Separation efficiency of a vacuum gas lift for microalgae harvesting

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Separation efficiency of a vacuum gaslift – Application to microalgae harvesting

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Abstract

The low energy and investment separation of microalgae from water has become an important issue with the increasing interest for this biomass. The present work is a contribution to the assessment of flotation under vacuum using a vacuum gaslift in different conditions. The harvesting efficiency (*HE*) and the concentration factor (*CF*) of the vacuum gaslift increased from around 50 % when airflow rate was reduced from 20 to 10 L min^{-1}. Reduced bubble size also multiplied *HE* and *CF* 10 times either by the use of specific micro bubble diffusers or by an increase of water salinity from <1 ‰ to 40 ‰. *HE* and *CF* were slightly affected by the initial concentration of microalgae in the culture. The reduction of the harvest volume extracted in one hour from 100 to 1 L allowed increasing the *CF* from 10 to 130 but meanwhile decreasing *HE* from 56 to 8 %. An optimized vacuum gaslift could harvest microalgae below 0.2 kWh kg^{-1} DW which allowed reducing harvesting energetic costs from 10 to 100 times compare to classical processes. The vacuum gaslift appeared as an efficient

and economic method to harvest microalgae and open interesting development perspectives in particularly for dewatering biomass cultivated in saline waters.

Keywords: Microalgae ; Foam ; Flotation ; Vacuum gaslift ; Harvesting efficiency ; Concentration factor

1. Introduction

As the world is facing an energy crisis with the depletion of fossil fuel reserves, microalgae are currently receiving a lot of attention as a source of biofuel. Microalgae production is an alternative to land crops for oil production which exhibits many advantages: (1) it has significantly higher biomass productivity (Chisti, 2007; Borowitzka, 2008; Chen et al., 2011; Park et al., 2011), combined with high fatty acids content (2) it doesn't compete with food production for agricultural land as arid and saline land are convenient for their cultivation (Amaro et al., 2011), (3) there is no need for pesticides and herbicides and (4), it can be a solution for industrial carbon dioxide bioremediation (Borowitzka, 2008). However, microalgae production for biofuel is not yet commercially viable given the still low fossil fuel prices (Park et al., 2011).

The choice of the microalgae harvesting method is of great importance as it represents 20-30 % of the total production cost (Molina Grima et al., 2003; Brennan and Owende, 2010). Lowering the energy cost of alga harvesting is thus considered a major challenge for full-scale production of algal biofuel (Sturm and Lamer, 2011; Christenson and Sims, 2011) as for all uses of microalgae biomass, though in an extent depending on their market price. The high cost is largely due to the small size of algal cells (< 20 µm) which have a density similar to water and are thus very difficult to collect without requiring energy intensive processes (Molina Grima et al., 2003; Park et al., 2011).

The selection of the most appropriate harvesting technique depends on the properties of the microalgal density, size or hydrophobicity (Golueke and Oswald, 1965; Park et al., 2011). It also depends on the culture conditions like water composition and salinity (Demirbas, 2010). This is particularly true for Diffused Air Flotation (DAF) systems, as the bubble size strictly depends on salinity (Ruen-ngam et al., 2008; Kawahara et al., 2009; Barrut et al., 2012).

The usual process for biomass separation is the continuous centrifugation as it is rapid, efficient and universal (Rawat et al., 2011). Nevertheless this method requires energy and a primary step of concentration to be considered for extensive biofuel production (Sun et al.,

2011). Gravity sedimentation is also used as it is simple and highly energy efficient (Rawat et al., 2011), however, this process only works for large-size and high density microalgae *e.g.* *Arthrospira* spp. or with pH increase and/or addition of chemical flocculants (Knuckey et al., 2006; Amaro et al., 2011; Chen et al., 2011) which is often expensive. A solution can be to induce auto-flocculation, which is a spontaneous aggregation of particles favouring their sedimentation. It may be caused by interrupting or limiting the carbon dioxide supply (Demirbas, 2010). Filtration by microstrainers is also commonly used for solid-liquid separation. Some problems encountered with this method include incomplete solids removal and membranes fouling by bacterial biofilm. If the former problem may be solved by using flocculation, the latter needs regular cleaning or membrane replacement, which results in important costs (Amaro et al., 2011; Rawat et al., 2011).

