Experimental system for the prevention of O_2– and air contamination during biogas upgrading with phototrophic microalgae

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Abstract

Several alternative biogas purification techniques are currently being examined for increasing the efficiency of the biogas production. Phototrophic microalgal strains have been tested for converting large quantities of CO_2 from biogas into algal biomass. However, nearly all studies on biogas upgrading with microalgae resulted in contamination of upgraded gas with O_2 caused by photosynthesis or air due to algal culturing in open ponds. To avoid impurities in upgraded biogas, we tested a discontinuous system at bench scale. We grew the well-studied green algae *Chlorella vulgaris* and the recently described green algae *Chloroparva pannonica* in a tubular photobioreactor with 3NBB medium. Subsequently, we used a detached gas scrubber to transfer CO_2 from biogas into dark-adapted microalgal suspensions. During the gas upgrading, the O_2- and CO_2 concentrations in biogas were monitored and corresponding reaction kinetics of mass transfer from biogas into algal medium were determined. The upgrading experiments resulted in a virtually complete removal of CO_2 from all biogas batches. Simultaneously, no O_2 or air was added to the upgraded biogases. Furthermore, we found varying CO_2 kinetics which indicated an algal-specific effect upon the CO_2 removal from biogas. These findings proved the suitability of our experimental system for detailed studies on biogas upgrading with phototrophic microalgae, including their culture media. Moreover, we demonstrated the feasibility of bench-scale biogas upgrading with microalgae without simultaneous contamination of the upgraded gas.

Keywords: *Bench-scale, Biogas upgrading, Gas contamination, Microalgae*

Zusammenfassung

Versuchsaufbau zur Vermeidung von Sauerstoff- und Lufteinträgen während der Biogasaufbereitung mit phototrophen Mikroalgen

Gegenwärtig werden verschiedene Mikroalgen als alternatives Biogasaufbereitungsverfahren untersucht. Bei der Umwandlung von Biogas-CO_2 in Algenbiomasse treten jedoch in nahezu allen Studien Verunreinigungen der aufbereiteten Gase auf. Diese erfolgen in Form von Sauerstoff durch Photosynthese sowie Luft infolge der Algenkultivierung in Becken. Um Gaskontaminationen zu vermeiden, kultivierten wir *Chlorella vulgaris* und *Chloroparva pannonica* in einem Photobioreaktor. In einem separaten Gaswäscher überführten wir anschließend Biogas in die dunkel-adaptierten Algensuspensionen. Während der Gasaufbereitung wurden die O_2- und CO2-Konzentrationen überwacht und entsprechende Kinetiken des Massentransfers von Biogas zu Algenmedium bestimmt. Die Experimente zeigten eine nahezu vollständige Entfernung des CO_2 aus allen eingesetzten Biogaschargen. Gleichzeitig wurde den aufbereiteten Gasen weder O_2 noch Luft hinzugefügt. Darüber hinaus fanden wir abweichende CO_2-Kinetiken, die auf eine algen-spezifische Beeinflussung der CO_2-Entfernung schließen lassen. Die Ergebnisse belegen die Eignung unseres Versuchsaufbaus für detaillierte Untersuchungen zur Biogasaufbereitung mit phototrophen Mikroalgen, einschließlich deren Kulturmedien. Zudem wurde die Machbarkeit der Biogasaufbereitung mittels phototropher Mikroalgen ohne die gleichzeitige Verunreinigung aufbereiteter Gase im Labormaßstab gezeigt.

Schlüsselworte: *Labormaßstab, Biogasaufbereitung, Gasverunreinigung, Mikroalgen*

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1 Introduction

Biogas typically consists of 40 to 75 % v/v methane (CH_4), 15 to 60 % v/v carbon dioxide (CO_2), water vapour, hydrogen sulphide and other trace gases, such as carbon monoxide, nitrogen and atmospheric oxygen (O_2) (Andriani et al., 2014). Particularly, the CO_2 proportion influences the energetic properties of biogas since higher CO_2 levels result in a decreasing calorific value of the gas mixture. Further, the efficiency of four-stroke biogas engines decreases with rising CO_2 concentrations in biogas (Bari, 1996; Edelmann, 2001; Deublein and Steinhauser, 2011). Besides energetic aspects, high CO_2 concentrations increase the biogas volume and the corresponding storage space. Biogas storage at atmospheric pressure in large, plastic bags is associated with size- or transportation problems (Andrea et al., 2011; Khoiyangbam et al., 2011). Therefore, the generation of biogas generally benefits from a CO_2 separation procedure. Chemico-physical processes, e.g. pressure swing adsorption and amine scrubbing, are state of the art for industrial biogas upgrading (Petersson and Wellinger, 2009). Besides these energy-intensive processes, biological approaches have high potential for CO_2 separation from biogas.

