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IMPROVING THE ENERGY BALANCE OF AN INTEGRATED MICROALGAL WASTEWATER TREATMENT PROCESS

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Abstract

The inclusion of a microalgal system in a wastewater treatment flowsheet for residual nutrient uptake can be justified by processing the waste biomass for energy recovery. Low energy harvesting technologies and pre-treatment of the algal biomass are required to improve the overall energy balance of this integrated system. *Scenedesmus obliquus* and *Chlorella* sp., achieving nitrogen and phosphorus removal rates higher than 90%, were used to compare cells recovery efficiency and energy requirements of two energy efficient harvesting systems: Dissolved Air Flotation (DAF) and Ballasted Dissolved Air Flotation (BDAF). In addition, thermal hydrolysis was used as a pre-treatment to improve biogas production during anaerobic digestion. The energy required for both systems was then considered to estimate the daily energy demand and efficiency of two microalgae wastewater treatment plants with a capacity of 25,000 and 230,000 p.e., respectively. Overall, a high algal cells recovery efficiency (99%) was achieved using low energy demand (0.04 kWh m^{-3} for BDAF) and a coagulant dose reduction between 42 and 50% depending on the algal strain. Anaerobic digestion of pre-treated *S. obliquus* showed a 3-fold increase in methane yield. Compared to a traditional activated sludge process, the additional tertiary microalgal treatment generates an integrated process potentially able to achieve up to 76% energy efficiency.

INTRODUCTION

Utilisation of algae as part of a nutrient removal strategy within wastewater treatment enables relatively passive polishing of residual nitrogen and phosphorus in reactors with residence times ranging between 2-4 days [1,2]. For instance, batch reactors operated over a 2-day cycle time containing *Chlorella vulgaris* and *Scenedesmus obliquus* resulted in 80 and 96% removal of ammonia respectively [3]. Extending residence times to 15 days with *S. obliquus* has demonstrated the capability to reach effluent concentration as low as 0.01 mg l^{-1} total phosphorus (TP) [2] indicating potential for small works to meet very low discharge consents as long as sufficient land is available. In addition to nutrient removal, microalgae can acts as CO_2 sequestration agent at rates of around 1.8 kg_{CO2} $kg_{biomass}^{-1}$ and so have the potential to be integrated into biogas upgrade loops as a means of CO_2 disposal.

A range of reactor configurations have been considered including algal ponds, photo-bioreactors, immobilisation and attached systems [4,5,6]. Photo-bioreactors are typically used when high value products are generated from the algae biomass where concentrations in the reactors can reach up to 2 kg m^{-3} [7,8]. In the case of wastewater treatment the majority of systems are based on algal ponds where biomass concentration remains below 1 kg m^{-3} with average values between 0.2 and 0.6 kg m^{-3} [8,9]. In either configuration two additional requirements must be met for them to be integrated into a wastewater treatment flowsheet. Firstly, the algae must be separated from the water phase prior to discharge and secondly the algae must be used/disposed of. In the wastewater context, anaerobic digestion of the collected biomass appears the most sensible option as the quantities are generally quite small and the AD assets already exist. In such cases an interesting opportunity presents itself whereby the energy required to operate the algae reactors may be offset by the additional energy produced through digestion of the used algal biomass. Examination of the requirements for integration of algae reactors into a standard wastewater flowsheet reveals two key components: (i) the need for a low energy cell recovery system to reduce energy requirement for biomass harvesting and (ii) the need to maximum biogas production from algae through pre-treatment of the algal cells.

Typical separation processes used for algae harvest include centrifuges or pressure and vacuum filters with associated energy demands ranging between 0.3 and 8 kWh m^{-3} [10]. At large scale, low energy systems (< 0.3 kWh m^{-3}) such as chemical flocculation, bio-flocculation or autoflocculation, are considered efficient pre-concentration technologies which can reduce operation costs when combine with traditional harvesting system [11,12]. The main alternative to those is the use of dissolved air flotation (DAF). The system generates micro bubbles of air which attach to algae cells and allow them to float [13]. Generation of the bubble is through released of a supersaturated water solution akin to beer production and has an energy associated with it of around 0.3 kWh m^{-3} [14]. Recent innovations in the technology have replaced the produced air with glass beads in a process called ballasted dissolved air flotation (BDAF) were the beads can be recycled enabling reduction in energy of 60-80% compared to traditional DAF systems [14]. Anaerobic digestion of algae in traditional mesophilic digesters yields between 30 and 50% of the potential theoretical values [15,16,17]. Higher efficiencies has been reported for thermophilic conditions or when co-digesting algae with other biomass [18,19]. In all cases, the hardness of the cell wall seems to represent the main inhibitor factor [17,20]. The cell wall of green algae is mainly composed of sugars (24-74%), such as glucose, mannose and galactose, forming cellulose and hemicellulose with biopolymers (e.g. sporopollenin, algaenan) which are responsible of the thickness and the resistance of the cells to bacteria degradation [21,22]. In order to overcome this limitation, a range of pre-treatment methods such as ultrasound, high temperature, French press and enzymes have been used to improve algae digestion and biomethane yields [21,23,24]. In relation to wastewater treatment, one of the most commonly used pre-treatment processes is the thermal hydrolysis [25,26]. The process works by applying a combination of temperature (150-170°C) and pressure (6-8 bar), which breaks down the physical structure of all the organic material including algae.

