for brewery wastewater treatment with high volumetric organic loading rate (VOLR) and its comparison with a traditional packed-fixed bed bioreactor. Two different biomass support materials were tested, including polyurethane (PU) and polypropylene (PP) for both configurations. The best global efficiency was reached by the structured-fixed bed reactor with polyurethane as biomass support (SB PU). For a VOLR of 14.0 kg CODt m^{-3} d^{-1} (HRT of 8 h) and 20.3 kg CODt m^{-3} d^{-1}(HRT of 12 h), the SB PU reached the average CODt removal efficiencies (E_{COD}) of 81% and 71%, respectively. The results show that ABFSB is a promising technology for high organic matter and solids concentration wastewater treatment, but the type of the biomass support had a big impact on the reactors performance.
Keywords: Brewery wastewater; Fixed-bed reactor; Packed bed; Structured bed; Anaerobic reactor.

INTRODUCTION

Due to its high popularity, beer has an important place in the worldwide economy, being the fifth drink most consumed in the world after tea, soft drinks, milk and coffee (Fillaudeau *et al*., 2006). As a result of the large production, the brewery industry demands high volumes of water and generates large amounts of wastewater. According to Santos (2015), from 4 to 10 L of water are consumed and from 3 to 6 L of wastewater are generated to produce 1 L of beer. In addition, the brewery wastewater has high concentrations of organic matter and suspended solids; therefore, it has a high potential for environmental pollution (Simate *et al*., 2011).

Much research was carried out to evaluate anaerobic reactor performance for brewery wastewater treatment (Alvarado-Lassman *et al*., 2008; Öktem & Tüfekçi, 2006; Parawira *et al*., 2005; Xiangwen *et al*., 2008). The results showed that brewery wastewater can be treated efficiently by anaerobic processes and has a high potential for biogas production. Suspended (or granular) anaerobic biomass processes, mainly up-flow anaerobic sludge blanked reactors (UASB), have been the most used technologies to treat brewery wastewater. In spite of its simple con-

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figuration and satisfactory efficiency, UASB reactors demand high hydraulic retention times (over 24 h) and low up-flow velocities (up to 0.7 m h^{-1}). As a result, the reactors become big and need large area to be constructed.

On the other hand, satisfactory removal efficiencies of organic matter, employing high volumetric organic loading rates (VOLR) and low HRT, can be achieved in fixed bed reactors. Generally, high concentration of biomass and long cellular retention time are reached by fixed bed reactors (Zaiat *et al.*, 1997). However, the traditional configurations of packed bed reactors are not recommended for wastewater with medium to high solid contents, since hydrodynamic problems, such as channelling and dead zones, can lead to low efficiencies and even to collapse by clogging of the reactor. To overcome this problem, Camiloti *et al.* (2014) proposed an innovative configuration of an anaerobic bioreactor with fixed-structured bed (ABFSB) in which the bed is not randomly packed, thus avoiding accumulation of solids in the interstices and preventing hydrodynamic anomalies.

The ABFSB aggregates advantages of both the up-flow anaerobic sludge blanket and fixed-bed reactors, such as easy solids separation and sedimentation, high concentration of biomass and high sludge retention time. Nevertheless, the type of support material used for biofilm reactors influences their biomass adhesion and their hydrodynamics, thus affecting overall system performance. Many types of support material for fixed bed reactors have been studied in the last decade, including polyurethane foam, plastic rings (polypropylene, polyethylene and PET), plastic plates and ceramic matrix.

Polyurethane (PU) foam as a biomass support has been shown to perform well in anaerobic biofilm reactors (Araujo Junior and Zaiat, 2009; Camiloti *et al.*, 2014). PU foam makes an excellent attached-growth material because of its high surficial area for biomass adhesion and its macroporous structure, promoting a gradient of substrate concentration and electron donors, contributing to establish several anaerobic microorganisms. On the other hand, polypropylene (PP) rings have been used the most as biomass support in biofilm reactors because of their low price and good mechanical resistance.

In this context, this work considers the application of an anaerobic bioreactor with fixed-structured bed for brewery wastewater treatment with high VOLR and its comparison with a traditional packed bed bioreactor. Two different biomass support materials were tested, including polyurethane (PU) and polypropylene (PP) for both configurations.

