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Co-digestion of sewage sludge and microalgae – Biogas production investigations

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HIGHLIGHTS

- Abs tract of previous results on co-digestion of sewage sludge and microalgae.
- Experiments at thermophilic and semi-continuous conditions are scarce.
- Synergetic effects are indicated in some studies but not proved.
- Microalgae and wastewater sludge have several similarities.
- System level investigations, with biogas production and nutrient recovery, are needed.

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ABSTRACT

In municipal wastewater treatment plants (WWTPs), algae could be utilised for cleaning the water and, at the same time, produce a biomass that can be used for energy. Through anaerobic digestion, microalgae can contribute to biogas production when co-digested with sewage sludge. In this paper, previous published results on the co-digestion of sewage sludge and microalgae are summarised and reviewed, and any remaining knowledge gaps are identified. The batch tests currently documented in literature mostly concern digestion under mesophilic conditions, and studies investigating thermophilic conditions are less common. The average biochemical methane potential (BMP) for 29 different mixtures co-digested under mesophilic conditions is 317 ± 101 N cm^3 CH_4 gVS^{-1} while the result for 12 different mixtures investigated under thermophilic conditions is a BMP of 318 ± 60 N cm^3 CH4 gVS^{-1}. An evaluation of the heat required for increasing the temperature from mesophilic to thermophilic conditions shows that increased methane production under thermophilic conditions can be enough to create a positive energy balance. For a full-scale WWTP, using thermophilic digestion on sludge, or a combination of sludge and microalgae could therefore be of interest. This is dependent on the demands on sanitation of the sludge and the possibilities for heat recovery.

Most of the mesophilic investigations indicate a synergetic effect for co-digestion, with enhancements of up to almost 70%. However, the results are uncertain since the standard deviations for some of the BMP tests are in the same order of magnitude as the identified enhancement. Neither of the presented publications provide an understanding of the basic mechanisms that led to higher or lower BMP when microalgae were mixed with wastewater sludge. We, therefore, call for care to be taken when assuming any effects related to the specification of substrates. Microalgae and wastewater sludge have several similarities, and the specific results of BMP in the mixtures relate more to the specifics of the respective materials than the materials themselves.

Investigations into semi-continuous processes of co-digestion of microalgae and sludge are scarce. The yields for three co-digestion studies show high variation, with an average of 293 ± 112 N cm^3 $gVS_{in}{}^{-1}$. The available results show strong potential for co-digestion of sewage sludge and microalgae. Further investigations are required to identify optimal conditions for biogas production, and analysis of microalgae implementation on wastewater treatment at a system level is also needed to identify the total mass balance of substrate and nutrient recovery.

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1. Introduction

Of possible renewable energy sources, biomass from microalgae is a promising resource [1]. Compared to other biomass resources, it has a high growth rate and it can be cultivated without competition for food, with production on valuable land areas. Brune et al. [2] have demonstrated that CO_2 mitigation of microalgae systems is 10 times more efficient than that in forests. There are many different pathways for microalgae cultivation and biofuel production, as described by Zhu [3] and Singh and Olsen [4]. A potential, strong process solution for municipal wastewater treatment plants is to utilize algae for cleaning water while producing biomass that can be used for energy [5–9]. Theoretical calculations based on stoichiometric balancing show a potential methane production of almost 20% higher per reduced N for microalgae based wastewater treatment plants, compared to traditional activated sludge processes [6] when utilizing microalgae for biogas production by anaerobic digestion. By introducing algae to the wastewater treatment plant, several benefits can be achieved. The algae provide a path for balancing the unfavourable carbon to nitrogen (C/N) ratio found in today's municipal wastewater treatment plants, based on the activated sludge process, by capturing CO_2 during growth, instead of using organic carbon. This will lead to more sustainable nutrient recovery and a higher biogas production, since more biomass is produced in the system. Microalgae also produce oxygen that can be used by the bacteria cleaning the wastewater, so the need for aeration of the treatment step decreases, which also contributes to a more energy efficient process. Several process solutions for introducing microalgae into municipal wastewater treatment leading to biogas production by anaerobic digestion are possible. For most solutions, however, microalgae are likely to be a co-substrate in the biogas production step, since there will still be primary and waste activated sludge if microalgae are only partly integrated or used to treat the reject water flow.

The use of microalgae for the up-grading of biogas by CO_2 capture, and the cultivation of microalgae in the digestate from biogas production, are other possibilities for utilizing microalgae in biogas production that have been reviewed and demonstrated by Yan et al. [9,10] and Zhu et al. [11].