Linking together the innovative approaches outlined here potentially improves the opportunity to be more sustainable and energetically balanced in relation to nutrient removal. The current paper considers this by evaluating the impact of inclusion of these technologies in a wastewater flowsheet containing an algal reactor for nutrient polishing (Figure 1). In particular the work compares Dissolved Air Flotation and Ballasted Dissolved Air Flotation for algae collection and the effect of a thermal hydrolysis pre-treatment on algal cell disruption and digestion yields using *S. obliquus* and *Chlorella* sp. The two technologies were combined in different scenarios to estimate the energy demand and the energy efficiency at two different scales of operation: 25,000 and 230,000 p.e., respectively.

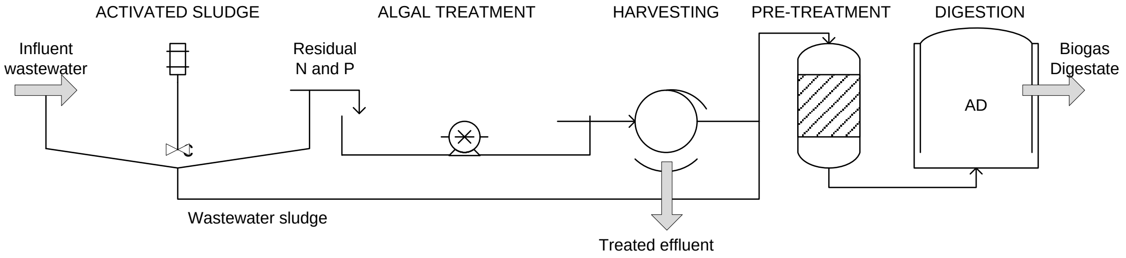

Figure 1: Schematic diagram of an integrated microalgae wastewater treatment process

MATERIALS AND METHODS

Algal culture

Experiments were conducted on two single cell green microalgae species: *S. obliquus* (276/42) and *Chlorella* sp. (211/BK) which were obtained from the Culture Collection for Algae and Protozoa (Oban, UK) and cultivated in Jaworski Media [27]. Algal growth was characterised using cell counting with soluble protein content (sPC) and soluble carbohydrate content (sCC) measured according to the methods described by Henderson et al. [27]. Solids content, chemical oxygen demand (COD) and soluble COD (sCOD) were measured according to APHA standard methods [28].

Microalgae harvesting

Jar tests experiments (1l) were undertaken using an EC Engineering DBT6 DAF jar tester (Alberta, CND). The DAF and BDAF tests were performed according to Henderson et al. [27] and Jarvis et al. [14], respectively. Biomass concentration of $5 \times 10^6 \pm 10^5$ cells ml^{-1} was used for the different testing condition. The pH was adjusted to 7 using a 0.1 M HCl and 0.1 M NaOH solution. 300 mg l^{-1} of low-density glass beads between 40 and 100 µm with a density of 100 kg m^{-3}, from Trelleborg Emerson and Cuming Inc. (Mansfiled, USA) were used after a pre-flotation test to eliminate non-floating beads [14]. Aluminium sulphate ($Al_2(SO_4)_3$) was used as coagulant. The clarified samples were analysed for residual cell content. All analyses were carried out in duplicate.

Thermal hydrolysis treatment

Thermal hydrolysis of the algal biomass was achieved using a Baskerville autoclave and steam generator WON15827 (Manchester, UK). The unit is composed of two connected pressure vessels. Steam generated at 165°C and 8 bar was flash-injected for 30 min into the reaction vessel where concentrated algae, 200 ml at 2.0 ± 0.5 g TS l^{-1}, were maintained at

90°C. Cell counting, solid content, COD, sCOD, sCP, sPC were measured in duplicate before and after treatment.