MATERIAL AND METHODS

Four up-flow fixed bed anaerobic reactors were studied in parallel for brewery wastewater treatment. The experimental setup is shown in Figure 1 and the description of each reactor is presented in the following:

- PB PU: fixed-packed bed reactor with Biobob® (cylindrical polyurethane foam surrounded by an external frame of polypropylene with diameter of 15 mm and length of 10 mm), made in Brazil by Bio Proj Tecnologia Ambiental Ltda. The characteristics of the polyurethane foam were 95% of void ratio and 28 kg/m³ of density;
- PB PP: fixed-packed bed reactor with polypropylene rings (diameter of 17 mm, length of 12 mm and surface area of 2621 mm^2);
- SB PU: fixed-structured bed reactor with longitudinal polyurethane foam strips (7 squared strips 16 mm on a side and 265 mm of length); The characteristics of the polyurethane foam were 95% of void ratio and 28 kg/m³ of density;
- SB PP: fixed-structured bed reactor with longitudinal bar constructed of polypropylene rings (7 bars 17 mm in diameter, 265 mm in length and surface area of 57880 mm^2).
- The reactors were operated during 181 days at 35 ± 1 °C. They were fed with raw brewery wastewater with increased influent flow rate, with a nominal hydraulic retention time (HRT, estimated from the total reactor liquid volume) of 32 h, 24 h, 18 h, 12 h and 8 h, and flow rates of 0.07 L h^{-1}, 0.11 L h^{-1}, 0.15 L h^{-1}, 0.22 L h^{-1} and 0.33 L h^{-1}, respectively. Due to variation of the wastewater concentration, the volumetric organic loading rate (VOLR) did not follow the linear flow rate tendency increase and the average values were between 2.0 and 28.6 kg COD m^{-3} d^{-1}.

Before reactor start-up, the biomass supports were inoculated with a full scale UASB sludge treating poultry slaughterhouse wastewater operated at 25 °C and pH 7, with volumetric organic loading rate of 2.0 kg COD m^3 d^{-1}. For packed-fixed bed reactors, the biomass supports were submerged in a tank with UASB sludge for 24 h. After this time, the supports were introduced inside the reactors and the volume was filled with tap water and then the operation started up.

