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Preliminary Study of Up-Flow Anaerobic Sludge Blanket (UASB) Technology for Energy Recovery from Domestic Wastewater

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Abstract

New efforts are increasingly oriented towards the search for sustainable Waste Water Treatment Plant (WWTP) designs. The use of anaerobic digestion processes allows energy production during the treatment of wastewater. However, this technology has been poorly implemented for domestic wastewater due its low organic matter content. In this work, the generation of biogas from municipal wastewater has been studied through anaerobic digestion treatment. UASB effluent has been fed to a membrane photobioreactor (MPBR) where developed indigenous microalgae-bacteria consortia contributes to organic matter and nutrients recovery from digested wastewater and membrane allows continuous regenerated wastewater production as permeate stream. The study was performed at pilot scale making use of an Y configuration UASB, operated under psychrophilic conditions.
In addition, the energy production potential of different valorisable substrates, which are residual streams from different treatment processes, was studied at lab scale: concentrate from direct ultrafiltration (DUF) membrane and sludge from conventional membrane bioreactors (MBR), in order to define the potentiality of technological trains with UASB reactors.
Anaerobic digestion yields interesting results that should be considered, such as the fact that energy recovery in MBR is lower than that achieved in DUF, where a higher concentration of organic matter is obtained, and therefore, a greater energy obtainment is achieved.

Key words

Anaerobic digestion, direct ultrafiltration, membrane bioreactor, UASB reactor, wastewater.

1. Introduction

Domestic wastewater is rich in organic matter, and the different ways to treat it could produce large amounts of sludge of variable composition as a function of the process or processes involved (e.g., aerobic biological processes or purely physical-chemical treatments). In addition, the volume of the sewage sludge is increasing and is a worldwide concern, due to the population growth and the important efforts carried out for building new sanitation systems and WWTPs [1], where nowadays sludge is generally considered as a waste, without taking into account its energy valorisation.

On the other hand, it is highlighted that the management of sludge entails serious environmental risks due to the high content of organic, toxic and heavy metal pollutants that it may contain. So, it requires an adequate management to ensure the neutralization or at least, the minimization of its impact, its disposal or its microbiological stabilization, in order to avoid the possible damages to the environment [2-3].

Locations under tropical and subtropical weather conditions have potential for the use of anaerobic wastewater treatment because during most of the year the temperature remains above 20ºC [4]. Therefore, the possible use of this type of technology in these territories is of great interest, since it allows the degradation of the organic compounds contained in the municipal wastewater (MWW) in the absence of oxygen, whose contribution could represent up to a 60% of the energy costs related to a conventional WWTP [5]. In addition, biogas rich in methane is produced during the anaerobic digestion treatment of the MWW, which can be used to produce energy through a combustion process. On the other hand, anaerobic digestion (AD) is also characterized by the slow growth of the biomass, leading to a sludge formation quite lower than that obtained during the conventional aerobic wastewater treatments. For this reason, in recent years more efforts are focused on the search of sustainable WWTP designs which incorporate the anaerobic digestion, either as the main MWW treatment or as a complementary one to recover the energy contained in the residual streams generated during the production of the reclaimed water.

Among the different anaerobic wastewater treatment technologies, Up-flow Anaerobic Sludge Blanket (UASB) reactors, which were initially developed in the Netherlands, are widely employed around the world due to their capability to treat different types of wastewaters at high loading rates [6]. In its original conception, the UASB is a vertical reactor that comprises three different zones: a sludge bed, a sludge blanket and a three-phase separator. The substrate is fed through the lower section of the UASB, forcing it to pass through the digestion zone (i.e. anaerobic sludge bed). This generates a vertical up-flow that expands the sludge creating the sludge blanket where the biomass is kept in suspension. Finally, the effluent and the biogas are obtained from the upper part of the UASB by means of a three-phase separator (G/L/S), where the baffle plates prevent the biomass washing-out from the reactor [7].