Finally, air flotation has also emerged as a potential alternative to obtain a significant harvesting of microalgae. DAF is often encountered in water treatment as efficient clarification step notably when treating water containing hydrophobic matter and algae (Demirbas, 2010; Sturm and Layer, 2011). It consists in air injection at the bottom of a water column with subsequent upward stream of bubbles. Micron-size air bubbles may attach to the surface of microalgae and carry them to the free surface, forming a concentrated layer of foam which is separated from the water by skimming. The main cost of this method is due to the power required by air injection. Moreover DAF is often used after a chemical flocculation which increases the total harvesting costs (Christenson and Sims, 2011).

Based on this statement of the potential interest of flotation, the present work is a contribution to assess the harvesting efficiency of a vacuum gaslift as compared to other separation systems currently used in microalgae production. This innovative technology combines flotation and foaming under negative pressure which develops a very large interface between the liquid and gas phases and then favours the retention of hydrophobic compounds present in the water.

2. Materials and methods

2.1 Experimental setup

The experimental equipment comprised a 2,000 L buffer tank (1) open to the air and connected to a vacuum gaslift kindly provided by COLDEP® (2) composed of two concentric vertical transparent 6 m long PVC pipes. The outer diameter (OD) of the internal pipe was 160 mm. The diameter of the external pipe was 315 mm (OD) along the first meter and 250 mm (OD) after the first meter and up to the top (Fig. 1). The top of the vacuum gaslift was hermetically closed and connected to a vacuum pump (3) (BUSCH – Mink MM.1100.BV) with a maximal airflow of 60 $m^3 h^{-1}$. The vacuum raises the water in the pipes. A pressure gauge (4) ranging from -1 bar to +1 bar, connected to the frequency converter of the pump's electric motor, was used to control the pressure and regulate the water height in the vacuum gaslift. The vacuum (i) increases the stripping of dissolved gases, especially dissolved oxygen which excess, has an inhibiting effect on photosynthesis (Park et al., 2011) and (ii) allows the gas removed from the fluid to be collected for storage and treatment if required. At the top of the vacuum gaslift, the water surface level was maintained above the internal tube (Fig. 1) in order to (i) establish the circulation between the riser (internal tube) and the downcomer (space between internal and external tube) and (ii) to collect the foam by skimming. The separated foam is then stored in a 100 L harvest tank under vacuum (6) and equipped with a valve at the bottom to get the harvest out. In the downcomer, the water flowed back to the pumping tank with a velocity ranging between 0.15 and 0.25 m s^{-1}, which is the range usually used for algal ponds (Craggs, 2005).

Fig. 1

Air was injected close to the bottom of the inner tube using an electric compressor (5) (BECKER DT4.40K), which delivers a maximum of 40 $m^3 h^{-1}$ at a pressure of 1 bar. Various types of injectors were used: an open tube diffuser which creates a swarm of large bubbles (>3 mm), an injector working at a pressure of 0.5 bar which creates fine bubbles (1 mm) and an injector working at a pressure of 1 bar which creates tiny bubbles (<1 mm). Injected air pressure was controlled by a pressure gauge and airflow was measured using a rotameter (Key Instrument MR 3000 Series Flowmeter ±5 L min^{-1}).

2.2 Microalgae culture description

Different populations of microalgae were characterized prior to each separation trial in terms of average size of particles and salinity. Two "reference" algae species from a natural pond

were chosen: (1) fresh water algae (salinity < 1 ‰), (2) sea water algae (salinity around 40 ‰). Separation trials at intermediate salinity tests were carried out by mixing fresh and sea water algae cultures without impairing their survival.

