# Influence of the diffuser type and liquid-to-biogas ratio on biogas upgrading performance in an outdoor pilot scale high rate algal pond

David Marín[1, 2, 3], Alessandro A. Carmona-Martínez[1, 2], Raquel Lebrero[1, 2], Raúl Muñoz*[1, 2]

[1] Department of Chemical Engineering and Environmental Technology, School of Industrial Engineering, Valladolid University, Dr. Mergelina, s/n, 47011, Valladolid, Spain.

[2] Institute of Sustainable Processes, Dr. Mergelina, s/n, 47011, Valladolid, Spain.

[3] Universidad Pedagógica Nacional Francisco Morazán, Boulevard Centroamérica, Tegucigalpa, Honduras.

* Corresponding author: mutora@iq.uva.es

## ABSTRACT

Four different types of biogas diffusers (metallic of 2 µm, porous stone, and two ceramic membranes of 0.2 and 0.4 µm) were evaluated to improve the quality of biomethane in an outdoor pilot scale photobioreactor interconnected to an external biogas absorption unit. Each type of diffuser was tested independently using three different liquid to biogas (L/G) ratios (0.5, 1 and 2). No significant difference was recorded in the $CH_4$ concentrations of biomethane (i.e. > 93.0%) working with the different types of diffusers at L/G ratios > 1. Only the metallic biogas diffuser supported $CH_4$ concentrations higher than 94.0% at a L/G ratio of 0.5. The increase in L/G ratio induced the stripping of the dissolved $N_2$ and $O_2$ into the biogas, which compensated the decrease in $CO_2$ concentration mediated by the higher pH value of the scrubbing solution. The ANOVA of the results here obtained confirmed that both the type of biogas diffuser and the L/G ratio significantly determined the quality of the upgraded biogas.

**Keywords:**

Algal-bacterial photobioreactor; Biogas upgrading; Diffusers; Liquid/gas ratio; Outdoor cultivation.

## 1. Introduction

Nowadays, the biogas generated as a byproduct from the anaerobic treatment of organic waste and wastewater might represent an environmental problem if it is not energetically valorized. Biogas must be partially purified prior use as a renewable energy vector capable of reducing the dependence on fossil fuels in order to produce electricity and heat for industrial and domestic applications [1,2]. A stricter biogas purification must be implemented in order to fulfil with international regulations for its injection into natural gas grids or use as vehicle fuel. Typical compositions in biomethane standards are: $CH_4 \geq 90$-95%, $CO_2 \leq 2$-4%, $O_2 \leq 1$ % and negligible amounts of $H_2S$ [2,3].

Algal-bacterial processes have emerged as an environmentally friendly and cost-competitive alternative to conventional physicochemical processes capable of simultaneously removing $CO_2$ and $H_2S$ in a single stage process [2,4–6]. In algal-bacterial cultures, sulfur oxidizing bacteria oxidize the $H_2S$ contained in biogas into $SO_4^{2-}$ using the high dissolved oxygen (DO) concentrations present in the cultivation broth as a result of photosynthetic activity, while $CO_2$ is photosynthetically fixed by microalgae using solar energy [7,8]. Microalgae-based biogas upgrading processes have been optimized under indoor conditions in photobioreactors interconnected to external biogas scrubbing units under artificial illumination and using metallic diffusers to sparge the biogas into the absorption column [8–11]. Similarly, photosynthetic biogas upgrading has been validated under outdoor conditions in different photobioreactor configurations. Posadas et al. [12] evaluated the simultaneous upgrading of biogas and wastewater treatment in a 180 L algal pond using a metallic diffuser and liquid to biogas (L/G) ratios of 0.5, 1.0, 2.0 and 5.0. Marín et al. [13,14] evaluated the influence of the seasonal variations of environmental conditions on biogas upgrading performance in a 180 L photobioreactor fed with carbonate supplemented centrate, using a metallic diffuser and L/G ratio of 1.0. Similarly, Rodero et al. [15] investigated the influence of biogas flow rate and L/G ratios on biomethane quality in a 9.6 $m^3$ algal pond using a polymeric membrane diffuser. In addition, Marín et al. [16] assessed the influence of the L/G ratio and alkalinity in the cultivation broth on the quality of the upgraded biogas in a 11.7 $m^3$ horizontal hybrid tubular photobioreactor using metallic diffusers. Table 1 summarizes the different types of photobioreactor configuration and biogas diffusers tested, along with the recorded $CH_4$ concentration in the upgraded biogas. Despite the promising results obtained so far, the effect of the type of diffuser used for biogas sparging in the absorption column on the biomethane quality has not been systematically assessed. The type of diffuser will directly impact on the mass transfer, and therefore on the removal of the target pollutants in the biogas scrubbing unit, thus constituting a key element of process optimization.