More recently, new UASB designs have been developed, with the Y variant standing out for its versatility, low manufacturing cost, ease of implementation and low footprint. Unlike the conventional design, in this type of UASB the three-phase separator is replaced by two two-phase separators:

- A G/L separator (vertical section) where biogas is obtained from the head of the UASB reactor.
- A L/S separator (45º inclined section) where the effluent is separated from the anaerobic biomass. This section acts as a lamellar clarifier, slowing down the large particles and returning it to the digestion section (bottom of the vertical section).

Although the optimization of the UASB reactors operating variables to treat municipal wastewater (e.g., HRT or OLR) has been studied in depth [6], there is still a lack of knowledge on the most appropriate combination of technologies in order to maximize the biogas production of the UASB (i.e. the best substrate from advance wastewater treatment technologies) producing a high quality effluent. In fact, the UASB digestate or liquid effluent shows high ammonia contents which limits its discharge to aquatic environments or soil.

Membrane bioreactors have gained in popularity in recent years, becoming one of the most widespread technologies for treating MWW. Its advantages include the production of high physical-chemical quality effluents, its ability to separate the HRT from the SRT and its small footprint. Although these processes are energy intensive (0.5–0.7 kWh/m^3) [8], the large amounts of biomass could be used in anaerobic digestion processes. On the other hand, although the absence of biological treatment does not allow obtaining effluents of such high quality as that of the MBRs through MWW direct ultrafiltration (DUF), if they are operated under adequate conditions, the effluent could be suitable for landscape and agricultural irrigation purposes [9]. Likewise, during DUF treatment it is not necessary to supply oxygen for microbial growth, thus significantly reducing the energy consumption, and avoiding the partial oxidation of the organic matter contained in the wastewater that is susceptible to being used in the AD process [10]. Therefore, new schemes suggest that the combination of MWW-DUF with AD processes to produce energy from a concentrated wastewater stream could be an interesting option.

The aim of the present work was to study the energy potential of several residual streams from two WWT processes by batch anaerobic digestion lab scale tests. The tested substrates were sludge from an aerobic conventional MBR and the high-concentrated reject from a Membrane DUF process. The results were compared with the biogas production of a Y configuration UASB fed with pre-treated wastewater operated at pilot scale, under psychrophilic conditions for long-term runs.

