Co-digestion of Sewage Sludge and Microalgae- Biogas Production Investigations

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Abstract

At municipal waste water treatment plants algae could be utilized for cleaning the water and in the same time produce biomass that can be used for energy utilization. By anaerobic digestion the microalgae can contribute to biogas production when co-digested with sewage sludge. In this paper previous published results on co-digestion of sewage sludge and microalgae are summarized and remaining knowledge gaps are identified. The available batch tests in literature mostly concern digestion at mesophilic conditions and studies on investigations of thermophilic conditions are less common. Most of the mesophilic investigations indicate a synergetic effect for the co-digestion. Also investigations of semi-continuous processes of co-digestion of microalgae and sludge are scarce. The available results show good possibilities for co-digestion of sewage sludge and microalgae. Further investigations are needed to find optimal conditions for biogas production and analysis on a system level of microalgae implementation on waste water treatment to also identify the total mass balance of substrate and nutrient recovery.

Keywords: biomass, waste water treatment, batch, continuous, BMP, anaerobic digestion

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1. Introduction

Among the possible renewable energy sources biomass from microalgae is a promising resource. Compared to other biomass resources the growth rate is high and it can be cultivated without competition to food production on valuable land areas. Brune et al. [1] have shown that CO_2 mitigation with microalgae systems are 10 times more efficient than forests. An attractive process solution for municipal waste water treatment plants is to utilize algae for cleaning the water and in the same time produce biomass that can be used for energy utilization [2-4]. Theoretical calculations based on stoichiometric balancing show a potential of almost 20% higher methane production per reduced N for a microalgae based waste water treatment plant compared to the traditional activated sludge process [2] when utilizing the microalgae biomass for biogas production by anaerobic digestion. By introducing algae in the waste water treatment plant several benefits can be achieved. By capturing CO_2 when growing, instead of using organic carbon, the algae provide a path to balance the unfavorable C/N ratio in today's municipal waste water treatment plants based on the activated sludge process. This will lead to a more sustainable nutrient recovery and higher biogas production since more biomass is produced in the system. The microalgae also produce oxygen that can be used by the bacteria cleaning the waste water and the need for aeration of the treatment step decrease which also contributes to a more energy efficient process. Several process solutions introducing microalgae in municipal waste water treatment with following biogas production by anaerobic digestion are possible. However, for most solutions microalgae will probably be a co-substrate in the biogas production process step since there will still be primary sludge and still also waste activated sludge if microalgae are only partly integrated or used to treat the reject water flow.

Experimental studies on co-digestion of sewage sludge and microalgae at different conditions including batch test and continuous tests are described in [5-17]. Important issues for a full-scale plant are the possibility to maintain stable operation and optimal

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biogas production but also suitable digestate characteristics. The compositions of the substrates are important for achieving stable degradation processes. Too low carbon to nitrogen (C/N) ratio can lead to high ammonia levels that inhibit the production of biomethane, especially at high process temperatures [7, 8, 10, 18, 19]. Another factor that can decrease the biomethane production is low availability of the substrates for the microorganisms, for example due to large particle size or cell wall resistance [7, 10, 19]. Concerning digestate characteristics, the possibility to dewater the digestate, to recover nutrients (phosphorous and nitrogen) and low levels of metals and other possible harmful substances are important [9-11]. In [6] and [9] it was shown that co-digestion with microalgae enhance the dewaterability of the digestate.

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 the results of previous studies, and identify remaining knowledge gaps for further understanding and development of process design for biogas production at waste water treatment plants with integrated algae cultivation.

2. Methods

The paper presents a compilation of significant literature in the area of microalgae as a co-substrate to sewage sludge for biogas production. Batch tests in both mesophilic and thermophilic conditions are included and compared. Possible synergetic effects are evaluated based on results of biochemical methane potential (BMP) tests on single substrates. The enhanced yield is expressed as the ratio between the difference between the measured and calculated BMP of the mixtures and the calculated BMP obtained from results of mono-digestion of the respective substrate. When the available data allows, the theoretical methane potential is determined from the content of lipids, carbohydrates and proteins and calculated based on the equation given by Symmons and

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Buswell [20] and previously used in for example studies by Angelidaki et al [21], Wang and Park [7] and Patinvoh et al [22], see equation 1.