Particularly, photosynthetic microorganisms are well investigated in terms of removing CO_2 from gaseous waste streams (Benemann et al., 2003; Wang et al., 2008; Kumar et al., 2010). Moreover, several studies on biogas purification with photosynthetic microalgae have been conducted (e.g. Schmack et al., 2009; Kaštánek et al., 2010). However, apart from a sophisticated multi-species process (Bahr et al., 2014), the large-scale approaches resulted in contamination of the upgraded biogas. These contaminations were either oxygen- (O_2) due to algal photosynthesis or air caused by algal culturing in open ponds. As a consequence, studies on biogas upgrading with phototrophic microalgae focus on the optimal biomass, whereas effects of the algal medium on biogas upgrading are disregarded. In order to prevent contaminations of upgraded biogas and to examine potential influences of the algal medium on the process, we follow a small-scale approach. In a first step, we tested a bench-scale system in which biogas is upgraded by microalgal suspension without simultaneous oxygen- or air contamination. For this purpose, the green algae *Chlorella vulgaris* and *Chloroparva pannonica* served as model organisms and were cultured under monitored conditions in a tubular photobioreactor. Subsequently, biogas was upgraded with dark-adapted algal suspension in a detached gas scrubber and reaction kinetics of the O_2- and CO_2 mass transfer from biogas into algal medium were determined.

2 Materials and Methods

2.1 Microalgal strain and culture medium

Two microalgal strains were grown as model organisms for biogas upgrading. The axenic Chlorella vulgaris 211-11B and the non-axenic Chloroparva pannonica 2358 were obtained from the SAG culture collection, University of Göttingen. Both strains grew in 3NBB medium according to the recipe of Starr and Zeikus (1993). We selected unicellular and agitation resistant green algal strains (Trebouxiophyceae, Chlorophyta) due to the expected mechanical stress during biogas upgrading. Both strains were phototrophic in order to be independent from organic nutrients and the associated risk of contamination.

2.2 Culturing of microalgae

A closed tubular photobioreactor (PBR) was used to culture *Chlorella vulgaris* and *Chloroparva pannonica* constantly at 20 °C with a light-dark cycle of 16/8 h and a photon flux density (PFD) of 60 µE . The PBR had a total volume of 4.9 l and consisted of transparent borosilicate glass tubes with an inner diameter of 25 mm and a total length of 9 m. Its glass components were arranged helically and connected with flange mountings. The PBR was equipped with sampling- and effluent junctions, a vertical backflow as well as a headspace with junctions for medium- and inoculum inlet. Culture conditions were monitored online with temperature and pH sensors PHD 2 (PCE-Germany).

Culture experiments with *Chlorella* were performed under sterile conditions. For this purpose, the PBR was cleansed by circulating a sodium hypochlorite solution (1.5 % v/v) for one hour. Subsequently, the tubes were rinsed twice with sterilised deionised water for 30 min. The PBR was filled with sterile 3NBB medium via a peristaltic pump Ismatec IP-ISM 942 and microalgal suspension was inoculated through the headspace via a custom setup for inoculation (Figure 1). After inoculation, the algal suspension circulated constantly through the bioreactor. The suspension flow was driven by a constant airstream of 0.75 l·min^{-1} provided by a micro membrane pump, model NPM NF-05D004 (Reichelt Chemietechnik, Germany). Air was filtered with sterile syringe filter (Rotilabo®, Germany) and inserted through a cannula at the lowest part of the PBR. After passage of the tubing, the air was vented in the headspace.

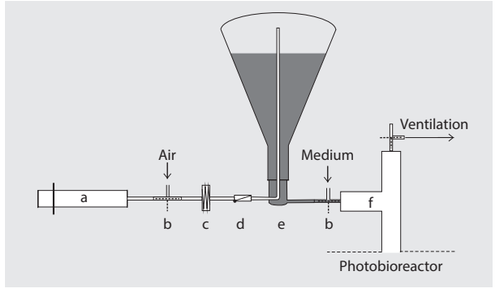

Figure 1
Custom setup for sterile inoculation of the photobioreactor; (a) gas syringe, (b) three-way valve, (c) sterile filter, (d) check valve, (e) conical flask with sterile algal suspension, (f) inoculum/medium junction at headspace of photobioreactor

Samples of algal suspension were taken daily from the bioreactor to determine biomass growth. The samples were filtered onto pre-weighted glass microfibre filters (WHATMAN, GF/F), dried at 60 °C for 24 hours and weighted again. In addition, algal growth was determined by triplicate cell countings using a Thoma counting chamber. The resulting cell densities are represented as mean and growth rates (µ) were calculated by stepwise optimization of the least deviation squares (Excel Solver). Losses of suspension by sampling and evaporation were compensated with 3NBB medium from an attached reservoir.