2.3 Methods to assess the concentration in microalgae and parameters tested

Each separation trial lasted one hour. Samples were collected at the beginning and at the end of each trial from the circulating suspension and from the foam at the top of the column. To evaluate the suspended solid concentration, all samples were centrifuged with a SIGMA 3-18K centrifuge, at 4,000 rpm during 20 minutes. The precipitate was dried in an aluminum cup, using a drying chamber for 24 h at 70°C. The cup was then weighted again to quantify the dry weight (DW) of the microalgae with salts. The weight of salts calculated on the basis of the salinity and of the volume of the precipitate was then deduced.
The concentration factor (*CF*) was calculated by dividing the microalgae concentration in the liquefied foam C_{foam} at the end of each trial by the average microalgae concentration in the initial suspension C_i:

$$CF = \frac{C_{foam}}{C_i} \quad (1)$$

The total biomass dry weight *Q* can be calculated by the relation:

$$Q = C \times V \quad (2)$$

where *C* is the concentration of microalgae in the suspension (g L^{-1} DW) and *V* is the volume of the suspension (L). The harvesting efficiency (*HE*) was calculated by dividing the weight harvested Q_{foam} by the weight of the suspension before beginning the trial Q_i:

$$HE = \frac{Q_{foam}}{Q_i} \times 100 \quad (3)$$

The combination and the range of variations of each parameter tested to quantify harvesting efficiency are given in Table 1.

Table 1

3. Results

3.1 Effect of airflow rate, injector type and bubble size on harvesting efficiency and concentration factor

A negative effect of high airflow rates on harvesting efficiency was observed, as it decreased from 8.8 % to 2.9 % when air was injected from 10 L min^{-1} to 100 L min^{-1} respectively (Table 2). High airflow rates had also a negative impact on the concentration factor. The increase from 10 to 20 L min^{-1} and from 20 to 40 L min^{-1} of air injection reduced the concentration factor from 54 % to 24 %, respectively. Over 40 L min^{-1}, the concentration factor remained stable around a low value of 1.5. The foam extracted during the experiments with airflow rates between 40 to 100 L min^{-1} was uncolored. At lower air injection, water flow was more stable and homogenous, which allowed the formation of green-colored foam, indicating concentration in microalgae.

Table 2

The harvesting efficiency increased from 2.1 % with fine air bubbling to 10.7 % with micro air bubbling whereas the difference of 0.4 % between open tube and a fine bubbling was low (Fig. 2). Switching from an open tube to a fine air bubbling or a microbubbling allowed to multuply the concentration factor by 1.2 or 5.7 respectively. The microalgae were more concentrated in the foam when the air bubble size was reduced.

Fig. 2

3.2 Effect of salinity and initial microalgae concentration in the culture on harvesting efficiency and concentration factor

The positive effect of salinity on harvesting efficiency appeared clearly as the efficiency increased from 2.6 % in fresh water to 22.8 % for a culture at 40 g L^{-1} salinity (Table 3). In fresh water, the foam was aerated, composed of large bubbles, difficult to liquefy and without any coloration whereas, in sea water, it was dense, green-colored and easier to liquefy into a

concentrated suspension of algae. There was also a positive relationship between the increase in salinity and the concentration factor in microalgae. In sea water and in the tested conditions (10 L min^{-1} of air microbubbles), concentration factor values were over 100. In sea water (40 ‰), the concentration factor is around 10 times higher than in fresh water.

Table 3

Doubling the microalgae concentration in the culture from 0.4 g L^{-1} to 0.8 g L^{-1} also doubled the concentration of the harvest from 33.6 g L^{-1} to 61.2 g L^{-1} (Fig. 3). The concentration of microalgae in the water also had a positive effect on foaming intensity and density. Nevertheless, in both cases, the concentration factor values were quite close and comprised between 76 and 87, namely a value slightly dependent of the initial concentration in microalgae.