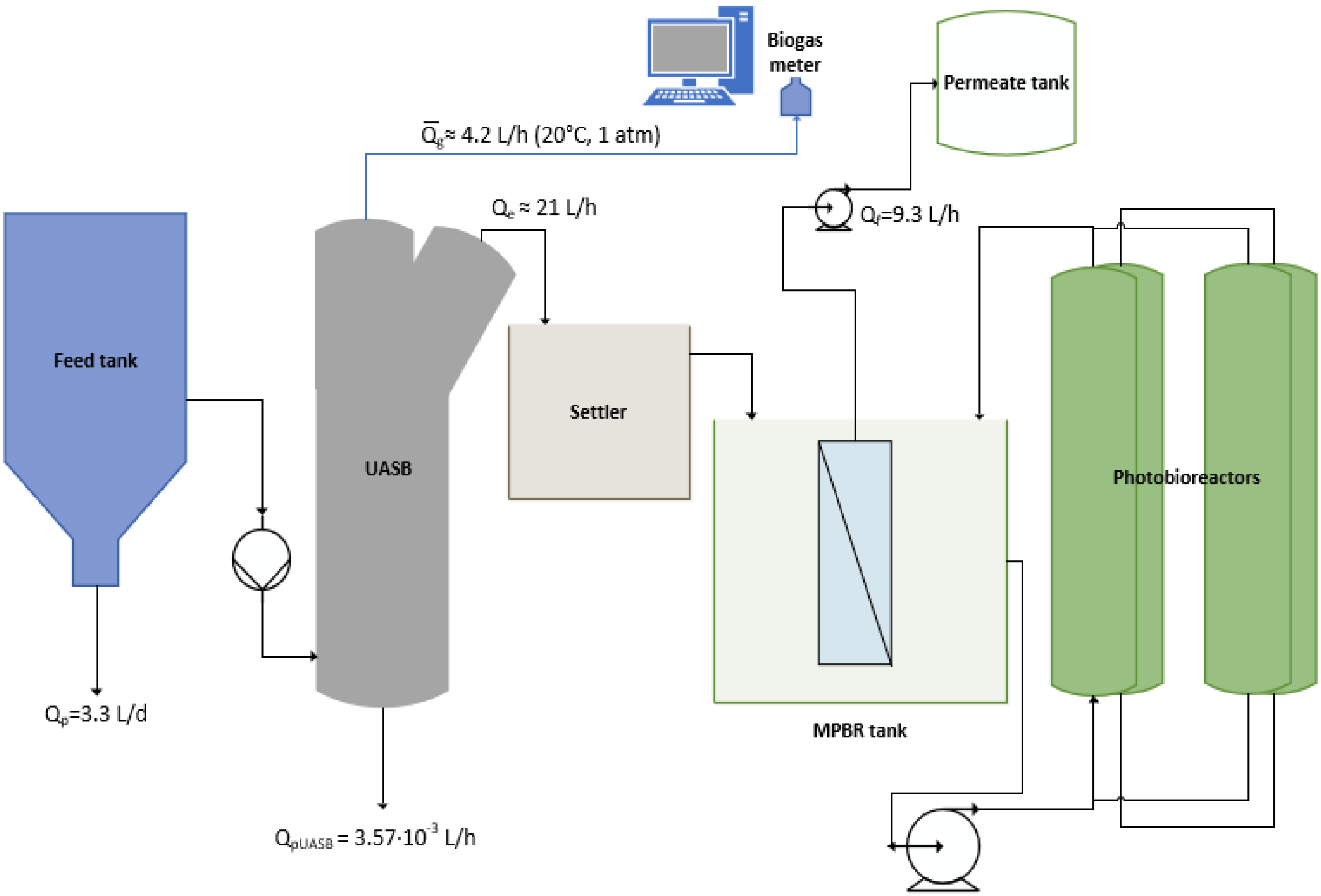

Fig 1. Diagram of the up-flow anaerobic sludge blanket (UASB) and membrane photobioreactor (MPBR) technology used in the study.

2. Methodology

A. Upflow Anaerobic Sludge Blanket (UASB) pilot plant

As shown in figure 1, an UASB pilot plant with a total height of 1,8 m and inner diameter of 25 cm, was operated under psychrophilic conditions (the average temperature during study period was 18º C). This unit was fed with urban wastewater previously treated by screening, degreasing and sedimentation. Feed water was pumped to UASB unit by a peristaltic pump (Watson Marlow, 520SN) and effluent flow-rate was established at 21 L/h. Therefore, the UASB operated at HRT of 4.3 hours and without significant purge of biomass (600 mL twice per week for biomass analysis). In addition, the organic loading rate (OLR) was 0.48-0.50 kg COD/m^3·d.

This UASB was previously inoculated with 24 L of anaerobic sludge from a sludge digester from a domestic WWTP. UASB stabilisation took approximately 6 months.

The different streams of the UASB were characterised through the following analysis: pH, conductivity, turbidity, alkalinity, ammonia nitrogen, total suspended solids (TSS), volatile suspended solids (VSS) and total and soluble chemical oxygen demand (COD and CODs, respectively), which were determined according to the Standard Methods for the Examination of Water and Wastewater [12]. Ionic composition was obtained using the Metrohm 882 Compact IC plus chromatograph, which was determined according to the Spanish Standard UNE EN ISO 14911:2000 and UNE EN ISO 10304-1:2009 [13-14].

B. Reject from membrane direct ultrafiltration (DUF) pilot plant

The DUF membrane pilot plant involved in this study is a compact ZeeBlok® membrane filtration system. The immersed PVDF hollow fiber membrane shows a nominal pore diameter of 0.04μm and filtration is carried out from outside to inside by vacuum.