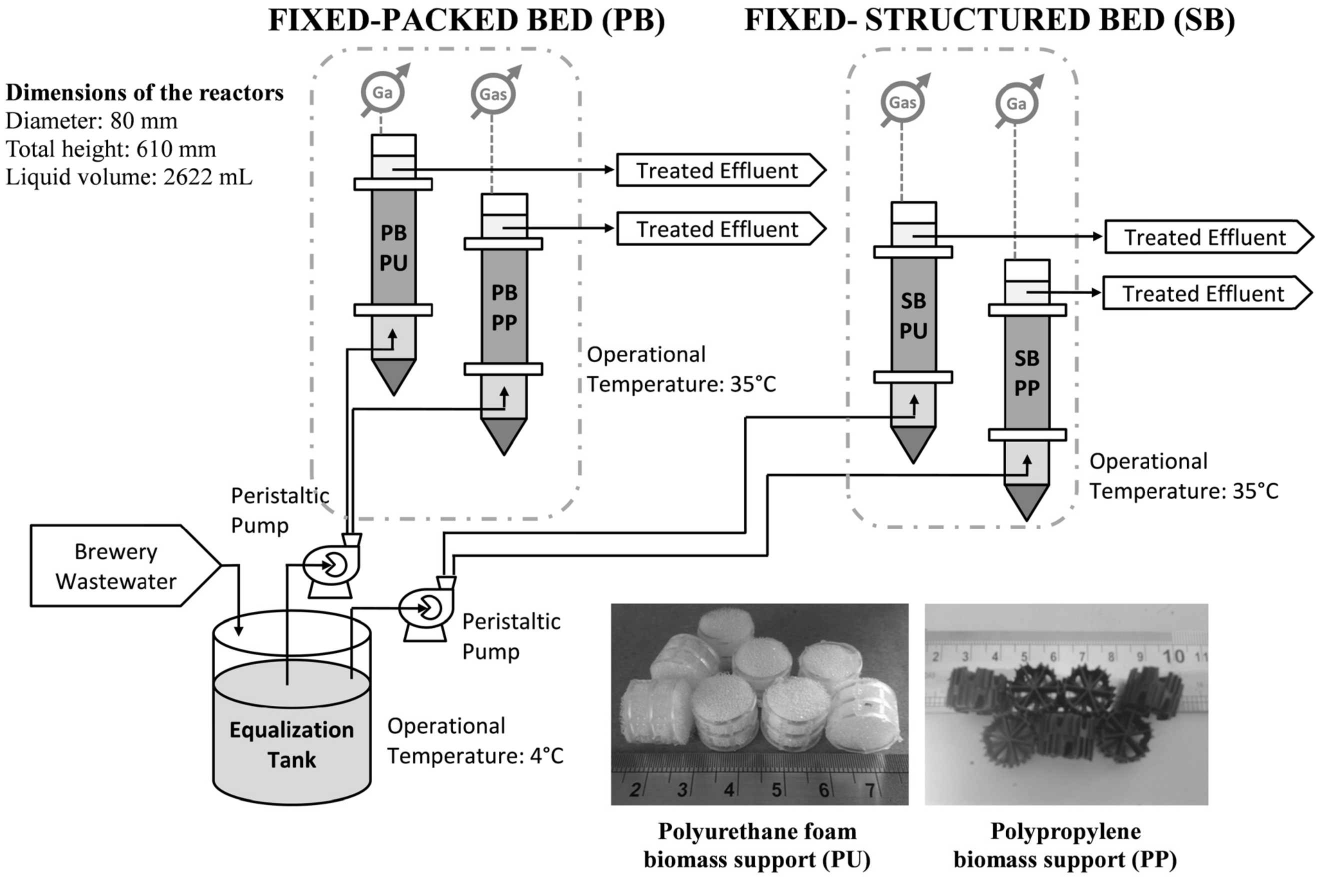

Figure 1: Experimental setup.

To inoculate the structured-fixed bed reactors, 1.0 L of the UASB sludge was introduced in the bottom of the reactors and the volume was filled with tap water, remaining at rest for 24 h and then the operation started up.

Weekly, the wastewater was taken from the brewery industry and stocked at 4 °C in a cooling tank with mechanical mixer to minimize biodegradation before feeding the reactor. To avoid acidification, the pH of the equalization tank was adjusted between 6.5 and 7.5 with sodium bicarbonate.

Samples of the influent and effluent from each reactor were taken and analyzed according to standard methods (APHA, 2012). Several monitoring parameters were evaluated during operation, including the total chemical oxygen demand (CODt), filtered chemical oxygen demand (CODf, filtered with a 1.2 μm membrane), total suspended solids (TSS), volatile suspended solids (VSS) and pH. The analyses of organic acids were performed on a Shimadzu GC-2010 (Kyoto, Japan) gas chromatograph with an HP-INNOWAX (30 m × 0.25 mm × 0.25 μm) capillary column (Agilent Technologies). The biogas flow rate in each reactor was measured by a Ritter Milligas Counter and the analyses of biogas composition were done with a Shimadzu GC-2010 (Kyoto, Japan) gas chromatograph with a thermal conductivity detector and Carboxen 1010 PLOT (30 m x 0.53 mm) column, with detection of hydrogen, carbon dioxide, nitrogen and methane.

RESULTS AND DISCUSSION

Following the real variation of the industrial wastewater CODt concentration, different hydraulic retention times (HRT) and volumetric organic loading rates (VOLR) were applied in the reactors during the operational period. Figure 2 shows the CODt in the influent and effluent of the reactors throughout the experimental time. Table 1 presents a summary of the main results for each operational step.