BioMethane Test (BMT)

The biomethane production was determined using a modified method of Angelidaki et al. [29]. Digested sludge seed (inoculum) was obtained from a local WWTP and incubated at 38°C for 2-3 weeks to eliminate any residual activity. Seed and pre-concentrated algal biomass were mixed to obtain a volatile solids (VS) ratio of 1:1 (VS_{seed}:VS_{algae}). 20 ml of the mix was then transferred to a 100 ml serum bottle. The pH was adjusted to a value of 7 using a 1 M NaOH solution and the bottles were filled with 40 ml of nutrient solution [29] to a final volume of 60 ml leaving a head space of 40 ml. All tests were flushed with N_2 gas, sealed with a PTFE crimp cap, and then placed into a shaking incubator at 38°C and 150 rpm. Biogas production and composition were determined at day 2, 5, 8, 12, 16, 21 and 25. The methane content was measured using a Servomex 1440 gas analyser (Crowborough, UK). All tests were conducted in triplicate using treated or untreated algae.

Energy efficiency evaluation

The daily energy demand and efficiency of an integrated wastewater plant involving an activated sludge (AS) system followed by a microalgal raceway pond and an on-site anaerobic digestion (AD) was evaluated using the data reported by Shi [25] and by Zamalloa et al. [30]. The efficiency of the WWTP is defined as the percentage amount of energy produced compare to the total energy demand. The treatment capacity and energy requirement of the two plant sizes considered are shown in Table 1. Six different scenarios with different configuration were considered including:

1. Activated Sludge and Anaerobic Digestion (AS+AD)
2. Activated Sludge, Algal Pond, DAF harvesting system and Anaerobic Digestion (AS+Pond+DAF+AD)
3. Activated Sludge, Algal Pond, BDAF harvesting system and Anaerobic Digestion (AS+Pond+BDAF+AD)
4. Activated Sludge and Anaerobic Digestion with a Pre-Treatment step (AS+Pre-treat.+AD)
5. Activated Sludge, Algal Pond, DAF harvesting system and Anaerobic Digestion with a Pre-Treatment step (AS+Pond+DAF+Pre-treat.+AD)
6. Activated Sludge, Algal Pond, BDAF harvesting system and Anaerobic Digestion with a Pre-Treatment step (AS+ Pond+BDAF+Pre-treat.+AD).

Harvesting energy demand values used were equivalent to 0.3 kW m^{-3} and 0.04 kW m^{-3} for DAF and BDAF system, respectively [14]. The energy generated by the wastewater sludge digestion was back calculated from the assumed energy efficiency (Table 1). Additional energy from algal digestion was estimated using the methane yields reported in the present work, applying a methane energy conversion of 9.7 kWh m^{-3} and 30% efficiency [25].

Table 1: Integrated WWTP parameter design

Traditional WWTP (AS+AD)	**TP25K**	**TP230K**
Capacity	25000 p.e.	230000 p.e.
Influent[a]	4200 m^3 d^{-1}	38640 m^3 d^{-1}
Energy demand (AS)[b]	0.6 kWh m^{-3}	0.45 kWh m^{-3}
Energy efficiency without AD pre-treatment[c]	25%	35%
Energy efficiency with AD pre-treatment[c]	40%	60%
Algal treatment	**TP25K**	**TP230K**
Pond dimension[d]	8.4 ha	77.3 ha
Biomass production (VS)[e]	1.06 ton d^{-1}	9.74 ton d^{-1}
Energy demand (cultivation)[f]	32.5 kWh ha^{-1} d^{-1}	32.5 kWh ha^{-1} d^{-1}

a) water availability of 210 l d^{-1} p.e. and a recovery coefficient of 0.8; *b)* electricity consumption [25]; *c)* assuming a thermal hydrolysis energy demand of 30 Wh pe^{-1} d^{-1}[26]; *d)* raceway pond with 4 d HRT [2] and 0.2 m depth [30] *e)* biomass concentration of 280 g VS m^{-3} and an harvesting recovery coefficient of 0.9 for both *S. obliquus* and *Chlorella* sp.; *f)* electricity consumption of a low level mixing system (paddle wheel) to guarantee a velocity 15 cm s^{-1} [30].