The unit requires a scape of approximately 1m x 0.9m x 1.8m. The main elements of the system are a process tank, a small control panel, a micro reversible pump for permeation and backwashing, a peristaltic pump for reject extraction and an air blower.

During this study, the pilot plant was operated under the following conditions:

Table I. Operational conditions implemented into the DUF pilot plant.

Inlet flow (L/h)	22.7
Outlet flow (L/h)	22.3
Purge flow (sludge) (L/h)	0.4
Tank capacity (L)	199.5
SRT (d)	20.8
HRT (h)	8.9

C. Sludge from MBR wastewater treatment plant

Real sludge from a Domestic Wastewater Treatment Plant (WWTP) equipped with MBR technology as secondary and nitrogen removal treatment was supplied for this study. MBR plant consists of three parallel biological reactors operated in two sequential phases: anoxic and aerobic. The biological suspension from reactors is filtered by ultrafiltration hollow fibre submerged membranes located into the so called membrane tanks. These membranes are similar to ZeeBlok® membranes installed in Membrane DUF pilot plant above described. The excess of sludge from MBR is sent to thickening and dehydration by centrifugal pumps, in order to water removal and to facilitate transport and final disposal in landfill. During this study, MBR was operated as indicated the table II:

Table II. - Operational conditions of the MBR plant.

Inlet flow (m^3/h)	203.9
Outlet flow (m^3/h)	195.9
Purge flow (sludge) (m^3/h)	8.0
Tank capacity (m^3)	6287.0
SRT (d)	32.7
HRT (h)	30.8

D. Biomethanization potencial (BMP)

Wet fermentation under mesophilic temperature conditions (37 °C) with constant agitation was carried out according to the methane potential batch test described by Angelidaki et al. [3]. A total of ninety-six gas-tight bottles with a volume of 80 mL served as reactors (Fig. 2). The substrates (30 mL) were inoculated with anaerobic sludge from a brewery (10 mL), also 1 mL/L of macronutrients and trace elements were incorporated and fermentation started under controlled conditions at the same time. All these samples were also referenced on a blank sample.

Throughout the incubation period, the volumes of biogas obtained and the environmental conditions (temperature, air pressure) were periodically recorded. Also, through a gas chromatograph (Agilent Technologies model 7820A) the composition of the biogas (CH_4, CO_2, O_2) was determined. Subsequently, the biogas yields of the raw materials were calculated and corrected to standard volumes taking into account the environmental conditions, the biogas yield of the inoculum and the proportion of methane.

In addition, for a better comparison, they were referenced to the mass of soluble chemical oxygen demand (COD) removed and to the mass of volatile solids fed determined through standardized methods [12].

Fig 2. Visualization of the vials after and before of the assay.

Finally, the following equations have been used to calculate the BMP [15]:

$$BMP = \frac{V\ CH_4(L)}{kg\ VSS_{feed}} \quad (1)$$

$$BMP = \frac{V\ CH_4(L)}{kg\ COD_{removed}} \quad (2)$$

$$COD_{removed} =$$
$$= COD_i - \left(COD_{f\ assay} - COD_{f\ blank} + COD_{CH_4}\right) \quad (3)$$

3. Results and discussion

A. Up-flow Anaerobic Sludge Blanket (UASB) pilot plant

The operation of the previously described UASB pilot plant fed with domestic wastewater (Table III), reported an average production of around 4.2 L of methane per day, being stable to fluctuations. Meanwhile, the analyses carried out allows estimate a production of 0.72 kWh/kg COD removed and 0.59 kWh/ kg SSV fed [16].
In addition, for a better comparison, the anaerobic digestion of the UASB feed water in a mesophilic regime is currently being studied on a laboratory scale.