2.3 Biogas upgrading at bench scale

Carbon dioxide was separated from biogas in a darkened gas scrubber. The scrubber was built up of two circuits, which were detached from the photobioreactor (Figure 2 b). The first circuit consisted of a loop-shaped gas scrubber with online sensors for pH (PHD 2, PCE-Germany) and dissolved O_2 (GMH3630, Greisinger Germany). This liquid-circuit was interconnected to a gas-circuit, in which biogas was driven by a membrane pump, model NPM NF-830 D005 (Reichelt Chemietechnik, Germany). Within the closed gas circuit, the biogas was transported through gastight hoses (Tygon®LP-1500) to a catalytic sensor for O_2, model GMH3691+GGO369S (Greisinger, Germany), and an infra-red sensor for CO_2 (Pewatron Carbonoxy). A cooled (3 °C) liquid trap was installed to prevent condensation inside the pump and sensors. The gas flow was monitored by a flow meter (AMW 3300V; Honeywell, USA). The experimental setup included a N_2-inlet for nitrogen purging, a bypass for the insertion of biogas and a ventilation junction.

Prior to the upgrading experiments, the gas scrubber was cleaned with ethanol (75 % v/v) and rinsed with autoclaved deionised water to remove contaminants. Subsequently, 520 ml of *Chlorella vulgaris*- and *Chloroparva pannonica* suspension, respectively, were pumped from the photobioreactor to the scrubber via a peristaltic pump (Reefdoser R02, Aqua Medic, Germany). Within the scrubber, the algal suspension circulated anticlockwise for 40 min with a flow rate of 3.1 l·min^{-1}.

The flow was driven by 840 ml biogas, which was upgraded simultaneously by passing the algal suspension. The upgrading experiments were performed as duplicates within one day. Experiments with *Chlorella* were performed with two batches of 34.33 mmol (ca. 840 ml) biogas with a mean content of 13.73 mmol CO_2 and 787 µmol O_2 before upgrading. In *Chloroparva* experiments, two batches of 34.33 mmol biogas with a mean content of 13.73 mmol CO_2 and 743 µmol were tested. All upgrading experiments were performed at constant 20 °C and 1004 ± 2 mbar atmospheric pressure.

3 Results

3.1 Preparation of algal suspension

Chlorella vulgaris and *Chloroparva pannonica* were successfully cultured in our tubular photobioreactor at bench scale (Figure 3). *Chlorella vulgaris* grew with a ratio of 0.55·d^{-1} to a maximum of approximately 40·10^6 cells·ml^{-1}. *Chloroparva pannonica* showed a growth ratio of 0.49·d^{-1} and a maximum cell density of approximately 248 · 10^6 cells·ml^{-1}. Both growth curves were characterised by a short lag phase of approximately two days, followed by a log phase of approximately five days. For both algal strains, the transition from exponential growth to stationary growth phase was detected after circa seven culture days.

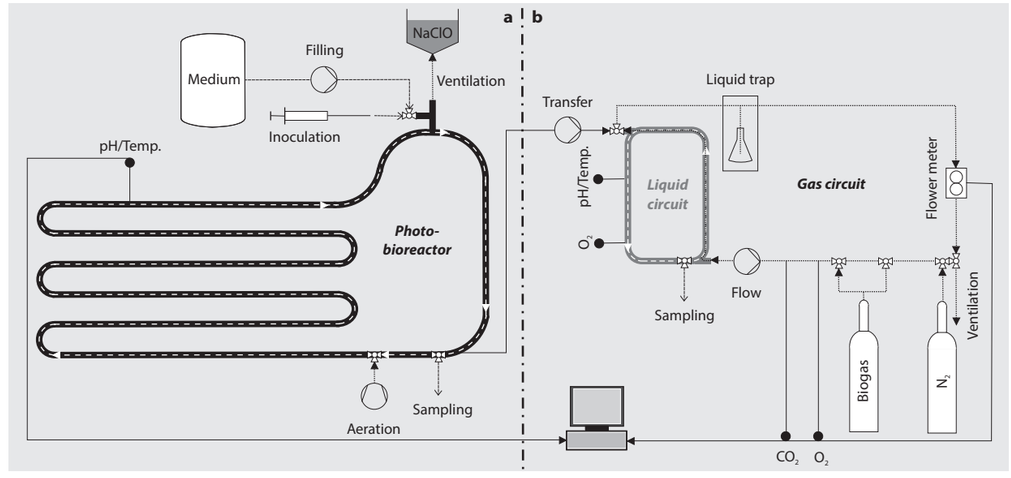

Figure 2
Scheme of a bench-scale system for biogas upgrading. (a) Closed tubular photobioreactor for culturing 4.9 l phototrophic microalgae, at 20 °C with a light-dark cycle of 16/8 h and a PFD of 60 µE. (b) Darkened gas scrubber for upgrading 34.33 mmol biogas with 520 ml microalgal suspension, at constant 20 °C and 1004 ± 2 mbar atmospheric pressure.