Experimental studies on the co-digestion of sewage sludge and microalgae under different conditions, including batch tests and continuous tests, are described in [12–24]. Important issues for a full-scale plant include maintaining a stable operation and optimal biogas production, while also maintaining suitable digestate characteristics. The compositions of the substrates are important for achieving a stable degradation process. A C/N ratio that is too low can lead to high ammonia levels that inhibit the production of biomethane, especially at high process temperatures [14,15,17,25,26]. Another factor that can decrease biomethane production is low substrate availability for microorganisms, for example due to large particle sizes or cell wall resistance [14,17,26]. The possibility for dewatering the digestate, to recover nutrients (phosphorous and nitrogen), and keeping low levels of metals and other possible harmful substances, is important and depending on its characteristics [16–18]. In [13,16], it was shown that co-digestion with microalgae enhances the dewaterability of the digestate.

Although, as described above, several studies have been conducted on the co-digestion of microalgae and sludge for biogas production, no conclusions or statements on the overall knowledge and directions for further studies have been presented. Some studies report on synergetic effects (for example [21,22,25]), while others indicate similar biomethane production from microalgae, sludge and their mixtures (for example [24]). In this paper, experiences and results from previous studies on co-digestion of sewage sludge and microalgae both in batch and continuous tests at mesophilic and thermophilic conditions are addressed. The aim is to summarize and compare these results, and identify remaining knowledge gaps for further understanding to aid the development of a process design for biogas production in wastewater treatment plants with integrated algae cultivation.

2. Review outline

The paper presents a compilation of literature covering microalgae as a co-substrate to sewage sludge for biogas production. Batch tests under both mesophilic and thermophilic conditions are included and compared. Possible synergetic effects are evaluated, based on the results of biochemical methane potential (BMP) tests on single substrates. Enhanced yield is expressed as the ratio between the differences between measured and calculated BMP of the mixtures, and the calculated BMP obtained from the results of mono-digestion of the respective substrate. When available data allow it, the theoretical methane potential is determined from the content of lipids, carbohydrates and proteins, and calculated based on the equation given by Symmons and Buswell [27] and previously used in studies by Angelidaki et al. [28], Wang and Park [14] and Patinvoh et al. [29], see Eq. (1).

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + sH_2S + (c-x)CO_2. \quad (1)$$

With the compositions of $C_5H_7O_2N$, $C_6H_{10}O_5$ and $C_{57}H_{104}O_6$ for proteins, carbohydrates and lipids, the theoretical biomethane potentials are 496, 415 and 1014 N cm^3 CH_4 gVS^{-1} [28]. The conversion efficiency is expressed as the ratio between the measured potential and the theoretical potential. When data for volatile solids (VS) degradation is available, the conversion efficiency is expressed as the ratio between the amounts of degraded VS and added VS instead.

Results from continuous digestion investigations are collected and compared. Here, the influence of the organic loading rate (OLR) and hydraulic retention time (HRT) on biomethane production and process stability are selected as factors for evaluation.

The heat balance between thermophilic and mesophilic digestion of microalgae and sewage sludge is also evaluated, based on results presented in two of the previous studies [15,17].

3. Microalgae as substrate for biogas production

3.1. Characteristics

In Table 1, the characteristics of the substrates used in the different tests are shown. An advantage of co-digestion could be the possibility for achieving an improved C/N ratio, and balance of other macro- and micronutrients, rapidly-degradable carbohydrates and slowly-degradable proteins and fats, as mentioned in [30]. From the characteristics given for different microalgae and sewage sludges (Table 1), it is not clear whether co-digestion of microalgae and sludge can provide those benefits, since the C/N ratios and compositions of lipids, carbohydrates and proteins are similar. The average C/N ratio of all of the microalgae samples investigated (7.4 ± 3) is only slightly higher than the C/N ratios observed in WAS (4.7–5.5). The characteristics, rather, indicate similar behaviour between the digestion of microalgae, sludge and mixtures of microalgae and sludge. Similar characteristics have been observed in previous studies (for example [18]).

Despite this, several studies report on synergetic effects when co-digesting microalgae and sludge (for example [14–15,18]). Another possible reason for the beneficial effects of co-digestion is improved balance of essential trace metals (Se, Co, Mo and Ni) [12,16]. In [16], it is demonstrated that the microalgae (M3) contain more Co, Mo and Ni than the sludge (S2 and S3).

The second culture of microalgae (M2) is dried, and microalgae 3, 6, 11 & 16 (M3, M6, M11 and M16) and sludge 14 & 15 (S14 and S15) are frozen. Microalgae 10 (M10) and sludge 9 (S9) are thermally pre-treated at 120 °C for 40 min. All of the other substrates (M1–M2, M5, M7–M9, M12–M15, S1–S8, S10–S13 and S16) are not pre-treated. According to Bohutskyi and Bouwer [31], studies have shown that drying can reduce the biogas potential of microalgae by up to 20%, while thermal pre-treatment can increase biogas potential, which is dependent on temperature, treatment duration and biomass concentration.