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + sH_2S + (c\text{-}x)\ CO_2 \qquad \text{Eq 1.}$$

With the compositions $C_5H_7O_2N$, $C_6H_{10}O_5$ and $C_{57}H_{104}O_6$ for proteins, carbohydrates and lipids the theoretical biomethane potentials are 496, 415 and 1014 Ncm^3 CH_4 gVS^{-1} [21]. 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 instead expressed as the ratio between the amounts of VS degraded and VS added.

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

3. Results

3.1. Characteristics

In Table 1 the characteristics of the substrates used in the different tests are shown. An advantage of co-digestion can be the possibility to achieve a better C/N ratio and better balance of also other macro- and micronutrients and of fast degradable carbohydrates and slower degradable proteins and fats as mentioned in [23]. From the characteristics given for the different microalgae and sewage sludge (Table 1) it is not obvious that co-digestion of microalgae and sludge can give those benefits since the C/N ratios and compositions of lipids, carbohydrates and proteins are similar. The average C/N ratio of all microalgae samples investigated (7.4±3) is only slightly higher than the C/N ratios observed in WAS (4.7-5.5). Another possible reason for beneficial effects for co-digestion is better balance of essential trace metals (Se, Co, Mo and Ni) [5, 9].

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Table 1. Characteristics of substrates used in the BMP and continuous tests.

Substrate	TS [%]	VS [% of TS]	C/N	Protein [% of TS]	Carbohydrates [% of TS]	Lipids [% of TS]	Ref.
M1-Microalgae 1 (cult. in lw)	4.3	70	9.4	26	36	7	[8]
M2-Microalgae 2 (cult. in mww)	90	65	7.8	26	31	3	[8]
M3-Microalgae 3 (cult. in mww)	8.4	59	5.9	33	35	3	[9]
M4-Microalgae 4 (*Chlorella*)	0.73	81	13.4[a]	47	-	-	[6]
M5-Microalgae 5 (*Micratinium*)	0.69	76	12.0[a]	52	-	-	[6]
M6- Microalgae 6 (*Spirulina platensis*)	1.5	50	6	-	-	-	[5]
M7- Microalgae 7 (*Isochrysis galbana*)	0.9-1.0	90	7.1	46	14	20	[10]
M8- Microalgae 8 (Selenastrum *capricornutum*)	0.9-1.0	98	9.2	39	29	30	[10]
M9- Microalgae 9 (*Chlorella vulgaris*)	10.84	79	4.6	55	16	0	[11]
M10- Microalgae 10 (pre-treated M9)	5.41	84	5.7	45	25	0	[11]
M11- Microalgae 11(*Spirulina maxima)*	4.5	86	4.2	-	-	-	[12]
M12- Microalgae 12 (*Chlorella sorokiniana*)	-	94[b]	5.3	-	-	-	[13]
M13- Microalgae 13 (*Chlorella Sp.)*	10	-	5.4	67	6	16	[14]
M14-Microalgae 14 (*Scenedesmus sp.)*	-	-	-	-	-	-	[15]
M15-Microalgae 15 (*Chlorella sp.)*	-	-	-	-	-	-	[15]
M16-Microalgae 16 (mix of *Chlorella sorokiniana and Scenedesmus sp*.)	0.68	84	33[a]	-	-	-	[16]
M17- Microalga 17 (*Chlorella sp.)*	0.77	64	66[a]				[17]
Average and standard deviation		77 ±14	7.4±3[a]				
S1-Sludge 1 (mixed WAS+ PS)	3.5	80	9.2	25	43	11	[8]
S2-Sludge 2 (WAS)	5.4	73	4.7	49	19	6	[9]
S3-Sludge 3 (PS)	5.5	77	12.7	18	45	9	[9]
S4-Sludge 4 (WAS)	0.74	73	10.3[a]	-	-	-	[6]
S5-Sludge 5 (WAS)	1.5	67	-	-	-	-	[5]
S6-Sludge 6 (mixed WAS+PS)	3.05	88	-	-	-	-	[10]
S7-Sludge 7 (WAS)	3.98	72	5.5	35	43	0	[11]
S8 – Sludge 8 (PS)	2.96	67	10.0	27	46	0	[11]
S9-Sludge 9 (pre-treated S7)	-	-	-	-	-	-	[11]
S10-Sludge 10 (PS)	4.8	78	14	-	-	-	[12]
S11-Sludge 11 (WAS)	-	-	4.9	-	-	-	[13]
S12-Sludge 12 (PS)	18.5	-	7.8	-	-	-	[14]
S13-Sludge 13 (mixed WAS+PS)	-	-	-	-	-	-	[15]
S14-Sludge 14 (WAS[c])	1	72	17[a]	-	-	-	[16]
S15-Sludge 15 (WAS[c])	1	78	16[a]	-	-	-	[17]
S16-Sludge 16 (WAS)	0.21	72	13[a]	-	-	-	
Average and standard deviation		74±7	9.5±3[a]				