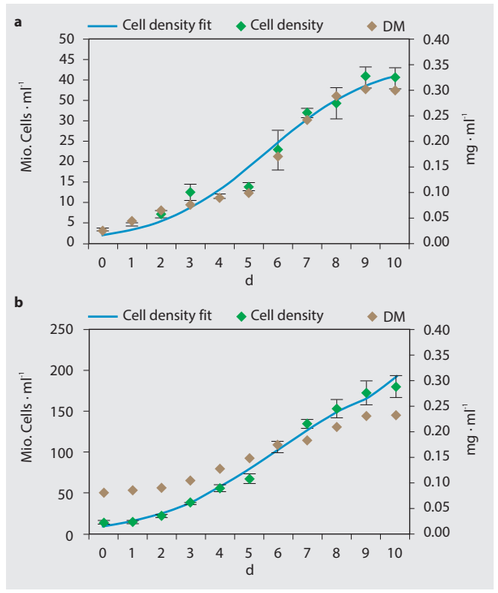

Figure 3
Cell density in Mio. cells per ml (n = 3) and algal biomass in mg per ml dry matter (DM) of (a) *Chlorella vulgaris* 211-11B and (b) *Chloroparva pannonica* 2358 in 3NBB-medium over a period of 10 days. Fit = fitted curve based on stepwise optimization of least deviation squares. Fed-batch cultures in a closed tubular photobioreactor at 20 °C, with a light-dark cycle of 16/8 h and a PFD of 60 µE.

Axenic *Chlorella* was cultured with a start biomass of 0.03 mg dry mass·ml^{-1}, whereas the non-axenic *Chloroparva* culture grew with a start biomass of 0.08 mg dry mass·ml^{-1}. Regarding maximum biomass concentration, *Chloroparva* grew to 0.23 mg·ml^{-1} and *Chlorella* to 0.30 mg·ml^{-1}, both after nine culture days. The cell growth curves of *Chlorella* corresponded with their biomass growth curves. In contrast, the usage of non-axenic cultures let to deviations between biomass growth rates and cell growth rates during the preparation of *Chloroparva* suspension.

3.2 Biogas upgrading

All upgrading experiments with dark-adapted algal suspensions resulted in a virtually complete removal of the CO_2 from the biogas batch within a short time (Figure 4). In each trial, a biogas batch was upgraded for 40 min at a fix gas to liquid ratio of 0.6 due to the construction of the gas scrubber. In tests with *Chlorella,* the CO_2 content of 34.33 mmol biogas dropped sharply by 94 % from 13.73 to 0.89 mmol within the first 10 seconds of the experiments. Subsequently, the CO_2 content decreased slightly to 0.02 mmol at 2:30 minutes and remained stable. Likewise, the pH of the *Chlorella* suspensions declined steeply from 8.91 to 6.57 during the first 10 seconds of the experiments. Subsequently, the pH dropped further to 6.14 at 1:10 minute and remained constant at 6.10 from 2:10 minutes onwards. Biogas scrubbing in *Chloroparva* suspension was characterised by a nearly logarithmic decline of CO_2 by 99 % from 13.73 to 0.02 mmol within 2:50 minutes. The pH in *Chloroparva* cultures declined steeply from 9.22 to 5.79 within the first 20 seconds of the tests. Subsequently, the pH dropped to 5.75 at 1:20 minute and 5.74 at 2:20 minutes.