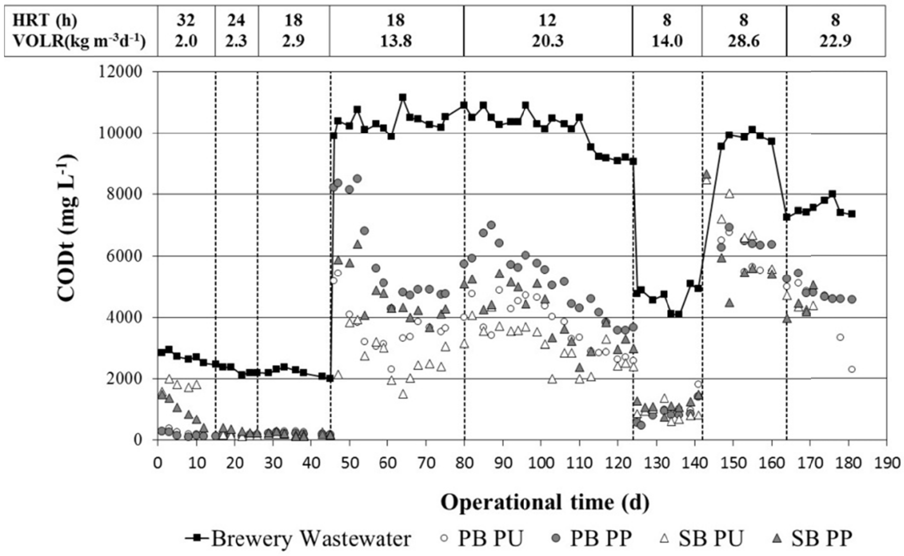

Figure 2: CODt throughout the experimental time.

Table 1: Summary of the main results for each operational step.

HRT (h)	**24**	**18**	**18**	**12**	**8**	**8**	**8**
VOLR (kg COD m^{-3} d^{-1})	**2.3**	**2.9**	**13.8**	**20.3**	**14.0**	**28.6**	**22.9**
CODt (mg L^{-1})							
Wastewater	2258±119	2201±135	10384±355	10050±623	4641±372	9475±993	7574±241
PB PU	164±31	245±38	3707±788	3703±813	988±391	5784±632	4267±1051
PB PP	141±17	204±21	5973±1574	5112±1094	836±285	6299±503	4784±303
SB PU	139±18	187±28	2709±698	3087±722	891±238	6757±1313	4330±82
SB PP	294±74	188±64	4699±819	4013±962	1139±220	5649±1504	4573±451
CODf (mg L^{-1})							
Wastewater	1650±86	1471±105	8562±410	8120±582	2733±103	6239±560	4923±160
PB PU	114±29	142±30	3230±619	3377±831	728±380	5203±707	3484±1001
PB PP	84±11	119±19	5343±1326	4733±1138	625±276	5448±465	4034±392
SB PU	87±18	113±23	2202±646	2754±645	564±79	5326±866	3477±438
SB PP	225±66	129±39	4234±756	3702±958	815±283	4455±1320	3787±257
TSS (mg L^{-1})							
Wastewater	-	-	-	1902±230	1191±102	3310±198	-
PB PU	-	-	-	517±166	456±60	1674±630	-
PB PP	-	-	-	493±158	487±110	1216±557	-
SB PU	-	-	-	224±22	546±0	1438±357	-
SB PP	-	-	-	605±291	527±0	988±1303	-
VSS (mg L^{-1})							
Wastewater	-	-	-	1658±198	986±89	2945±120	-
PB PU	-	-	-	495±166	388±61	1481±437	-
PB PP	-	-	-	465±153	435±124	1053±405	-
SB PU	-	-	-	204±23	538±0	1400±0	-
SB PP	-	-	-	566±267	-	1470±0	-
pH							
Wastewater	7.2±0.2	7.2±0.3	7.1±0.4	7.6±0.3	7.9±0.3	7.6±0.3	7.1±0.5
PB PU	7.5±0.1	7.6±0.1	7.8±0.7	8.2±0.1	7.8±0.1	6.8±0.2	7.1±0.3
PB PP	7.4±0.1	7.6±0.2	7.7±0.8	8.1±0.1	7.8±0.1	6.8±0.2	6.8±0.2
SB PU	7.4±0.1	7.7±0.2	8.2±0.5	8.2±0.1	7.7±0.1	6.3±0.5	6.7±0.2
SB PP	7.3±0.2	7.7±0.2	8.0±0.7	8.2±0.1	7.7±0.1	6.7±0.5	6.9±0.2

PB PU: fixed-packed bed reactor with Biobob®; **PB PP:** fixed-packed bed reactor with polypropylene rings; **SB PU:** fixed-structured bed reactor with longitudinal polyurethane foam strips; **SB PP:** fixed-structured bed reactor with longitudinal bar constructed of polypropylene rings.

The first step of reactor operation (15 days with HRT of 32 h and VOLR of 2.0 kg CODt m^{-3} d^{-1}) was used to acclimatize the biomass to the substrate. The start-up of the packed-fixed bed reactors was fast, reaching E_{COD} higher than 90% after 2 days from the inoculation. On the other hand, the structured-fixed bed reactors had a slower start up, achieving the same performance after 15 days from the inoculation. This fact was due to the different type of inoculation procedure done for each configuration. The CODt removal efficiencies (E_{COD}) throughout the experimental time are presented in Figure 3.