**<Table 1>**

In this sense, the influence of four different types of biogas diffusers with different pore sizes (namely metallic of 2 µm, porous stone, ceramic membrane of 0.2 and 0.4 µm) at three L/G ratios on biogas upgrading performance was herein investigated in an outdoor pilot scale photobioreactor interconnected to an external biogas absorption unit.

## 2. Materials and methods

### 2.1 Biogas and synthetic digestate

A synthetic biogas mixture composed of $CO_2$ (29.5%), $H_2S$ (0.5%) and $CH_4$ (70%) was used as a raw biogas in the present study (Abello Linde; Spain). The synthetic digestate (SWW) used consisted of (per liter of distilled water): 6.00 g $NaHCO_3$, 3.00 g $Na_2CO_3$, 0.94 g $K_2HPO_4$, 1.91 g $NH_4Cl$, 0.02 g $CaCl_2·2H_2O$, 0.005 g $FeSO_2·7H_2O$, 0.10 g $MgSO_4·7H_2O$ and 5 ml of a micronutrient solution (composed of 0.10 g $ZnSO_4·7H_2O$, 0.10 g $MnCl_2·4H_2O$, 0.20 g $H_3BO_3$, 0.02 g $Co(NO_3)_2·6H_2O$, 0.02 g $Na_2MoO_4·2H_2O$, 0.0005 g $CuSO_4·5H_2O$, 0.70 g $FeSO_4·7H_2O$ and 1.02 g $EDTA·2Na·2H_2O$ per liter of distilled water). The resulting composition of the SWW was: total organic carbon 51 ± 8 mg $L^{-1}$, inorganic carbon 1211 ± 51 mg $L^{-1}$ and total nitrogen 528 ± 33 mg $L^{-1}$. The composition of the SWW, characterized by a high nutrient concentration and high alkalinity, was selected according to Toledo-Cervantes et al., [8] and Wilkie et al., [17].

## 2.2. Experimental set-up

The experimental plant used for this experimentation was located outdoor at the Institute of Sustainable Processes of Valladolid University (Spain). The experimental set-up was integrated by a 180-L open photobioreactor divided in two water channels and with one baffle at each side of the photobioreactor. The open photobioreactor has an illuminated surface of 1.20 $m^2$ (length of 170 cm; depth of 15 cm; width of 82 cm). The cultivation broth inside the photobioreactor was recirculated with a velocity of 20 cm $s^{-1}$ by a 6-blade paddlewheel. A biogas scrubbing column of 2.5 L (height: 165 cm; internal diameter: 4.4 cm) operating at atmospheric pressure was interconnected to the photobioreactor through a conical settler of 8 L. (Fig. 1). The implementation of a biogas scrubbing bubble column, and consequently the need for diffusers to sparge biogas, was selected due to the fact that the high concentrations of biomass present in the recirculating liquid will entail a severe clogging and malfunctioning in other types of biogas scrubbing technologies such as spray towers or packed absorption columns.