RESULTS AND DISCUSSION

Harvesting technologies

Full algal cells recovery (>99%) was achieved using both harvesting systems: BDAF confirming the potential to use a lower energy alternative to traditional DAF. The associated energy saving of using BDAF as opposed to DAF was estimated at 0.26 kW m^{-3} resulting in an overall reduction in energy of 0.98 MWh d^{-1} at the small scale and 9.04 MWh d^{-1} at the larger scale (Table 3). An additional benefit of using the BDAF configuration was observed in association to chemical usage with a 40% reduction in metal coagulant use at the operating pH of 7 with *S. obliquus* and 50% lower with *Chlorella* sp (Table 2). The difference in coagulant demand between *S. obliquus* and *Chlorella* sp. relates to differences in the AOM (Algogenic Organic Matter) composition for the two algae [31] with the reduced charge density associated with the AOM produced from *Chlorella* sp. requiring less coagulant for optimal removal. It was estimated that the BDAF allows coagulant saving up to 100 g $Al_2(SO_4)_3$ m^{-3} of influent water depending on the algal species. This reduction could represent an economic saving of 525 € d^{-1} at small scale, and 4057 € d^{-1} at larger scale, based on the current average market price [32] of the aluminium salts.

Table 2: Cells recovery, energy input and coagulant dose required (mean ± SD) for DAF and BDAF.

	Cell recovery %	Coagulant dose mg Al l^{-1}	Energy input* kW m^{-3}	Coagulant dose mg Al l^{-1}	Energy input* kW m^{-3}
		DAF		BDAF	
S. obliquus	99	40 ± 14	0.3	23 ± 9	0.04
Chlorella sp.	99	8 ± 2	0.3	4 ± 1	0.04

* According with Jarvis et al. [14].

Thermal hydrolysis of the algal biomass

Thermal hydrolysis has a significant impact on the properties of the algal biomass of both species. To illustrate, in the case of *S. obliquus* the ratio between volatile suspended solids and volatile solids (VSS/VS) of the concentrated biomass decreased from 0.8 ± 0.2 to 0.5 ± 0.2 as a result of pre-treatment. Whereas, in the case of *Chlorella* sp. the VSS/VS ratio decreased from 1 ± 0.2 before treatment to 0.8 ± 0.1 after treatment indicating a greater resistance to the impact of elevated temperatures and pressures. Microscopic analysis supported the observation of a difference in impact due to species selection based on the percentage of cells disrupted which decreased from 70 % in the case of *S. obliquus* to less than 50 % in the case of *Chlorella* sp. In addition, both algae showed post treatment aggregates as a consequence of releasing high amount of intracellular molecules which suggest that cells wall was disrupted [21]. The impact of these differences in terms of the released organic material were most noticed in terms of proteins where application of the pre-treatment step increase the level of soluble proteins from 25 mg l^{-1} to 8149 mg l^{-1} in the case of *S. obliquus* compared to an increase from 27 mg l^{-1} to 2722 mg l^{-1} in the case of *Chlorella* sp. A smaller level of difference was observed as a function of algal type in the case of soluble COD, which increased by 7528 mg l^{-1} and 5306 mg l^{-1} for *S. obliquus and Chlorella* sp. respectively. Whereas more similar changes in soluble carbohydrates were observed at 2018 mg l^{-1} for *S. obliquus* and at 2137 mg l^{-1} for *Chlorella* sp.