The E_{COD} for low VOLR (2.0 and 2.3 kg CODt m^{-3} d^{-1}) was similar for all reactors, with average E_{COD} between 90% and 94%. Figure 4 shows the average CODt removal efficiency (E_{COD}) for each applied VOLR.

For VOLR of 13.8 kg CODt m^{-3} d^{-1}(HRT of 18 h) and 20.3 kg CODt m^{-3} d^{-1}(HRT of 12 h) the best performances were reached by the reactors with polyurethane foam as biomass support. However, the structured-fixed bed reactor (SB PU) was over 9% more efficient than the packed-fixed bed reactor (PB PU), with E_{COD} of 74 ± 7% and 70 ± 6%, respectively, for each applied VOLR. The high superficial area of the polyurethane foam increased the fixed biomass concentration and the structured bed minimized the dead zones in the reactor, both conditions contributing to the increase in reactor performance.

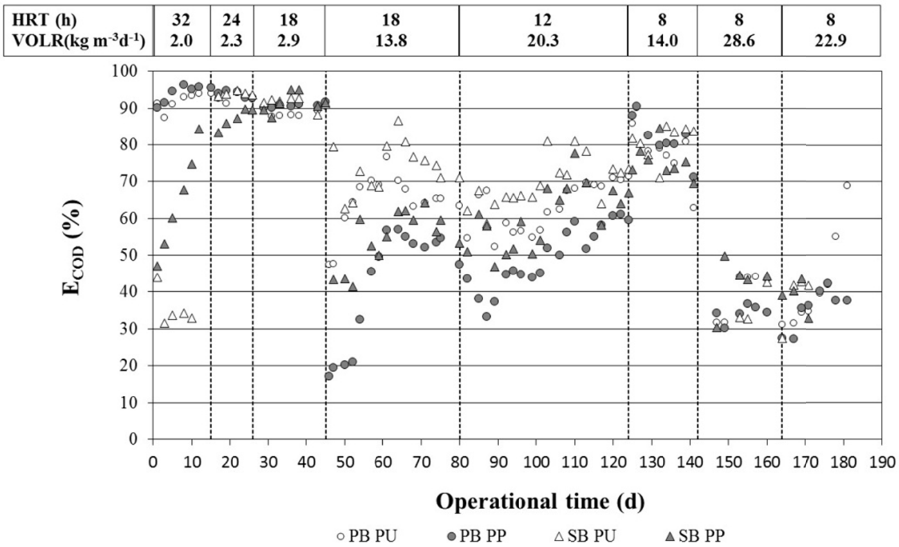

Figure 3: E_{COD} throughout the experimental time.

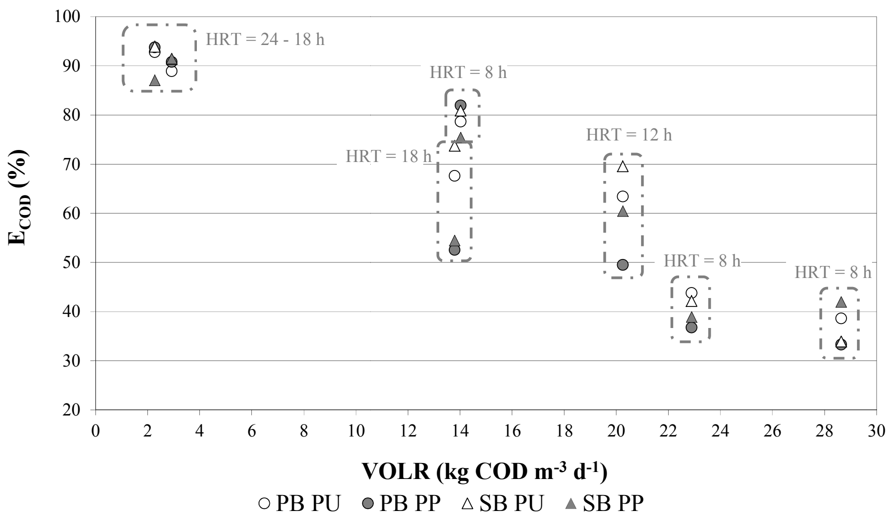

Figure 4: E_{COD} as a function of the VOLR.