**<Figure 1>**

## 2.3. Operational conditions and sampling procedures

Process operation was carried out from September the 4th to October the 8th 2019. The photobioreactor was inoculated with a culture previously grown in an outdoors photobioreactor at an initial concentration of 450 mg total suspended solids $L^{-1}$. The microalgal inoculum was composed of *Mychonastes homosphaera, Pseudanabaena sp. and Scenedesmus sp.* with a share (based on the number of cells) of 82, 17 and 1%, respectively. The photobioreactor was fed with SWW as a nutrient source at a flow rate of 3.5 L $d^{-1}$. Four different types of biogas diffusers with different pore sizes were successively installed at the bottom of the scrubbing unit in order to analyze their influence on biogas upgrading performance: a cylindrical metallic diffuser with a pore size of 2 µm (height: 2.3 cm; diameter: 1.7 cm), a rectangular porous stone with a heterogeneous pore size distribution (length: 3.0 cm; height: 1.5 cm; width: 1.5 cm), a cylindrical ceramic membrane with a pore size of 0.2 µm (height: 20.0 cm; diameter: 1.0 cm) and a cylindrical ceramic membrane with a pore size of 0.4 µm (height: 20.0 cm; diameter: 1.0 cm). Three different L/G ratios were tested under process operation with each diffuser. In this sense, the biogas was sparged into the scrubbing unit, through the different types of diffusers at 72 L $d^{-1}$. The liquid recirculation from the settler to the absorption unit was operated under co-current flow at rates of 36, 72 and 144 L $d^{-1}$ (corresponding to hydraulic retention times, HRT, in the column of 100, 50 and 25 min, respectively), resulting in L/G ratios of 0.5, 1.0 and 2.0, respectively. The different combinations of diffusers and L/G ratios were tested sequentially for each type of diffuser, starting with the lowest L/G ratio of 0.5 and ending with the highest L/G ratio of 2.0. The pH in the photobioreactor remained constant during all experimentation period at an average value of 9.1 ± 0.1. Tap water was supplied in order to compensate water evaporation losses in the open photobioreactor and allow process operation without effluent. Gas samples of 100 µL of the upgraded biogas were drawn every two hours to monitor the gas concentrations of $CO_2$, $H_2S$, $N_2$, $O_2$ and $CH_4$. The pH in the photobioreactor and in the scrubbing unit was also monitored every two hours. The photosynthetic active radiation (PAR), DO concentration, and ambient and photobioreactor temperatures were daily monitored in each test (Table A1).

### 2.4. Analytical procedures

Gas concentrations of $CO_2$, $H_2S$, $N_2$, $O_2$ and $CH_4$ in the raw and upgraded biogas were determined using a Varian CP-3800 GC-TCD according to Posadas et al. (2015) (Palo Alto, USA). pH was determined with an Eutech Cyberscan pH 510 (Eutech instruments, The Netherlands). PAR, DO concentrations, and ambient and photobioreactor temperature were measured according to Marín et al., [13].

### 2.5. Statistical analysis

The results here presented were provided as the average values along with their standard deviation from five replicate measurements for each test run. An analysis of variance (ANOVA) was performed to determine the influence of the biogas diffusers on the quality of the upgraded biogas.

## 3. Results

### 3.1 Metallic diffuser

$CO_2$ concentration in the upgraded biogas reached values of 3.4, 3.4 and 1.3% and removal efficiencies (REs) of 88.9, 88.8 and 95.7% at L/G ratios of 0.5, 1.0 and 2.0, respectively (Fig. 2a). The pH in the scrubbing unit decreased by 4.5, 4.4 and 2.9%, at L/G ratios of 0.5, 1.0 and 2.0, respectively (Table 2). $H_2S$ from raw biogas was completely removed regardless of the L/G ratio. On the other hand, $N_2$ concentrations reached values of 1.5, 1.9 and 3.0%, while $O_2$ concentrations in the upgraded biogas reached values of 0.2, 0.1 and 0.5% at L/G ratios of 0.5, 1.0 and 2.0, respectively (Fig. 2a). Finally, $CH_4$ concentrations in the upgraded biogas of 94.9, 94.6 and 95.2% were recorded at L/G ratios of 0.5, 1.0 and 2.0, respectively (Fig. 2a).

**<Table 2>**

**<Figure 2>**

### 3.2 Porous stone diffuser

$CO_2$ concentration in the biomethane accounted for 11.1, 3.8 and 1.2%, which corresponded to $CO_2$-REs of 63.4, 87.3 and 95.9% at L/G ratios of 0.5, 1.0 and 2.0, respectively (Fig. 2b). The reduction in the pH of the recirculating culture medium in the absorption unit at L/G ratios of 0.5, 1.0 and 2.0 were 10.0, 5.4 and 4.4%, respectively (Table 2). $H_2S$ from the raw biogas was completely removed regardless of the L/G ratio. $N_2$ concentration reached values of 0.4, 1.1 and 3.0%, while $O_2$ concentrations accounted for 0.1, 0.2 and 1.0% at L/G ratios of 0.5, 1.0 and 2.0, respectively. Finally, the $CH_4$ concentrations observed at a L/G ratio of 0.5, 1 and 2 were 88.4, 94.8 and 94.7%, respectively (Fig. 2b).