Fig. 3

3.3 Effect of harvested volume on harvesting efficiency, concentration factor and energetic costs

In the case of a vacuum gaslift optimized for harvesting microalgae (microbubbles and air diffusion at 10 L min^{-1}), the influence of the harvest volume on harvesting efficiency is presented in table 4. For the same device, the highest the harvested volume, the highest the harvesting efficiency: 6.5 % and 49.5 % for 1 and 100 L of harvested volume respectively. However, when the harvested volume increases, the concentration factor decreased from 130 for 1 L harvested to 10 for 100 L harvested. Conversely, the final dry weight of microalgae harvested is more important when the volume of harvest increases, even if less concentrated, with 385 g for 100 L harvested and only 50 g for 1 L.

Table 4

The microalgae harvesting costs of an optimized vacuum gaslift depends on the volume of harvest (Table 5). A low harvest volume corresponds to less harvested biomass and a higher harvesting cost and conversely.

Table 5

4. Discussion

4.1 Airflow rate

As indicated by Rubin et al. (1966), the optimum harvesting efficiency of microorganisms like microalgae was obtained with low air injection flow rates. The increase of airflow leads to an increase in water flow and turbulences. The interactions between air bubbles and particles, like collision, adhesion and detachment are influenced by the capillary force, the particle weight and the intensity of turbulences (Phan et al., 2003; Nguyens and Evans, 2004; Nguyen and Nguyen, 2009). Moreover, the formation of foam at the top of the vacuum gaslift is sensitive to turbulences and the foaming intensity decreased with increased airflow rates. At high rates, concentrated particles in the foam are set back in suspension which results in a less concentrated foam.

The harvesting efficiency and the concentration factor of the vacuum gaslift thus appeared to be higher with low airflow, which resulted in energy costs reduction. Whatever the airflow rate, the harvesting and concentration efficiencies remained however limited (concentration factor lower than 10) using fine bubble air diffusion.

4.2 Injector type and bubble size

The choice of a microbubbling revealed critical (even if the concentration factor remained low in this experiment, Fig. 2). Microbubble air diffusion resulted in a swarm of bubbles with a diameter inferior than 2 mm, significantly smaller than with fine or large bubbles where the bubble diameter was comprised between 2 and 5 mm or superior than 5 mm respectively (Barrut et al., 2012). The capture efficiency of bubble has been shown to decrease with an increase in size due to less interaction at the gas/liquid interface (Cassell et al., 1975; Nguyen and Kmet, 1992; Huang, 2009; Liu et al., 2010). The foam was therefore more concentrated in microalgae with microbubble air diffusion. The small differences between fine bubbles and open tube air injection in the harvesting efficiency and in the concentration factor values are probably due to low values obtained in these conditions *i.e.* with an airflow rate of 40 L min^{-1}.

This difference would probably have been higher with an airflow rate of 10 L min^{-1}, for which the harvesting efficiency and the concentration factor are increased.

4.3 Salinity

Increasing salinity allows to reduce the average air bubble size and to maintain micron-size bubbles without massive coalescence (Ruen-ngam et al., 2008; Kawahara et al., 2009), which resulted in an increased harvesting efficiency and concentration factor.
In sea water, the absence of bubble coalescence allows for an average air bubble diameter smaller than in fresh water. The specific surface area developed is then higher, the interactions are more efficient and the foam is more concentrated. The presence of surface active substances in sea water also allowed the formation of a dense and large layer of foam on the surface (top of the vacuum gaslift) favorable to foam fractionation (French et al., 2000; Suzuki et al., 2008; Teixeira et al., 2010). Knowing that the harvesting efficiency is higher in sea water is critical as microalgae cultured in this environment for sustainable production of biofuels would not compete with food crops for fresh water (Borowitzka, 2008)