cult.= cultivated, lw=lake water, mww= municipal waste water, [a] COD/N ratio instead of C/N ratio, the values are not included in the average, [b] VS given as kg/kg, [c] from a short solids retention time (SRT) activated sludge systems, aerobic phase (S14) and anaerobic phase (S15), WAS=waste activated sludge, PS= primary sludge, - = data not available

In [9] it is shown that the microalgae (M3) contain more Co, Mo and Ni than the sludge (S2 and S3).

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The second culture of microalgae (M2) is dried. Microalgae 3, 6, 11 and 16 (M3, M6, M11and M16) and Sludge 14 and 15 (S14 and S15) are frozen. Microalgae 10 (M10) and Sludge 9 (S9) are pre-treated thermally at 120°C for 40 minutes. All other substrates (M1-M2, M5, M7- M9, M12-M15, S1- S8, S10-S13, and S16) are not pre-treated. According to Bohutskyi and Bouwer [24] studies have shown that drying can reduce the biogas potential of microalgae up to about 20% while thermal pre-treatment can increase the biogas potential and the increase is dependent on temperature, treatment duration and biomass concentration.

3.2. Batch tests

The results of the batch tests are presented in Table 2 and 3. Table 2 shows the results from batch tests conducted at temperatures 33-37 °C, corresponding to mesophilic conditions, while the results presented in Table 3 are from tests conducted at temperatures 50-55 °C, corresponding to thermophilic conditions. In both Table 2 and 3 the measured BMP values are given for digestion of single substrates as well as for digestion of mixtures and for the tests on mixtures the BMP calculated from the BMP of the single substrates is also given. In Figure 1 the average BMP for the sludge, microalgae and mixtures of sludge and microalgae in tests 1-7 and 12-18 are shown and the standard deviations are also indicated. The ten different types of sewage sludge used in the mesophilic tests 1-7 and 12-18 have a BMP of 304 ± 118 Ncm^3 CH_4 gVS^{-1}, the 13 different microalgae used in the same tests have a BMP of 258 ± 106 Ncm^3 CH_4 gVS^{-1} and the BMP for the 29 different mixtures co-digested is 317 ± 101 Ncm^3 CH_4 gVS^{-1}, which shows that the variation is large.

For the microalgae, the methane production decreases in thermophilic conditions compared to the production in mesophilic conditions while sewage sludge digestion result in higher methane yields in thermophilic conditions. Also for the thermophilic tests the variation in the results is large with a BMP of 210 ± 78 Ncm^3 CH_4 gVS^{-1} for the microalgae and a BMP of 318 ± 60 Ncm3 CH4 gVS-1 for the different mixtures.

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Table 2a. Results of batch tests at mesophilic conditions. Batch tests 1-10