Table III. Average properties of the UASB feed water.

pH	7.6
Total COD (mg O_2 /L)	648
Soluble COD (mg O_2 /L)	212
Turbidity (NTU)	329
Conductivity (µS/cm)	1663
Total suspended solids (TSS) (mg/L)	291
Volatile suspended solids (VSS) (mg/L)	246
HCO_3^- (mg/L)	779

B. Comparison of substrates for feeding the UASB

Incubation of samples was carried out during 42 days for DUF reject samples, 30 days after the biogas production began, and during 25 days for the MBR sludge samples, 19 days after the biogas production began. The average physical-chemical properties of the incubated samples are presented in Table IV and in Figures 3 and 4.

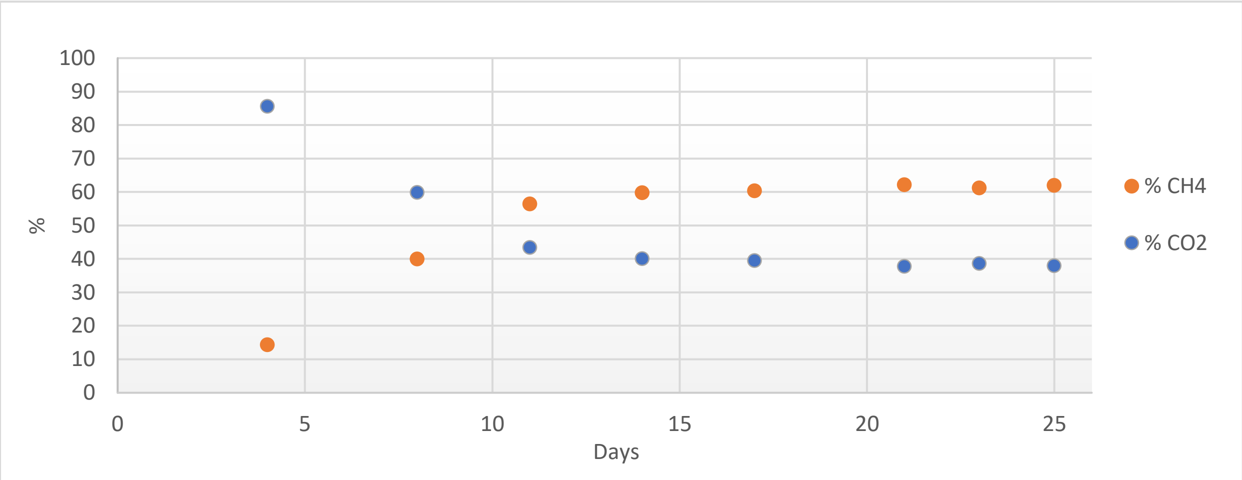

Fig 3. Biogas production from anaerobic digestion DUF sample.