Although having a similar applied VOLR, the operation with a HRT of 8 h (14 kg CODt m^{-3} d^{-1}) had a better efficiency of CODt removal than operation with 18 h (13.8 kg CODt m^{-3} d^{-1}) for all reactors. This fact can be related to the highest interstitial velocity in the reactor bed for 8 h of HRT, which decreases the mass transfer resistance between biofilm and substrate and increases the substrate utilization rate (Sarti *et al.*, 2001). However, a specific hydrodynamic test was not carried out to prove this hypothesis. For this condition, both the SB PU and PB PP had better performances, with an average E_{COD} of 81 ± 5% and 82 ± 6%, respectively.

Methane and carbon dioxide were predominant in the biogas composition for all reactors during all operational steps. The hydrogen and nitrogen gas concentrations were not significant or zero in the biogas. The temporal biogas production flow rate and the methane average concentration in the biogas for each operational step are presented in Figure 5 and Table 2, respectively.

With the increase of the VOLR, there was a decrease in the CODt removal efficiency and a consequent decrease of the biogas production. However, the methane yield (Y_{CH4}) did not change significantly during the operational period (Figure 6), with average values between 70% and 90% of the maximum stoichiometric value (250 g CH_4 $kg^{-1}COD_{removed}$), evidencing the stabilization of the methanogenic activity for all reactors.

Because of the wastewater characteristics, the influent concentration of total organic acids had a large variation during the reactors operation. Despite this variation, the organic acids were consumed by all reactors for VOLR less than 20.3 kg CODt m^{-3} d^{-1}, evidencing the predominance of the methanogenic activity. However, for VOLR of 22.9 kg CODt m^{-3} d^{-1} and 28.6 kg CODt m^{-3} d^{-1} the effluent organic acid concentration was higher than the influent, evidencing the predominance of acidogenic activity in these operational steps. The total organic acid concentration (TOA) throughout the experimental time is presented in Figure 7.

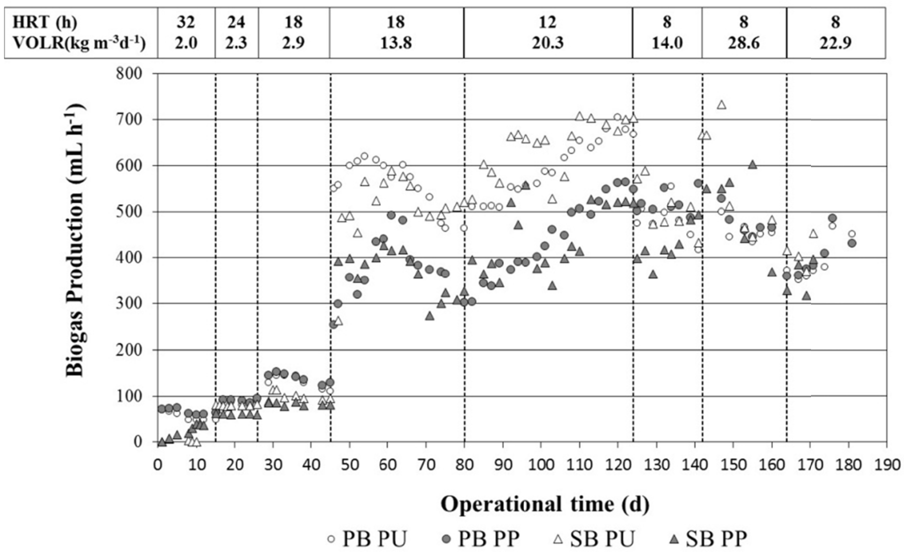

Figure 5: Biogas production throughout the experimental time.

Table 2: Methane concentration (%) in the biogas for each operational step.

HRT (h)	24	18	18	12	8	8	8
VOLR (kg COD m^{-3} d^{-1})	2.3	2.9	13.8	20.3	14.0	28.6	22.9
PB PU	86±3	91±1	79±13	88±3	81±2	70±7	78±1
PB PP	88±2	90±2	77±16	90±1	80±2	69±6	77±1
SB PU	88±3	89±3	83±13	90±2	82±2	69±7	74±5
SB PP	91±1	90±1	89±6	92±2	83±5	74±6	76±8

PB PU: fixed-packed bed reactor with Biobob®; **PB PP:** fixed-packed bed reactor with polypropylene rings; **SB PU:** fixed-structured bed reactor with longitudinal polyurethane foam strips; **SB PP:** fixed-structured bed reactor with longitudinal bar constructed of polypropylene rings.