### 3.3 Ceramic Membrane

The $CO_2$ concentrations achieved when using the ceramic membrane diffuser of 0.2 µm at L/G ratios of 0.5, 1.0 and 2.0 were 12.3, 3.9 and 1.4%, respectively, and 11.8, 1.2 and

1.1% when using the ceramic membrane of 0.4 µm, respectively. Therefore, the $CO_2$-REs corresponded to 59.5, 87.1 and 95.3% (ceramic membrane of 0.2 µm), and 61.0, 95.9 and 96.3% (ceramic membrane of 0.4 µm) (Fig. 2c; 2d). The decrease in pH in the cultivation medium in the experiment conducted with the ceramic membrane of 0.2 µm was higher than that with a pore size of 0.4 µm at L/G ratios of 0.5 and 1.0, and negligible in both membranes at a L/G ratio of 2 (Table 2). $H_2S$ from raw biogas was completely removed in both ceramic membranes regardless of the L/G ratio. On the other hand, $N_2$ concentration in the experiments with the ceramic membrane of 0.2 µm reached values of 0.9, 2.4 and 4.2%, respectively, and 1.5, 2.5 and 3.9% in the ceramic membrane of 0.4 µm at L/G ratios of 0.5, 1.0 and 2.0. $O_2$ concentration in the upgraded biogas reached values of 0.2, 0.7 and 0.7% when using the ceramic membrane of 0.2 µm at L/G ratios of 0.5, 1 and 2, and 0.7, 0.3 and 0.5% with the ceramic membrane of 0.4 µm, respectively, (Fig. 2c; 2d). Finally, $CH_4$ concentrations in the upgraded biogas using the ceramic membrane of 0.2 µm were 86.7, 93.0 and 93.6%, respectively, and 86.0, 96.0 and 94.5% with ceramic membrane of 0.4 at L/G of 0.5, 1 and 2, respectively (Fig. 2c; 2d).

## 4. Discussion

The diffuser that provided the most efficient upgrading of biogas at a L/G of 0.5 was the 2 µm metallic diffuser, which was the only one that fulfilled with most international regulations required for biogas injection into natural gas grids or use as a vehicle fuel: $CH_4 \geq 90\text{-}95\%$, $CO_2 \leq 2\text{-}4\%$, $O_2 \leq 1\ \%$ and negligible amounts of $H_2S$ [2,18,19]. When a L/G ratio of 1.0 was used, the four diffusers exhibited a similar upgrading performance in terms of $CH_4$ concentration, reaching values up to 96.0%. This increase in $CH_4$ concentrations was promoted by the increase in pH in the absorption unit, which supported a higher $CO_2$-REs due to the enhanced gradient of $CO_2$ concentration between the biogas and liquid phase. Similarly, the four diffusers provided comparable $CH_4$ concentrations (up to 95.2%) at a L/G of 2. However, this increase in the cultivation medium pumped into the biogas scrubbing unit resulted in increased in $N_2$ and $O_2$ concentrations regardless of the type of diffuser tested. This can be explained by the superior dissolved gas stripping at higher liquid flowrates, which negatively impacted on the final concentration of $CH_4$ in the upgraded biogas [20]. The biogas quality at a L/G ratios of 1 and 2 fulfilled with the current European biomethane standard regardless of the diffuser configuration [2,18,19]

Overall, the results herein obtained confirmed that the metallic diffuser was the best system to purify biogas at the L/G ratios typically implemented in photosynthetic biogas upgrading processes in open photobioreactors. These results were in accordance to Marín et al. [16], who reported higher $CH_4$ concentrations at decreasing L/G ratios. Indeed, the $CH_4$ content in biomethane decreased from 89% at L/G of 1 to 87% at L/G of 5 in an outdoor horizontal hybrid tubular photobioreactor constructed with metallic diffusers for biogas upgrading.