4.4 Initial microalgae concentration in the culture

As Edzwald (2010) had already shown, when starting from a more concentrated culture in microalgae, the harvest is also more concentrated. However the concentration factor was slightly reduced (11.6 %) with a doubling from 0.4 to 0.8 g L^{-1} DW of the initial microalgae concentration in the culture, it did not seemed to be sensitive to this initial concentration. Therefore, this system is probably able to concentrate an algal pond at low microalgae concentration with nearly the same efficiency than a highly concentrated culture. The high concentration factor obtained (around 80) with relatively low initial microalgae concentrations showed that, conversely to centrifugation, the vacuum gaslift does not need high concentration of microalgae (over 1 g L^{-1} DW) to be economically satisfying. This result is also of great purpose if using this system for microalgae pre-concentration as the vacuum gaslift is able to concentrate, without harming, microalgae from low density cultures. This system could be used, either to accelerate the increase in density of algal pond or to inoculate large volumes of a monospecific selected microalgae in controlled conditions.

4.5 Harvested volume and energetic costs

Increasing the harvested volume of the vacuum gaslift per hour is associated to a less concentrated harvest and an increased harvest volume required to reach 1 kg of microalgal dried biomass. Important volumes are generally less interesting for an industrial use because (i) the drying step will require additional costs and (ii) larger volumes require more important storing capacity.

Harvesting small volumes allows reducing the final treatment (centrifugation), transport and storing costs. Moreover, when the foam is concentrated, auto-flocculation rapidly occurred due to the frequent cell-cell encounters (Chen et al., 2011). For a given type of microalgae in given culture conditions, the microalgae concentration in the flocculated culture remains constant irrespective of the harvest concentration and represents around 90 % of the microalgae biomass (Knuckey et al., 2006). Nevertheless, the volume of the flocculated culture as well as the flocculation time vary with the cell density of the harvest. By eliminating the clarified upper part of the harvested volume after sedimentation, almost all the microalgae biomass may be harvested without any additional energy. Regarding energy consumption, there is no need for concentrating the harvest over the auto-flocculation value, which was observed to be achieved, in a reasonable time (under 30 min), at around 3 to 5 g L^{-1}. For energetic costs reduction, it is thus necessary to harvest the largest volume with a sufficient concentration in microalgae so that auto-flocculation occurs.

According to Cadoret and Bernard (2008), the production and harvesting costs of microalgae are comprised between 3.5 and 50 € kg^{-1} of dry matter, depending on the method used. From these costs 20 to 30 % comes from harvesting, namely 0.9 to 12.5 € kg^{-1} DW (corresponding at that time to around 8.2 to 32 kWh kg^{-1} DW). At this price, the algal biomass produced could only be commercialized into high value products like cosmetics or highly valuable molecules (Park et al., 2011).

For biofuel production, the algae biomass with high lipid content, needs to be produced at a cost of around 0.7 € kg^{-1} DW or less, namely harvesting costs below 0.2 € kg^{-1} DW (Borowitzka, 2008). In our case, harvesting costs would be comprised between 0.02 and 0.4 € kg^{-1} DW (0.16 and 3.37 kWh kg^{-1} DW) which could suit for biofuel production (Table 5).

It is however difficult to obtain harvesting costs for different processes from literature. Nevertheless, as a comparison, the company Microphyt, which produces microalgae in tubular photobioreactors at a concentration comprised between 2.5 and 3.0 g L^{-1} has a mean harvesting energetic cost of 3.5 kWh kg^{-1} DW using centrifugation. Starting from a

concentration in microalgae close to our working conditions (around 0.35 g L^{-1}), the harvesting energetic cost with centrifugation would reach 27.5 kWh kg^{-1} DW. Using centrifugation allow for concentration factor over 80, but with around 100 times higher energetic costs than using processes based on air diffusion (Demirbas, 2010; Amaro et al., 2011; Rawat et al., 2011).