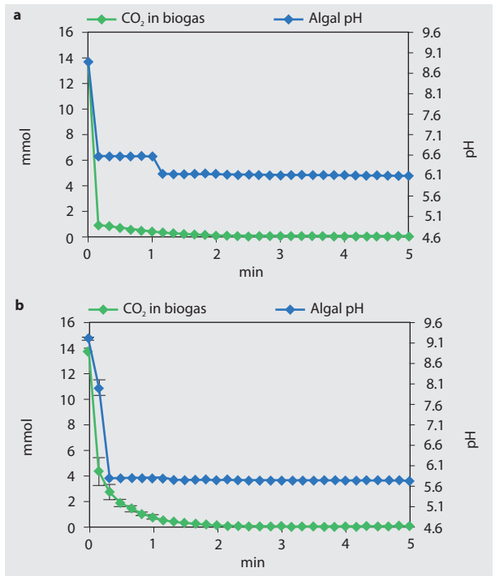

Figure 4
Removal of CO_2 [mmol] from biogas batches and pH value of darkened microalgal suspension during the first 5 min of biogas upgrading experiments. (a) Batches of 34.33 mmol (840 ml) biogas with an original CO_2 content of 13.73 mmol scrubbed in *Chlorella vulgaris* suspension with a start pH of 8.91. (b) Batches of 34.33 mmol (ca. 840 ml) biogas with an original CO_2 content of 13.73 mmol scrubbed in *Chloroparva pannonica* suspension with a start pH of 9.22. Biogas sparged repeatedly through 520 ml algal suspension in a darkened, loop-shaped gas scrubber for 40 min. CO_2 contents measured in the gas compartment and pH values measured in the liquid compartment of the gas scrubber at constant 20 °C and 1004 ± 2 mbar atmospheric pressure. N = 2.

3.3 Biogas contamination

No air- or O_2 contaminations were detected subsequent to biogas upgrading experiments. During upgrading, the aggregated levels of O_2 in the liquid and gaseous compartment were consistently lower than the O_2 contents in biogas prior to upgrading (Figure 5). Biogas upgrading in *Chlorella* suspension resulted initially in an increase of dissolved O_2 in the algal suspension. The maximum of dissolved O_2 in algal suspension (72 µmol) was reached after 12 minutes of biogas upgrading. This increase was followed by a decrease to 42 µmol, which was sustained through minute 40. The O_2 content in biogas reached a maximum of 733 µmol at minute 28 while passing the suspension repeatedly. Accordingly, the aggregated O_2 content in gas- and liquid compartment of the gas scrubber (O_2 total) increased to a steady maximum of 776 µmol at minute 28. Likewise, biogas upgrading with *Chloroparva* suspension showed a steady increase of dissolved O_2 in algal suspension. A peak of 42 µmol was measured after 4 minutes. Subsequently, dissolved O_2 declined to 30 µmol during the further progress of the experiments. A maximum of 700 µmol O_2 was detected in biogas after 27 minutes of passing the algal suspension repeatedly. As a result of the *Chloroparva* upgrading, the aggregated O_2 levels grew to a constant maximum of 732 µmol at minute 27.

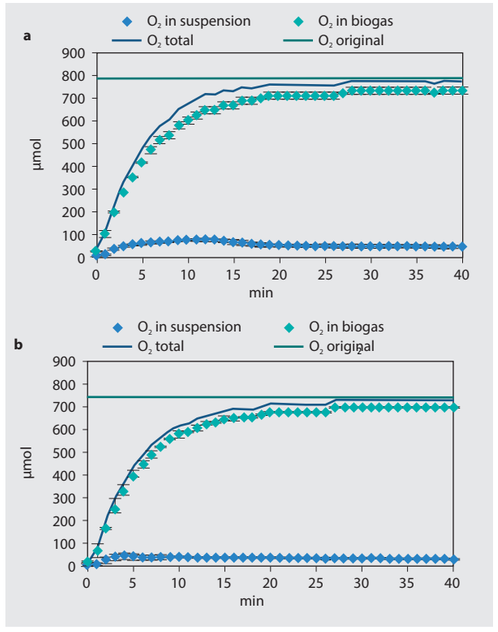

Figure 5
Increase of O_2 content [µmol] in 840 ml biogas and 520 ml darkened microalgal suspension during 40 minutes of biogas upgrading. (a) Batches of 34.33 mmol biogas with an original O_2 content of 787 µmol scrubbed in *Chlorella vulgaris* suspension. (b) Batches of 34.33 mmol biogas with an original O_2 content of 743 µmol scrubbed in *Chloroparva pannonica* suspension. O_2 content in biogas measured in the gas compartment and O_2 content in algal suspension measured in the liquid compartment of a darkened, loop-shaped gas scrubber at constant 20 °C and 1004 ± 2 mbar atmospheric pressure. Dotted line = original O_2 content of biogas prior to upgrading. N = 2.