Finally, an ANOVA test was carried out to elucidate the influence of the type of diffusers and the L/G ratio on the quality of the upgraded biogas. The F critical value (value that will define if the means for each component are significantly different) was 3.2 for the three different L/G ratios tested in this work. The F values (ratio between the mean square of the component and the mean square of the error) for $CH_4$, $CO_2$, $N_2$ and $O_2$ were 206.7, 274.5, 28.9 and 36.3, respectively, at the L/G ratio of 0.5 (Table 3a). On the other hand, the F values at L/G ratio of 1.0 were 18.5, 152.6, 53.3 and 21.4 for the above mentioned gases, respectively (Table 3b). Finally, the F values at L/G ratio of 2.0 were 16.7, 3.4, 19.2 and 4.0 for $CH_4$, $CO_2$, $N_2$ and $O_2$, respectively (Table 3c). The F values were greater than the F critical value of 3.2 regardless of the biomethane component, which confirmed that the quality of biomethane varied significantly with the type of diffuser and the L/G ratio implemented in the photosynthetic biogas upgrading process.

**<Table 3>**

Unfortunately, the concentration of methane in the cultivation broth returned to the algal pond has not been measured in this particular study. However, no methane slippage into the photobioreactor was expected due to the low aqueous solubility of methane (according to its Henry´s Law constant, $H_{CH4} \approx 0.03$ at 25 ºC) compared to other contaminants (i.e. $CO_2$ and $H_2S$, $H_{CO2} \approx 0.83$ and $H_{H2S} \approx 2.45$ at 25 ºC). In addition, it was hypothesized that the inherent presence of bacteria (e.g. methanotrophs) would eventually oxidize any $CH_4$ transferred to the cultivation broth.

## 5. Conclusions

This study demonstrated the statistically significant influence of the type of biogas diffuser and the L/G ratio in the scrubbing unit on the quality of biomethane in an outdoor pilot scale photobioreactor. L/G ratios > 1.0 supported a significant decrease in $CO_2$ concentration in the upgraded biogas along with a superior stripping of $O_2$ and $N_2$ from the scrubbing solution regardless of the type of diffuser used. The 2 µm metallic diffuser provided the highest $CH_4$ concentration in the upgraded biogas regardless of the L/G ratio (94.6-95.2%), which complied with most international regulations for biomethane injection into natural gas grids.

## Acknowledgements

This work was supported by Fundación Domingo Martinez and the Regional Government of Castilla y León and the EU-FEDER programme (CLU 2017-09 and UIC 071). The financial support of the Regional Government of Castilla y León for the PhD grant of David Marín is also acknowledged.

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# FIGURE CAPTIONS

**Figure 1**. Schematic diagram of the outdoor experimental pilot plant used for the photosynthetic purification of biogas.

**Figure 2.** Concentration of $CH_4$, $CO_2$, $N_2$ and $O_2$ in the upgraded biogas using (a) metallic 2 µm, (b) porous stone, (c) ceramic membrane 0.2 µm and (d) ceramic membrane 0.4 µm diffusers.

**Figure 1.** Schematic diagram of the outdoor experimental pilot plant used for the photosynthetic purification of biogas.