5. Conclusion

The harvesting efficiency and the concentration factor increased when airflow rates and air bubble size were reduced, either by the use of specific micro bubble diffusers or by an increase of water salinity. In our experiment no significant impact of microalgae concentration in the culture was observed on concentration factor or harvest efficiency. The reduction of the harvest volume allowed an increase of the concentration factor but at the expense of the harvesting efficiency. An optimized vacuum gaslift appears as an efficient and economic method to harvest microalgae with a possible costs reduction of 10 to over 100 times which opens interesting development perspectives in particularly for dewatering biomass cultivated in brackish of hyper saline waters at low microalgae concentration.

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Figure captions:

Fig. 1: The vacuum gaslift set-up employed in this work.

Fig. 2: Concentration factor (*CF*) and harvesting efficiency (*HE*) obtained for different injection type with an airflow of 40 L min^{-1} in a culture volume of 2 m^3 at 40 ‰ of salinity and for an harvest volume of 20 L.

Fig. 3: Harvest concentration and concentration factor (*CF*) obtained for two different initial microalgae concentration of 1 m^3 cultures at 50 ‰ of salinity with an airflow of 10 L min^{-1} in microbubbles air diffusion and an harvest volume of 1 L.

Table legends:

Table 1: Combination of all parameters tested to quantify microalgae harvesting efficiency (*HE*) and concentration factor (*CF*) and harvesting efficiency of the vacuum gaslift.

Table 2: Microalgae harvesting efficiency (*HE*) and concentration factor (*CF*) after one hour for different airflow rates with fine bubble air injection from a culture volume of 2 m^3 at 40 ‰ salinity and with an harvest volume of 40 L.

Table 3: Microalgae harvesting efficiency (*HE*) and concentration factor (*CF*) after one hour for different salinities in a culture volume of 1 m^3 and an harvest volume of 2 L with a microbubbles airflow of 10 L min^{-1}.

Table 4: Microalgae harvesting efficiency (*HE*) and concentration factor (*CF*) obtained in one hour for different harvested volumes from a microalgae culture with a volume of 2 m^3 and a salinity of 40 ‰ and with an airflow of 10 L min^{-1} in microbubbles air diffusion.

Table 5: Energetic costs of microalgae separation by vacuum gaslift flotation as a function of the harvested volume obtained in one hour.