The impact of this greater release of soluble material in the case of *S. obliquus* is observed in relation to the BMT (anaerobic digestion for 25 days at 38°C) where application of a pre-treatment step increased the methane yield from 0.13 ± 0.02 m^3 kg^{-1} VS_{add} to 0.32 ± 0.05 m^3 kg^{-1} VS_{add}. This value is closer to the range of the theoretical methane content (0.53 - 0.54 m^3 kg^{-1} VS_{add}) as calculated by Heaven et al. [16]. Untreated *Scenedesmus* biomass was reported to yield between 0.12 and 0.18 m^3 kg^{-1} VS_{add} [15,21]. Our results compare favourably to the one reported by Gonzalez-Fernandez et al. [21] who obtained a methane production of 0.22 m^3 kg^{-1} VS_{add} (133 dm^3 kg^{-1} COD_{in}) after thermal treatment at 90°C for 3h. Similarly, Alzate at al. [24] achieved a final methane production of 0.36 and 0.40 m^3 kg^{-1} VS_{add}, closer to our values, digesting a mixed culture (10 gTS kg^{-1}, 20% *Scenedesmus* sp.) after treatment at 140°C (1.2 bar) and 170°C (6.4 bar), respectively. The equivalent trial with *Chlorella* sp. generated only a small change in methane yield, from 0.10 ± 0.01 to 0.15 ± 0.01 m^3 kg^{-1} VS_{add}, suggesting lower impact of the combined heat and pressure treatment on the cell wall. Theoretical methane conversion values for this algae range between 0.45 and 0.57 m^3 kg^{-1} VS_{add} [16]. Different authors [15,33] reported higher methane yields than the one reported in this paper digesting untreated *Chlorella* biomass (0.15 - 0.35 m^3 kg^{-1} VS_{add}). However, our biogas yields were similar to the one reported in literature and increased from 0.29 ± 0.01 to 0.49 ± 0.03 m^3 kg^{-1} VS_{add} after the pre-treatment (Figure 3). The lower methane yields obtained suggest a potential inhibition of the methanogenesis process, probably related to the chemical composition of the algal biomass. Moreover, the thermal pre-treatment of *Chlorella* sp. released a similar amount of carbohydrates and COD, but less proteins then *S. obliquus.* These differences have generated different C:N ratios in the two systems which, as reported by other authors [20], could have affected the overall biogas composition. This is confirmed by the methane content in the biogas which decreased from 60 to 51% after pre-treatment whit *Chlorella* sp. (Figure 3b), while increased from 46 to 73% whit *S. obliquus* (Figure 2b). Microscopic observations of the digested samples showed no residual intact cells only for pre-treated *S. obliquus* (Figure 4b). In all the other cases, residual algal biomass was identified in the residual solids after digestion (Figure 4a, 4c and 4d) indicating the pre-treatment had not sufficiently enhanced digestion of *Chlorella* sp. The results presented here are in agreement with Valo et al. [34], who demonstrated that thermal hydrolysis pre-treatment of a specific biomass (waste activated sludge) resulted in enhanced biogas production and methane yield due to a reduction of the solids content and a parallel increase of organic compounds released. However, the current work identifies that in the specific case of microalgae the impact is likely to be highly related to a given algal species. The differences are likely to be due to the thickness and composition of the cell wall, which is known to vary between species [15,20].

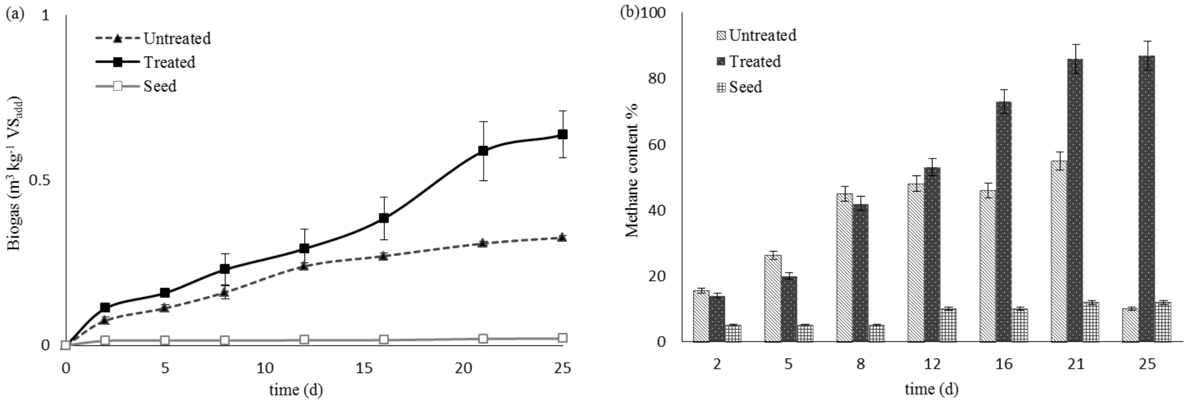

Figure 2: *S. obliquus* BMT cumulative biogas production (a) and percentage methane content (b) of treated and untreated algal biomass at 38°C.