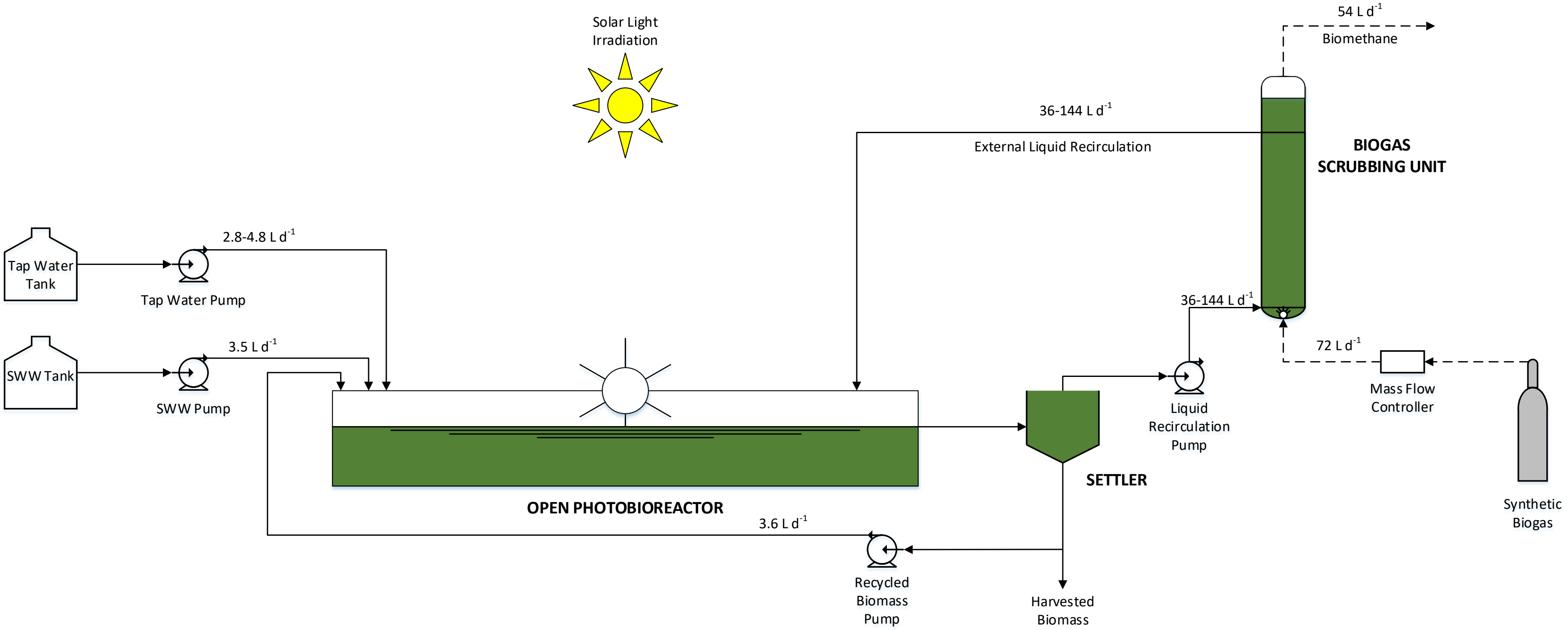

**Figure 2.** Concentration of $CH_4$, $CO_2$, $N_2$ and $O_2$ in the upgraded biogas using (a) metallic 2 µm, (b) porous stone, (c) ceramic membrane 0.2 µm and (d) ceramic membrane 0.4 µm diffusers.