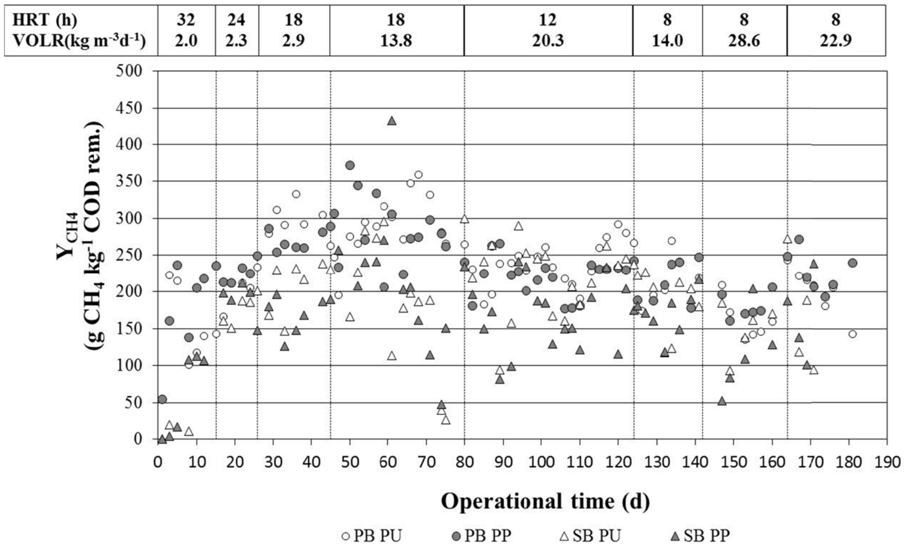

Figure 6: Methane yield (Y_{CH4}) throughout the experimental time.

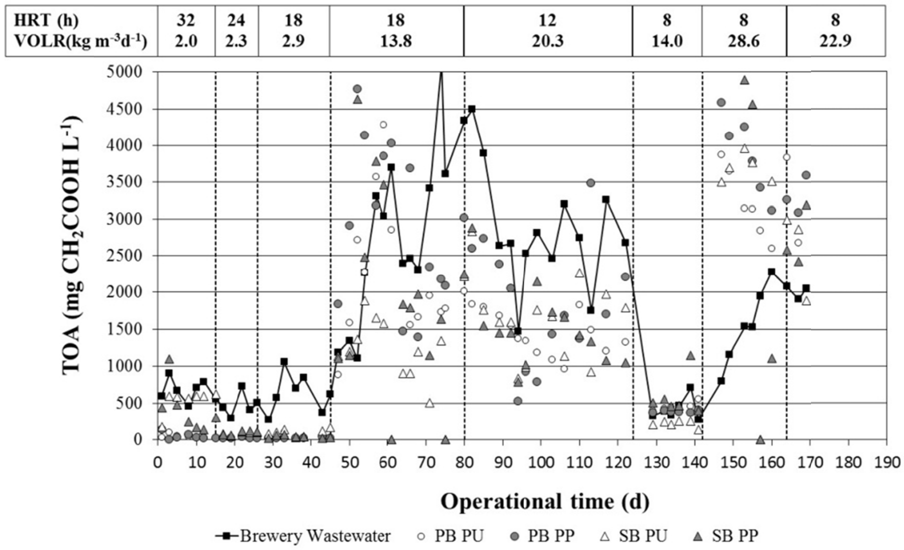

Figure 7: TOA throughout the experimental time.

For VOLR up to 20.3 kg CODt m^{-3} $d^{-1}$the effluent pH values were alkaline (Figure 8). However, for VOLR of 22.9 and 28.6 kg CODt m^{-3} d^{-1}, the reactors were overloaded and the effluent was acidified by organic acid generation.

The anaerobic bioreactor with fixed-structured bed (ABFSB) provides a good alternative for treatment of wastewater with high concentration of organic matter and solids, because it aggregates advantages of both up-flow anaerobic sludge blanket (low risks of dead zones and bed clogging) and fixed-bed (high sludge retention time) reactors. However, the type of biomass support had a big impact on the reactor performance. The SB PU had the best global efficiency compared with all tested reactors, but the SB PP was similar to the packed-fixed bed reactors. Due to its geometry, the structured-fixed bed reactor has a smaller volume of support material than the packed-fixed bed reactor. Thus, to minimize this fact, the biomass support for the structured-fixed bed reactor has to present high superficial area, such as in the polyurethane foam.