4 Discussion

The use of microalgae for lowering the CO_2 content in biogas has been studied extensively. Scrubbing of biogas in 15 l *Arthrospira sp.* resulted in a CO_2 decrease from 44 to 48 % to 2.5 to 11.5 % in an unspecified biogas volume (Travieso et al., 1993). Similar results were achieved by Conde et al. (1993) with *Chlorella vulgaris*, under the same experimental conditions. Tietze et al. (2006) reported a CO_2 reduction as well as simultaneous O_2 formation in 34.9 l biogas after passing through 6 l of *Chlorella vulgaris* C-1 (IPPAS, Moscow) suspension. Their experiments were performed in two different illuminated gas scrubbers and resulted in a CO_2 reduction from 30.1 % to 6.1 % and 31.3 % to 7.6 %. Simultaneously, O_2 increased from 1.7 % to 26.6 % and 0.8 % to 25.4 %. Studies of Converti et al. (2009) resulted in a nearly complete removal of CO_2 from 140 to 200 l biogas when scrubbed in 1 l *Arthrospira platensis* suspension. The removal was accompanied by enrichment of O_2 in the upgraded gas in the range of 10 to 24 %. Similar results were achieved by scrubbing 3 l biogas in 450 ml *Chlorella vulgaris* 211 to 11B suspension by Mann et al. (2009). In these experiments the CO_2 proportion in biogas was lowered from 41 % to 1.2 % while O_2 increased from 1.0 % to 23.4 %. Schmack et al. (2009) reported a CO_2 removal of 92 % with a simultaneous increase of 2 % O_2 and 7 % N_2 to the cleaned gas.

Virtually all approaches in which photosynthetic microalgae were applied to biogas upgrading resulted in oxygenation of the upgraded gas. However, literature on the utilization of this type of product is scarce. Oxygenated biogas can be used, e.g., for the production of polyhydroxy butyric acid by methanotrophic organisms (Bäzold et al., 1998) or biochemical desulphurization of biogas (Krüger et al., 2007). Another promising process is based on the assimilation of CO_2 and O_2 by a microalgal-bacterial consortium (Bahr et al., 2014). However, this approach is H_2S-dependent and still subject of optimization.

In the present study, CO_2 was successfully removed from biogas. The reaction kinetics of the CO_2 removal from biogas and the pH value of the algal suspensions during upgrading (Figure 4) indicate that CO_2 was nearly completely absorbed by the algal medium. The CO_2 mass transfer was primarily affected by the volumetric ratio of biogas and liquid upgrading suspension (G/L ratio) as well as the pH of the upgrading suspension. In our experiments, 99 % of CO_2 (13.72 mmol) were removed from biogas at a fixed G/L ratio of 0.6 at pH values of 8.91 (*Chlorella*) and 9.22 (*Chloroparva*). The comparison of our findings with the literature is limited due to missing information about molar concentrations of CO_2 as well as varying parameters of CO_2 mass transfer in other studies. For example, the pH values of the algal suspension ranged from 6.8 (Tietze et al., 2006) to 9.5 (Converti et al., 2009). In addition, G/L ratios were between 0.6 and 200. However, Schmack et al. 2009 reported a CO_2 removal from biogas of 92 %. The biogas was upgraded in a mixture of *Chlorella* and *Spirulina* at a pH of 8.8 and a G/L of 0.6. Compared to these findings, the CO_2 removal of 99 % in our experiments resulted in upgraded biogas with a higher calorific value and less of a requirement for storage space. The mass transfer of CO_2 from biogas to *Chloroparva* suspension was also almost complete (13.718 mmol). However, in contrast to the *Chlorella* experiments, we found higher pH shifts in algal

suspension and slightly delayed CO_2 decreases in biogas. The deviations indicate a biological effect on CO_2 removal from biogas since the upgrading experiments with both algal species were performed under identical physical and chemical conditions. Such an effect could be caused by carbon concentration mechanisms (CCM), which can be found in other Trebouxiophyceae (Meyer and Griffith, 2013). However, further analyses of algal biomasses and -media are required to determine the exact mechanisms of this algal-specific influence on the CO_2 mass transfer.

Unlike previous reports on biogas upgrading with microalgae, we removed CO_2 from biogas without simultaneous oxygenation. During upgrading, the aggregated amounts of dissolved O_2 in algal media and gaseous O_2 in biogases were constantly lower than the original O_2 content in biogases prior to upgrading (Figure. 5). The apparent increase of O_2 in biogas until minute 28 (*Chlorella*) and 27 (*Chloroparva*) was a result of the biogas distribution within the gas scrubber and did not reflect the actual amount of substance in the system. In contrast, the absorption of O_2 in algal media was detected in real-time. The transition of O_2 into media was feasible since the media were undersaturated with O_2 which was a result of dark adaption prior to biogas upgrading. We assume that a part of the dissolved O_2 was respired by the dark-adapted algae since the aggregated O_2 levels in the gas scrubber were 1.4 % (*Chlorella*) and 1.5 % (*Chloroparva*) below the original O_2 contents. The respiration, in turn, lead to the formation of CO_2 during the upgrading process. However, the minimal CO_2 input did not have a significant impact on the overall CO_2 removal.