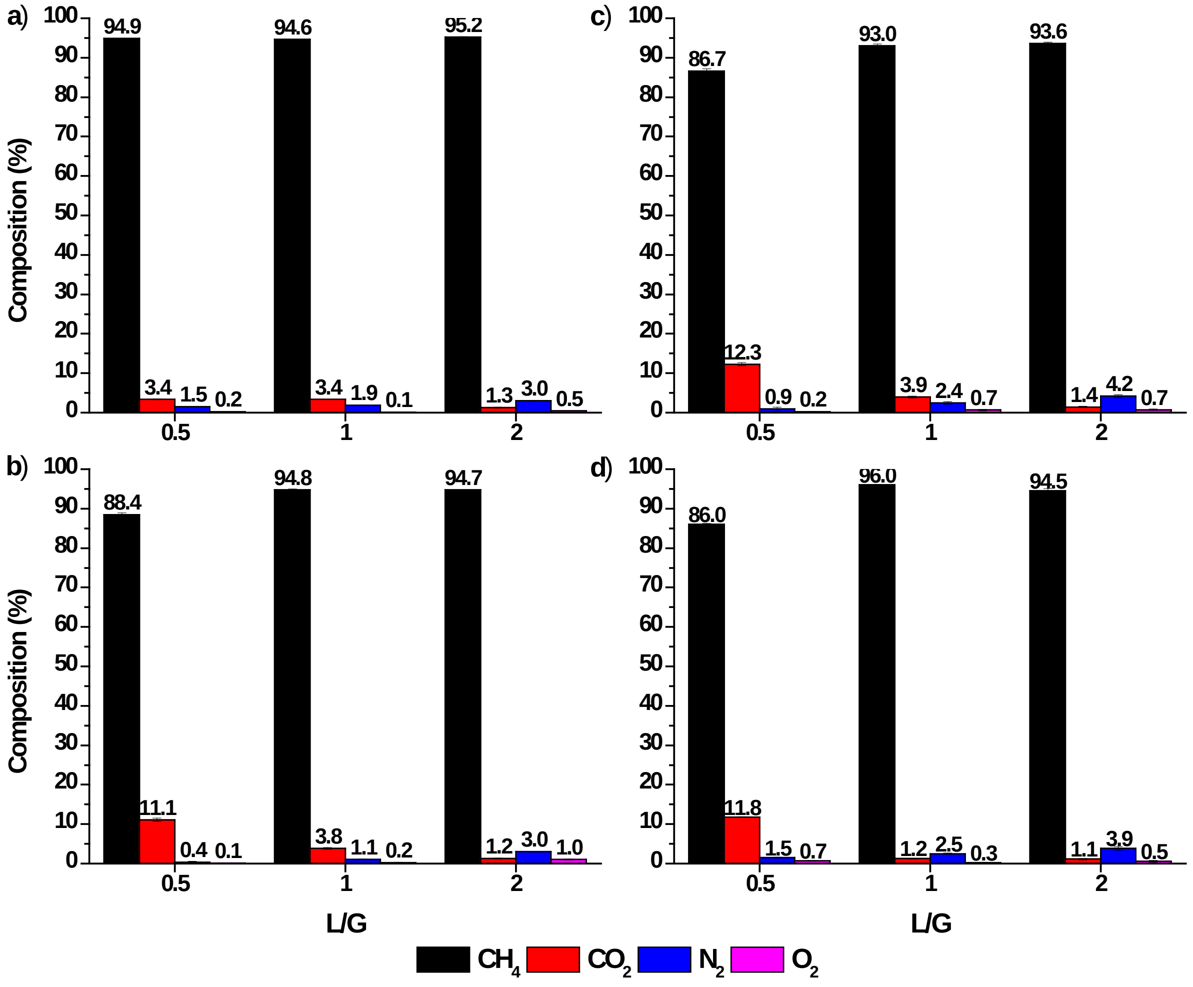

**Table 1.** $CH_4$ concentration in the upgraded biogas using different photobioreactor configurations with different types of diffuser.

| Reference | Photobioreactor configuration | L/G ratios tested | Type of Diffuser | $CH_4$ concentration (%) |
|---|---|---|---|---|
| Toledo-Cervantes et al. (2016) | Indoor 180 L HRAP | 1; 5; 10 and 20 | Metallic 2 µm | 95; 88; 68 and 68 |
| Toledo-Cervantes et al. (2017) | Indoor 180 L HRAP | 0.3; 0.5; 0.8 and 1 | Metallic 2 µm | 95; 98; 98 and 96 |
| Rodero et al. (2018) | Indoor 180 L HRAP | 1 | Metallic 2 µm | 98 |
| Posadas et al. (2017) | Outdoor 180 L HRAP | 0.5; 1; 2 and 5 | Metallic 2 µm | 86; 90; 92 and 80 |
| Marín et al. (2018a) | Outdoor 180 L HRAP | 1 | Metallic 2 µm | 85 – 98 |
| Rodero et al. (2019b) | Outdoor 9.6 $m^3$ HRAP | 1.2; 2.1 and 3.5 | Polymeric membrane | 85; 89 and 90 |
| Marin et al (2019) | Outdoor 11.7 $m^3$ horizontal hybrid tubular photobioreactor | 0.5; 1; 2; 3; 4 and 5 | Metallic 2 µm | 87; 90; 88; 89; 88 and 87 |

**Table 2.** pH values and decrease (as percentage) in the of the cultivation broth in the biogas scrubbing unit using the different types of diffusers.

| | **L/G** | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | **0.5** | | | **1** | | | **2** | | |
| **Type of diffuser** | **Bottom** | **Top** | **Decrease (%)** | **Bottom** | **Top** | **Decrease (%)** | **Bottom** | **Top** | **Decrease (%)** |
| Metallic | 8.95 | 8.55 | 4.5 % | 9.10 | 8.70 | 4.4 % | 9.20 | 8.93 | 2.9 % |
| Porous Stone | 9.09 | 8.18 | 10.0 % | 9.13 | 8.64 | 5.4 % | 9.14 | 8.74 | 4.4 % |
| Ceramic Membrane 0.2 µm | 9.08 | 8.03 | 11.6 % | 9.11 | 8.29 | 9.0 % | 9.03 | 8.66 | 4.1 % |
| Ceramic Membrane 0.4 µm | 9.02 | 8.68 | 3.8 % | 9.05 | 8.75 | 3.3 % | 9.15 | 8.78 | 4.0 % |