Compared with previously studied reactors (Table 3), in spite of the higher VOLR and lower HRT, the SB PU had satisfactory efficiency for organic matter removal for brewery wastewater treatment.

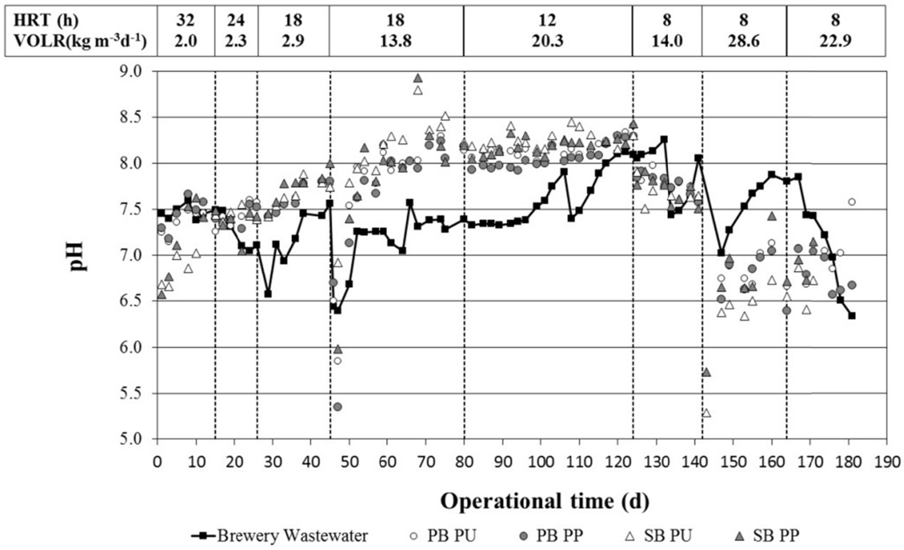

Figure 8: pH variation throughout the experimental time.

Table 3: Results of previous studies for brewery wastewater treatment.

Reactor Configuration	VOLR (kgCOD $m^{-3}d^{-1}$)	HRT (h)	E_{COD} (%)	Temp. (°C)	Reference
IFBR[a]	10	5	90	35	Alvarado-Lassman *et al* (2008)
UASB	7	84	95	35	Öktem and Tüfekçi (2006)
UASB	12.5	24	57	37	Parawira *et al* (2005)
ASBR	5	8[b]	90	33	Xiangwen *et al* (2007)
PB PU	14.0/ 20.3	8 / 12	79 / 63	35	Current study
PB PP	14.0 / 20.3	8 / 12	82 / 49	35	Current study
SB PU	14.0 / 20.3	8 / 12	81 / 70	35	Current study
SB PP	14.0 / 20.3	8 / 12	75 / 60	35	Current study

[a]IFBR: inverse fluidized bed reactor
[b]Batch cycle time: feeding (1 h), reacting (6.35 h), settling (0.5 h), decanting (0.15 h)
PB PU: fixed-packed bed reactor with Biobob®; **PB PP:** fixed-packed bed reactor with polypropylene rings; **SB PU:** fixed-structured bed reactor with longitudinal polyurethane foam strips; **SB PP:** fixed-structured bed reactor with longitudinal bar constructed of polypropylene rings.

CONCLUSIONS

The anaerobic bioreactor with fixed-structured bed (ABFSB) is a promising technology for high organic matter and solids concentration wastewater treatment. This reactor promotes high sludge retention time with a fixed-biofilm and low risk of bed clogging because of its bed geometry. However, the results show that the type of the biomass support had a big impact on the reactor performance. The SB PU had the best global efficiency compared with all tested reactors, but the SB PP was similar to the packed-fixed bed reactors.

For a VOLR of 14.0 kg CODt m^{-3} d^{-1} (HRT of 8 h) and 20.3 kg CODt m^{-3} d^{-1} (HRT of 12 h), the SB PU reached the average E_{COD} of 81% and 71%, respectively. For a VOLR over 22.9 kg CODt m^{-3} d^{-1}, the reactors were overloaded and the effluent was acidified by the increase of the concentration of organic acids, so the methanogenic activity was severely affected.

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