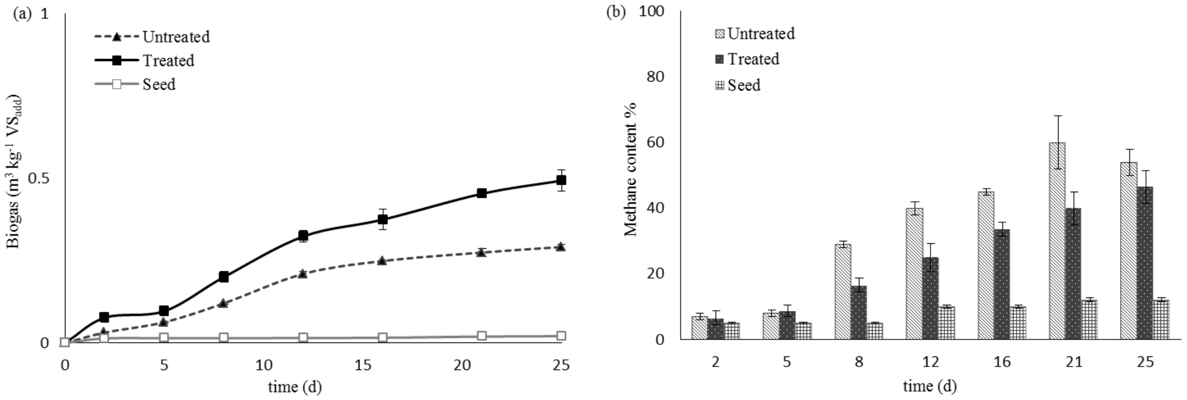

Figure 3: *Chlorella sp.* BMT cumulative biogas production (a) and percentage methane content (b) of treated and untreated algal biomass at 38°C.

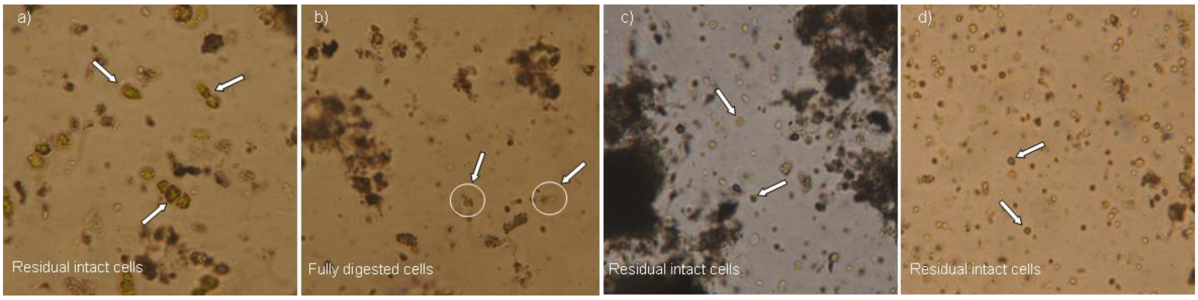

Figure 4: Microscope analysis of digested sample (optical microscope x40); a*) S. obliquus untreated,* b) *S. obliquus treated,* c) *Chlorella* sp. untreated, d) *Chlorella* sp. treated.

Energy balance

Anaerobic digestion of the collected sludge generates 25% and 35% of the total energy demand required to run the works for the control case (scenario1, no algae, no pre-treatment) for the small and the large scale respectively (Table 3). The remaining difference demonstrates the importance of sludge imports on the overall energy balance on operating sites. Generating additional solids for anaerobic digestion through the algal reactors, a possible alternative to sludge imports, (scenario 2) resulted in an increase of the overall net energy demand of the works by 61 and 95% for the small and large cases for both algal types. The increase was a result of the energy required to operate the pond and DAF units not being offset by the increased energy production. Adoption of the innovative BDAF process (scenario 3) reduced this impact with an increase in net energy demand of only 9 and 14.5%. These levels are similar to those of other tertiary nutrient removal processes which suggest algal reactors may be suitable for use on an energy basis even with low biogas yields. For instance, the energy values related to alternative tertiary treatments, such as wetlands (0 – 0.21 kWh m^{-3}) [35] always required additional energy demand and do not produce a valuable feedstock.

Inclusion of a sludge pre-treatment device in the non-algal case (scenario 4) resulted in an increase in energy production of 0.68 MWh d^{-1} at the smaller scale and 8.48 MWh d^{-1} at the larger scale. The additional energy production resulted in an increase in the net energy balance across the works whereby the site produced 40 and 60% of the total demand at the small and large scale respectively. The increased energy production from inclusion algae into the pre-treated sludge mix (scenario5) enabled a greater proportion of the increased energy demand from inclusion of the pond and the DAF unit to be met at both scales. To illustrate, inclusion of an algae nutrient process decreased the overall energy efficiency of the works to 36% at the smaller scale using *Chlorella* sp., a decrease of 4% compared to the pre-treated sludge only case (Figure 5, scenario 4). At the larger scale, the energy efficiency decreased by 12% to a total value of 48% of the works demand due to the limited impact of the pre-treatment on the algal methane production. In comparison, *S. obliquus*, which showed higher energy production after pre-treatment, reported a 4% energy efficiency improvement at small scale. However, at large scale the overall efficiency decreased from 60 to 57%. Switching to the BDAF unit for harvest, changed the balance significantly. In the case of the small works an increase in net energy demand of 0.12 MWh d^{-1}, compare with the control case, was observed only considering *Chlorella* sp., although this included the entire energy demand of the pre-treatment unit and so generated the lowest energy option in total. This was further magnified at the larger scale where the increased energy generation from the pre-treated algal biomass more than offset the energy demand of the pond, BDAF and pre-treatment units leading to a net energy gain of 4.48 MWh d^{-1} for *S. obliquus* and 1.08 MWh d^{-1} for *Chlorella* sp. In this case the energy production from biomass generated on site (sludge and algae) was able to meet 76 and 64% of the total demand for energy, which represents an increase of 16 and 4 % over the sludge only case (scenario 4).