In our photobioreactor, we grew *Chlorella vulgaris*, which is a well-studied organism with respect to carbon dioxide removal from gaseous waste streams (Yun et al., 1996; Keffer and Kleinheinz, 2002; Douskova et al., 2009). In addition, we tested the recently described *Chloroparva pannonica* (Somogyi et al., 2011) for its growth characteristics in a photobioreactor. The photobioreactor cultures yielded 0.30 $g \cdot l^{-1}$ (*Chlorella*) and 0.23 $g \cdot l^{-1}$ (*Chloroparva*) dry matter. At the start of culturing, cell densities and biomasses of *Chloroparva* were higher than in *Chlorella*. On the one hand, this resulted from the comparatively small *Chloroparva* cells, which hindered matching the cell densities of the *Chlorella* cultures during the preparation of the photobioreactor inoculum. On the other hand, the *Chloroparva* cultures were not axenic and their biomass could not be used for matching the start biomass of the *Chlorella* cultures. Hence, the differences in algal growth characteristics in the photobioreactor cannot be clearly attributed to a specific factor. Nevertheless, the bench-scale photobioreactor proved to be suitable for the preparation of algal suspension for biogas upgrading. We grew *Chlorella* without contamination since sterilisable components and a custom setup for sterile inoculation were applied. Moreover, we demonstrated that *Chloroparva* can be grown in a photobioreactor.

Different from Schmack et al. (2009) and Bahr et al. (2014), we applied a discontinuous procedure to avoid contamination of upgraded biogas. We prevented air-contamination by culturing microalgae in a detached photobioreactor and inhibited oxygenation by upgrading in a darkened scrubber. In addition, we determined reaction kinetics of O_2- and CO_2 mass transfer from biogas into algal suspension in an innovative gas scrubbing loop. The present study also revealed potential for improvement of the system. During our experiments, a small quantity biogas was upgraded and, so far, effects on the methane content in the biogas were not determined. Also, the contact time for the phase transition of O_2 and CO_2 during gas scrubbing needs to be optimized since it was limited by the height of the gas scrubber and large bubble sizes. Finally, discontinuous processes are generally time-intensive. Despite its few technical limitations, our experimental system proved to be appropriate for studying the effects of microalgae and their culture media on biogas upgrading. These studies comprise the enhancement of the upgrading performance since the energy surplus from upgraded biogas determines the energy expenditure for its upgrading. In addition, valuable algal strains will be studied since a profitable algal production can compensate potential costs of biogas upgrading.

5 Conclusion

The present study describes a bench-scale system for detailed studies on the effects of microalgal strains and -media on the biogas upgrading process. In particular, the effects of the algal medium upon the CO_2- and O_2 mass transfers during biogas purification, which are largely disregarded in the literature, have been illustrated. Moreover, we demonstrated that the recently described green alga *Chloroparva pannonica* can be grown in a bench-scale photobioreactor. With our experimental upgrading system we created the basis for future studies on biogas upgrading with phototrophic microalgae. These studies include analyses of buffering substances, which cannot be used as carbon sources by microalgae, and biogas upgrading with alkaline algal suspensions.

References

Andrea M, Aspell J, Epathite P, Faupel J, Clifford M (2011) Appropriate technology: biogas : design and development of a biogas compression and storage system capable of implementation in the developing world ; final report. Nottingham : Univ, 5 p

Andriani D, Wresta A, Atmaja TD, Saepudin A (2014) A review on optimization production and upgrading biogas through CO_2 removal using various techniques. Appl Biochem Biotechnol 172:1909-1928

Bahr M, Díaz I, Dominguez A, Díaz I, González A, Muñoz R (2014) Microalgal-biotechnology as a platform for an integral biogas upgrading and nutrient removal from anaerobic effluents. Environ Sci Technol 48:573-581

Bari S (1996) Effect of carbon dioxide on the performance of biogas/diesel duel-fuel engine. Renew Energy 9(1-4):1007-1010

Bäzold D, Kretschmer A, Menschel C, Pannig F, Scharr S (1998) Verfahren und Vorrichtung zur photobiologischen Trennung von kohlendioxid- und methanhaltigen Gasgemischen. Patent No DE19721280A1, 19 11 1998

Benemann J, Pedroni PM, Davison J, Beckert H, Bergman P (2003) Technology roadmap for biofixation of CO_2 and greenhouse gas abatement with microalgae [online]. To be found at <http://www.netl.doe.gov/publications/proceedings/03/carbon-seq/PDFs/017.pdf> [quoted 14.07.2016]