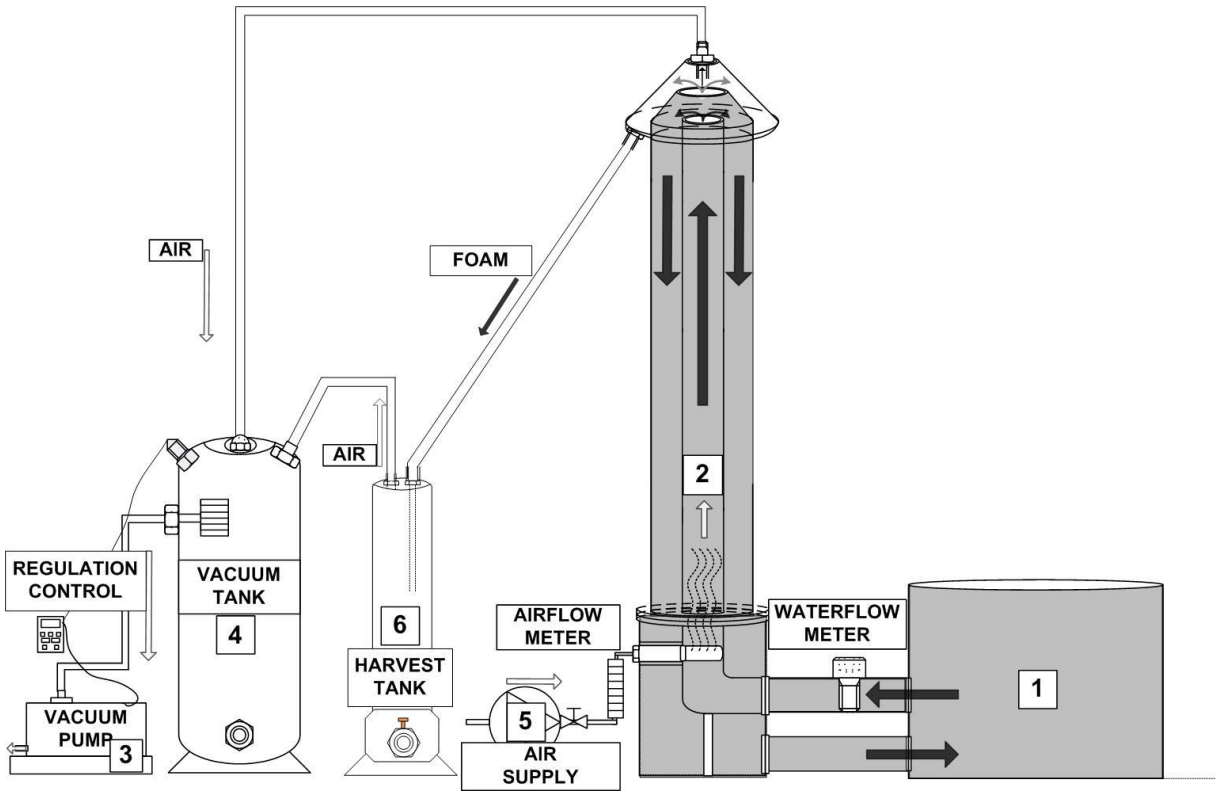

Figure 1:

Table 1:

Air flow Q_G (L min^{-1})	Injection type	Salinity (‰)	Microalgae concentration (g L^{-1} DW)	Harvest volume (L)
10, 20, 40, 60 or 100	Open tube, Fine bubbles or Microbubbles	0, 5, 10, 20 or 40	0.4 or 0.8	1, 2, 20, 40 or 100

Table 2:

Airflow (L min^{-1})	Initial concentration (g DW L^{-1})	Final concentration (g DW L^{-1})	Initial biomass (g DW)	Harvested biomass (g DW)	HE (%)	CF
10	0.346	0.315	692	60.7	8.8 ± 0.76	4.4 ± 0.38
20	0.421	0.404	843	34.4	4.5 ± 0.47	2.0 ± 0.21
40	0.280	0.272	561	17.5	2.9 ± 0.36	1.6 ± 0.19
60	0.409	0.397	818	23.9	2.9 ± 0.67	1.5 ± 0.34
100	0.269	0.261	538	15.4	2.7 ± 0.76	1.4 ± 0.40

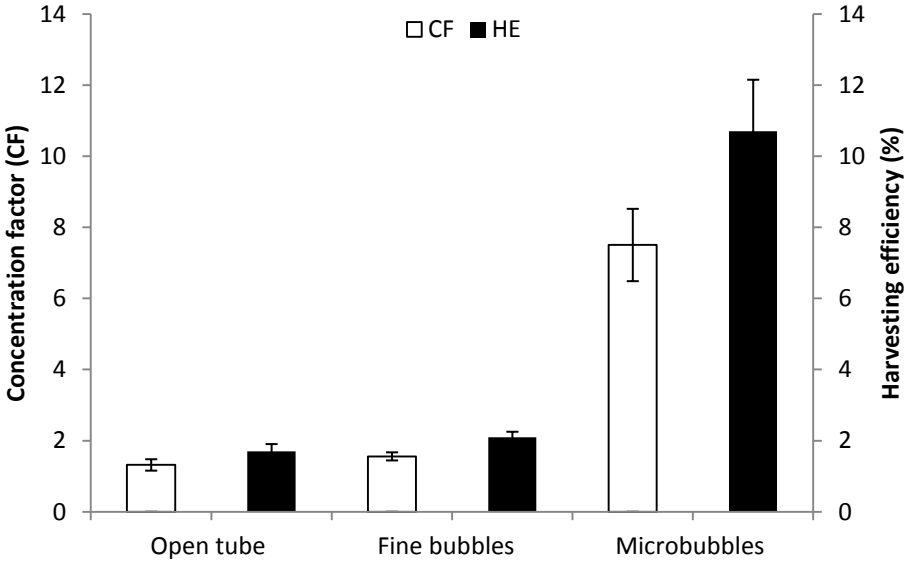

Figure 2:

Table 3:

Salinity (‰)	Initial concentration (g DW L^{-1})	Final concentration (g DW L^{-1})	Initial biomass (g DW)	Harvested biomass (g DW)	HE (%)	CF

0	0.144	0.140	144	3.8	2.6 ± 0.28	13.2 ± 1.31
5	0.217	0.202	217	14.1	6.5 ± 0.67	32.6 ± 3.35
10	0.248	0.224	248	24.4	9.8 ± 0.75	49.6 ± 3.78
20	0.338	0.280	338	58.3	17.2 ± 1.42	86.1 ± 4.89
40	0.319	0.246	319	72.7	22.8 ± 0.22	114.1 ± 0.94

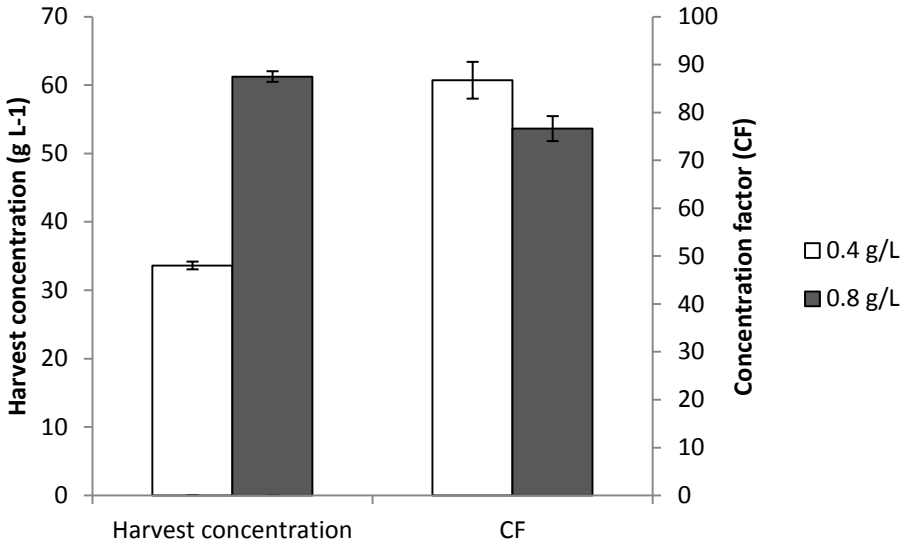

Figure 3:

Table 4:

Harvest volume (L)	Initial concentration (g DW L^{-1})	Final concentration (g DW L^{-1})	Initial biomass (g DW)	Harvested biomass (g DW)	HE (%)	CF
1	0.386	0.361	772	50.4	6.5 ± 0.54	130.6 ± 8.51
2	0.396	0.353	792	86.9	11.0 ± 0.75	109.7 ± 9.55
20	0.396	0.315	792	167.7	21.2 ± 4.29	21.2 ± 5.84
40	0.414	0.310	827	219.0	26.5 ± 4.18	13.2 ± 3.78
100	0.389	0.207	778	384.9	49.5 ± 6.37	9.9 ± 1.63

Table 5:

Harvested volume	Concentration in the foam (g L^{-1}	Harvested biomass (g DW)	Vacuum gaslift energy used (kWh)	Harvesting energetic costs

(L)	DW)			(kWh kg^{-1} DW)
1	50.4	50.4	0.06 - 0.17	1.19 – 3.37
2	43.4	86.9	0.06 - 0.17	0.69 – 1.96
20	8,4	167.7	0.06 - 0.17	0.36 – 1.01
40	5,5	219.0	0.06 - 0.17	0.27 - 0.78
100	3,8	385.0	0.06 - 0.17	0.16 - 0.44