Table 3: Energy demand and efficiency of different integrated WWTPs configurations for both treatment plants and algal strains.

Scenarios description			Energy$_a$ (MWh d^{-1})							
			Energy demand				*S. obliquus*		*Chlorella* sp.	
			Activated Sludge	Algae Pond	Algae Harvest	Sludge/Algae Pre-treat.	AD Energy recovery	Net energy consumption	AD Energy recovery	Net energy consumption
TP 25K	1	AS+AD	2.52				-0.63_b	1.89_b	-0.63_b	1.89_b
	2	AS+Pond+DAF+AD	2.52	0.27	1.13		-0.88	3.04	-0.88	3.04
	3	AS+Pond+BDFA+AD	2.52	0.27	0.15		-0.88	2.06	-0.88	2.06
	4	AS+Pre-treat.+AD	2.52			0.75	-1.31_b	1.96_b	-1.31_b	1.96_b
	5	AS+Pond+DAF+Pre-treat.+AD	2.52	0.27	1.13	0.75	-2.05	2.62	-1.68	2.99
	6	AS+Pond+BDAF+Pre-treat.+AD	2.52	0.27	0.15	0.75	-2.05	1.64	-1.68	2.01
TP 230K	1	AS+AD	17.39				-6.09_b	11.30_b	-6.09_b	11.30_b
	2	AS+Pond+DAF+AD	17.39	2.51	10.43		-8.35	21.98	-9.65	21.98
	3	AS+Pond+BDFA+AD	17.39	2.51	1.39		-8.35	12.94	-9.65	12.94
	4	AS+Pre-treat.+AD	17.39			6.90	-14.57_b	9.72_b	-14.57_b	9.72_b
	5	AS+Pond+DAF+Pre-treat.+AD	17.39	2.51	10.43	6.90	-21.37	15.86	-20.24	19.26
	6	AS+Pond+BDAF+Pre-treat.+AD	17.39	2.51	1.39	6.90	-21.37	6.82	-20.24	10.22

a) positive numbers represent electricity consumption values while negative numbers show electricity produced; *b*) the value reported for scenarios 1 and 4 represent energy generated from wastewater sludge digestion. In all the other scenarios the value shows the energy generated from algae/sludge co digestion by adding the two estimated energy values;

Overall, the results demonstrate that when appropriate choices are made around the ancillary equipment then the use of algae for nutrient removal can represent a viable source of energy production and hence provide an energy neutral nutrient removal strategy. Critical to this is the use of pre-treatment to ensure the inclusion of algae in the anaerobic digestion generates sufficient biogas to justify its inclusion. In such case algae could be viewed as an appropriate alternative to co-digestion of imported non-sewage sludge wastes. The importance of this is that it avoids logistic and regulatory barriers and it enhances biogas production in digesters meant for sewage sludge processing. However, pre-treatment alone is insufficient as the energy demand of traditional technologies for algal separation is likely to be too high to justify the approach. In such case the significance of BDAF system becomes more important as it lowers the total energy demand by 1 MWh d^{-1} at small scale and 9 MWh d^{-1} at larger scale compared to the traditional DAF system. Ultimately both components are required to enhance the potential for inclusion of algae as a nutrient removal process.