Conde JL, Moro LE, Travieso L, Sánches EP, Leiva A, Dupeirón R, Escobedo R (1993) Biogas purification process using intensive microalgae cultures. Biotechnol Lett 15(3):317-320

Converti A, Oliveira RPS, Torres BR, Lodi A, Zilli M (2009) Biogas production and valorization by means of a two-step biological process. Bioresour Technol 100:5771-5776

Deublein D, Steinhauser A (2011) Biogas from waste and renewable resources : an introduction. Weinheim : Wiley-VCH, 486 p

Douskova I, Doucha J, Livansky K, Machat J, Novak P, Umysova D, Zachleder V, Vitova M (2009) Simultaneous flue gas bioremediation and reduction of microalgal biomass production costs. Appl Microbiol Biotechnol 82(1):179-85

Edelmann W (2001) Biogaserzeugung und Nutzung. In: Kaltschmitt M, Hartmann H (eds) Energie aus Biomasse. Berlin : Springer, pp 680

Kaštánek F, Šabata S, Šolcova O, Malěterová Y, Kaštánek P, Bránykiová I, Kuthan K, Zachleder V (2010) In-field experimental verification of cultivation of microalgae *Chlorella sp.* using the flue gas from a cogeneration unit as a source of carbon dioxide. Waste Manage Res 28(11):961-966

Keffer JE, Kleinheinz GT (2002) Use of *Chlorella vulgaris* for CO_2 mitigation in a photobioreactor. J Ind Microbiol Biotechnol 29(5):275-280

Khoiyangbam RS, Gupta N, Kumar S (2011) Biogas technology : towards sustainable development. New Delhi : Energy and Ressources Inst, 200 p

Krüger K, Hirtz E, Fürstenhof U (2007) Verfahren und Vorrichtung zur Erzeugung von methanreichem Biogas. Patent No DE102005025040B4, 16 p

Kumar A, Ergas S, Yuan X, Sahu A, Zhang Q, Dewulf J, Malcata FX, van Langenhove H (2010) Enhanced CO_2 fixation and biofuel production via microalgae : recent developments and future directions. Trends Biotechnol 28(7):371-380

Mann G, Schlegel M, Schumann R, Sakalauskas A (2009) Biogas-conditioning with microalgae. Agron Res 7(1):33-38

Meyer M, Griffiths H (2013) Origins and diversity of eukaryotic CO_2-concentrating mechanisms : lessons for the future. J Exp Bot 64(3):769-786

Petersson A, Wellinger A (2009) Full scale technology for biogas upgrading. In: Petersson A, Wellinger A (eds) Biogas upgrading technologies - developments and innovations. IEA Bioenergy, pp 9-12

Schmack D, Schneider G, Nusko R (2009) Effizienzsteigerung der Biogasnutzung durch Solarenergie : EBSIE-Technikumsphase ; Abschlussbericht [online]. To be found at <http://www.fnr-server.de/ftp/pdf/berichte/22017105.pdf> [quoted 14.07.2016]

Somogyi B, Felföldi T, Solymosi K, Makk J, Homonnay ZG, Horváth G, Turcsi E, Böddi B, Márialigeti K, Vörös L (2011) *Chloroparva pannonica* gen. et sp. nov. (Trebouxiophyceae, Chlorophyta) : a new picoplanktonic green alga from a turbid, shallow soda pan. Phycologia 50:1-10

Starr RC, Zeikus JA (1993) UTEX - the culture collection of algae at the University of Texas at Austin. J Phycol 29(Suppl S2):1-47

Tietze M, Schalk T, Hoeft S, Kühn V, Krebs P (2006) Verbundvorhaben: Labor- und halbtechnische Untersuchungen zur Entwicklung eines Algenreaktors für die Anreicherung von Methan in Biogasen aus der anaeroben Klärschlammfaulung : Abschlussbericht ; Teil 2 [online]. To be found at <http://www.cleaner-production.de/fileadmin/assets/bilder/BMBF-Projekte/02WS0182_-_Abschlussbericht.pdf> [quoted 14.07.2016]

Travieso L, Sánches EP, Benitez F, Conde JL (1993) Intensive cultures for food and biogas purification. Biotechnol Lett 15(10):1091-1094

Wang B, Yanqun L, Wu N, Lan CQ (2008) CO_2 bio-mitigation using microalgae. Appl Microbiol Biotechnol 79:707-718

Yun YS, Park JM, Yang JW (1996) Enhancement of CO_2 tolerance of *Chlorella vulgaris* by gradual increase of CO_2 concentration. Biotechnol Tech 10(9):713-716