**Table 3.** Analysis of variance of biogas at L/G ratios of (a) 0.5, (b) 1 and (c) 2.

**a)**

| | **Sum of squares** | **Degrees of freedom** | **Mean square** | **F** | **F critical** |
|---|---|---|---|---|---|
| $CH_4$ | 224.0 | 3.0 | 74.7 | 206.7 | 3.2 |
| Error | 5.8 | 16.0 | 0.4 | | |
| $CO_2$ | 242.9 | 3.0 | 81.0 | 274.5 | 3.2 |
| Error | 4.7 | 16.0 | 0.3 | | |
| $N_2$ | 4.9 | 3.0 | 1.6 | 28.9 | 3.2 |
| Error | 0.9 | 16.0 | 0.1 | | |
| $O_2$ | 1.0 | 3.0 | 0.3 | 36.3 | 3.2 |
| Error | 0.1 | 16.0 | 0.0 | | |

**b)**

| | **Sum of squares** | **Degrees of freedom** | **Mean square** | **F** | **F critical** |
|---|---|---|---|---|---|
| $CH_4$ | 10.8 | 3.0 | 3.6 | 18.5 | 3.2 |
| Error | 3.1 | 16.0 | 0.2 | | |
| $CO_2$ | 23.1 | 3.0 | 7.7 | 152.6 | 3.2 |
| Error | 0.8 | 16.0 | 0.1 | | |
| $N_2$ | 6.0 | 3.0 | 2.0 | 53.3 | 3.2 |
| Error | 0.6 | 16.0 | 0.0 | | |
| $O_2$ | 0.7 | 3.0 | 0.2 | 21.4 | 3.2 |
| Error | 0.2 | 16.0 | 0.0 | | |

**c)**

| | **Sum of squares** | **Degrees of freedom** | **Mean square** | **F** | **F critical** |
|---|---|---|---|---|---|
| $CH_4$ | 6.6 | 3.0 | 2.2 | 16.7 | 3.2 |
| Error | 2.1 | 16.0 | 0.1 | | |
| $CO_2$ | 0.3 | 3.0 | 0.1 | 3.4 | 3.2 |
| Error | 0.5 | 16.0 | 0.0 | | |
| $N_2$ | 5.7 | 3.0 | 1.9 | 19.2 | 3.2 |
| Error | 1.6 | 16.0 | 0.1 | | |
| $O_2$ | 0.4 | 3.0 | 0.1 | 4.0 | 3.2 |
| Error | 0.6 | 16.0 | 0.0 | | |

# Supplementary Material

# Influence of the diffuser type and liquid-to-biogas ratio on biogas upgrading performance in an outdoor pilot scale high rate algal pond

David Marín[1, 2, 3], Alessandro A. Carmona-Martínez[1, 2], Raquel Lebrero[1, 2], Raúl Muñoz*[1, 2]

[1] Department of Chemical Engineering and Environmental Technology, School of Industrial Engineering, Valladolid University, Dr. Mergelina, s/n, 47011, Valladolid, Spain.

[2] Institute of Sustainable Processes, Dr. Mergelina, s/n, 47011, Valladolid, Spain.

[3] Universidad Pedagógica Nacional Francisco Morazán, Boulevard Centroamérica, Tegucigalpa, Honduras.

* Corresponding author: mutora@iq.uva.es

**Table A1.** Environmental parameters during each test.

| | **Diffuser and L/G** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Metallic** | | | **Porous Stone** | | | **Ceramic Membrane 0.2 µm** | | | **Ceramic Membrane 0.4 µm** | | |
| **Parameter** | **0.5** | **1** | **2** | **0.5** | **1** | **2** | **0.5** | **1** | **2** | **0.5** | **1** | **2** |
| Ambient Temperature (ºC) | 10.0 | 13.0 | 13.0 | 14.0 | 15.0 | 11.0 | 13.0 | 13.0 | 12.0 | 14.0 | 11.0 | 10.0 |
| Photobioreactor Temperature (ºC) | 11.2 | 12.1 | 11.6 | 14.9 | 15.1 | 10.7 | 12.3 | 11.4 | 14.1 | 13.7 | 11.1 | 12.3 |
| PAR (µmol m-2 s-1) | 69 | 54 | 58 | 84 | 88 | 126 | 73 | 67 | 27 | 65 | 396 | 83 |
| DO (mg O2 L-1) | 3.1 | 4.2 | 3.9 | 6.4 | 6.8 | 6.8 | 7.3 | 6.4 | 3.7 | 6.6 | 7.2 | 4.9 |