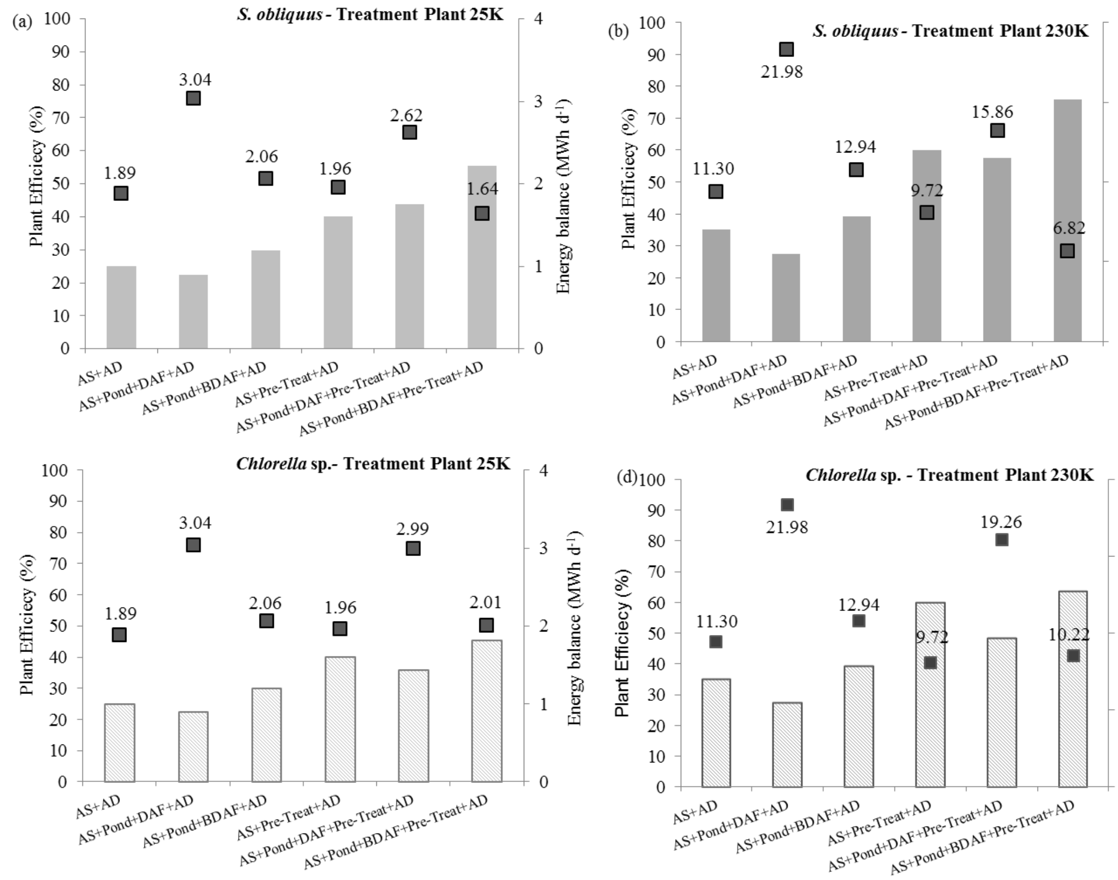

Figure 5: Plant efficiency (column) and Energy balance (square) of the scenarios: *S. obliquus* in TP 25K (a) and TP 230K (b); *Chlorella* sp. in TP 25K (c) and TP 230K (d).

The impact of which algae are used within the nutrient removal process was demonstrated in this study by looking at two similar single cell green algae both of which are commonly used in algal biomass production. In the current case an 8-9% difference was seen on the overall balance as a function of species with *Chlorella* sp. generating less energy than *S. obliquus.* The difference is thought to occur due to the combination of the strong species–specific wall structure found within *Chlorella* sp. [20,36] and the differences within the AOM generated and released after pre-treatment, effecting the final biogas composition. Given that the structure of the two algae strains is reasonably similar it is reasonable to assume that when using other algae species significantly different outcomes may occur. Common algae species found in the UK include filamentous strains of green, diatoms and blue-greens all of which have examples of appendages and mobility associated to them [37]. Previous work on separation of algae has shown that such differences can have a significant impact on the chemical and energy requirements for harvesting [31,38]. In addition previous studies on different algae have also shown species-specific outcomes in relation to the impact of pre-treatment and the biogas production achieved [15,23,24]. Importantly the selection of the most appropriate algae species for enhanced nutrient removal from wastewater in temperate climates remains unclear and highlights that understanding the overall impact of the use of algae cannot be determined without knowledge of the species involved.

CONCLUSIONS

The adoption of low energy harvest and algal biomass pre-treatment has been shown to have a significant impact on the overall suitability of using algae for nutrient removal in wastewater treatment. The BDAF process reduced the overall energy requirements between 30 and 40% depending on the plant size. Thermal hydrolysis pre-treatment allowed a complete utilisation of the included *S. obliquus* cells under mesophilic temperatures maximising the potential energy gain from inclusion of the biomass. The combination of the two technologies demonstrated the possibility of achieving high-energy efficiency (76%) and a more sustainable WWTP. Adoption of the approach needs knowledge of the specific species involved in the removal process as different strains of algae require different pre-treatment conditions and will be able to release different amount of energy and this remains a key research challenge going forward.

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