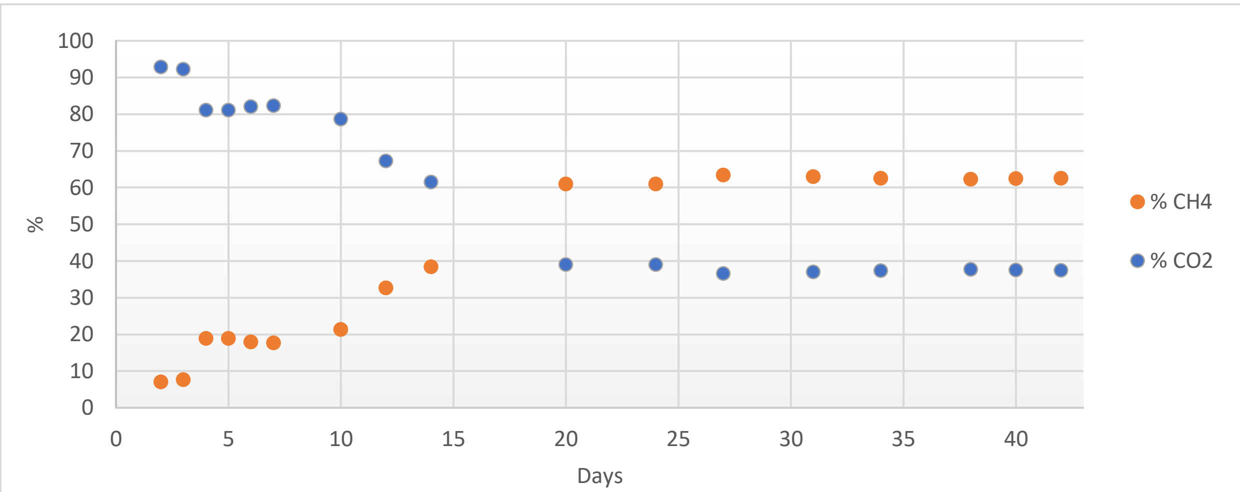

Fig 4. Biogas production from anaerobic digestion MBR sample.

Table IV. Average characteristics of DUF reject and MBR sludge.

	DUF	MBR
pH	7.6	7.2
Total COD (mg O_2 /L)	9378	4426
Soluble COD (mg O_2 /L)	554	132
Turbidity (NTU)	1734	2375
Conductivity (µS/cm)	6745	1086
Total suspended solids (TSS) (mg/L)	5195	4433
Volatile suspended solids (VSS) (mg/L)	4323	3800
HCO_3^- (mg/L)	952	866

Regarding the DUF reject, the highest pressure in all vials was reported at the 20th day except in the blank one. In the blank sample, anaerobic sludge was completely developed and it showed the optimal microbiology. In the sludge samples, organic matter consisted mainly in complex molecules and previous hydrolysis and acetogenesis steps should be needed for allowing the development of methanogenic microorganisms, concluding that the process was slower than expected.

It should be noted that initially, the samples showed a high content of insoluble organic matter, in terms of total COD, while the soluble COD was quite lower. This could be due to DUF sludge samples taking longer to produce biogas by themselves.

Regarding to MBR samples, biogas production was approximately 60-62% methane (Fig 4.) at the end of the monitoring period.

It must be noted that a similar percentage of methane does not necessary mean the same global production. In fact, the quantity of biogas in DUF suggests a completed cycle of batch methanization process, while in the case of the MBR the cycle was not completed after 25 days, since biogas production was still detected when digestion was stopped.

In any case, it can be assumed that methane production in the case of DUF should be higher than in MBR due to the higher organic load shown by the parameters analysed. Methane production from DUF concentrate was higher than the blank one almost every day, but it was only reported after 4 days on MBR sludge samples. Moreover, it is remarkable the higher production of DUF reject regarding to MBR sludge at the 25th day, despite the initial data showed a slower rise of methane production, probably due to the complex degradation of organic matter by microorganisms. Finally, the average biomethanization potential for the DUF technology was 4.8 kWh/kg SVV, assuming that the hydrolysis had already been completed, and 3.5 kWh/kg COD removed.

Regarding the MBR, it shows worse results than the DUF: 1.5 kWh/kg SVV, indicating an incomplete digestion and a value of 1.8 kWh/kg COD removed [16].

4. Conclusions

From the preliminary studies, the exhaustive and extensive characterisation of concentrate from membrane DUF, and its decentralised character without aeration, make it an interesting technology to be implemented in coastal areas with territorial limitations, as many Canary Islands scenarios.

In addition, higher values of organic matter recovery can be obtained in DUF reject, regarding to MBR sludge, in terms of COD and VSS, leading a greater energy recovery potential for DUF processes. Therefore, it can be concluded in terms of energy recovery via anaerobic digestion, that the DUF technology seems to develop a better and more valuable substrate than that obtained from a MBR process.

On the other hand, DUF UASB effluents share a similar environmental concern: its final disposal. Both effluents exhibit high nitrogen content which limits their discharge to the environment. In this sense, membrane photobioreactors for nutrient and residual organic matter recovery could be an interesting via for enhancing the final effluent quality.

In addition, the anaerobic digestion of domestic wastewater or DUF reject by the UASB process seems to be a promising strategy to be included in the new WWTP schemes.

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