Batch test nr	Substrate [% of VS content]	Temp. [°C]	Meas. BMP [Ncm^3 CH_4 gVS^{-1}]	Calc. BMP [Ncm^3 CH_4 gVS^{-1}]	Enhanced yield [%]	Theor. BMP [Ncm^3 CH_4 gVS^{-1}]	Conv. Effi. [%] Meas./ Theor.	Ref.
1	100 % S1	37	331±35	-	-	521	64	[8]
1	88% S1 + 12% M1	37	344±15	335	3	519	66	[8]
1	75% S1+25% M1	37	358±61	350	2	516	69	[8]
1	63% S1+ 37% M1	37	408±17	355	15	514	79	[8]
1	100 % M1	37	367±5	-	-	503	73	[8]
2	88% S1+ 12% M2	37	387±67	313	24	512	75	[8]
2	75% S1+ 25% M2	37	348±65	293	19	502	67	[8]
2	63% S1+ 37% M2	37	325±67	283	15	494	63	[8]
2	100 % M2	37	179±38	-	-	447	40	[8]
3	35% S2 + 65% S3	35	317±2	-	-	595	64	[a]
3	19%S2 +39% S3+42%M3	35	239±9	235	2	526	45	[a]
3	100% M3	35	120±2	-	-	447	40	[a]
4	100 % S4	mesoph.	243	-	-	-	60[b]	[6]
4	79% S4 + 21% M4	mesoph.	253	240	5	-	56[b]	[6]
4	100 % M4	mesoph.	230	-	-	-	42[b]	[6]
5	79% S4+ 21% M5	mesoph.	236	236	0	-	59[b]	[6]
5	100 M5	mesoph.	209	-	-	-	40[b]	[6]
6	100 % S6	33	347±9	-	-	-	-	[10]
6	75 % S6+25% M7	33	318±5	345	-8	-	-	[10]
6	50 % S6+50% M7	33	356	343	4	-	-	[10]
6	25 % S6+75% M7	33	343	340	1	-	-	[10]
6	100 % M7	33	338±3	-	-	562	62	[10]
7	75 % S6+25% M8	33	303±11	312	-3	-	-	[10]
7	50 % S6+50% M8	33	302±3	278	9	-	-	[10]
7	25 % S6+75% M8	33	254±5	243	5	-	-	[10]
7	100 % M8	33	209±5	-	-	632	33	[10]
8	100 % S7	35	80±2[c]	-	-	494	-	[11]
8	75 % S7+25% M9	35	92±2[c]	87[c]	5	-	-	[11]
8	50 % S7+50% M9	35	91±8[c]	94[c]	-4	-	-	[11]
8	25 % S7+75% M9	35	107±8[c]	101[c]	6	-	-	[11]
8	100 % M9	35	108±1[c]	-	-	460	-	[11]
9	100 % S8	35	266±14[c]	-	-	490	-	[11]
9	75 % S8+25% M9	35	252±4[c]	227[c]	11	-	-	[11]
9	50 % S8+50% M9	35	210±3[c]	187[c]	12	-	-	[11]
9	25 % S8+75% M9	35	171±3[c]	148[c]	16	-	-	[11]
10	100% S9	35	95±3[c]	-	-	408	-	[11]
10	75 % S9+25% M10	35	103±3[c]	115[c]	-11	-	-	[11]
10	50 % S9+50% M10	35	140±6[c]	135[c]	3	-	-	[11]
10	25 % S9+75% M10	35	152±6[c]	155[c]	-4	-	-	[11]
10	100 % M10	35	176±5[c]	-	-	393	-	[11]
11	75 % S8+25% M10	35	293±10[c]	254[c]	15	-	-	[11]
11	50 % S8+50% M10	35	283±15[c]	243[c]	16	-	-	[11]
11	25 % S8+75% M10	35	262±3[c]	232[c]	13	-	-	[11]

[a] tests described in [9] but data not previously published, [b]conversion efficiency based on VS degradation, [c]the unit for the results are Ncm^3 CH_4 $gCOD^{-1}$,- = data not available

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Table 2b. Results of batch tests at mesophilic conditions. Batch tests 11-18

Batch test nr	Substrate [% of VS content]	Temp. [°C]	Meas. BMP [Ncm^3 CH_4 gVS^{-1}]	Calc. BMP [Ncm^3 CH_4 gVS^{-1}]	Enhanced yield [%]	Theor. BMP [Ncm^3 CH_4 gVS^{-1}]	Conv. Effi. [%] Meas./ Theor.	Ref.
12	100% S11	35	362	-		-	-	[13]
12	75%S11+25% M12	35	442	351	26	-	-	[13]
12	50%S11+50% M12	35	380	340	12	-	-	[13]
12	25%S11+75% M12	35	354	329	8	-	-	[13]
12	100% M12	35	318	-	-	-	-	[13]
13	100%S12	35	127 ± 7.2[d]	-	-	-	-	[14]
13	50%S12+50%M13	35	116 ± 3.5[d]	76	53	-	-	[14]
13	100% M13	35	25 ± 2[d]	-	-	-	-	[14]
14	100%S13	37	414	-	-	-	-	[15]
14	50%S13+50%M14	37	411	382	8	-	-	[15]
14	100%M14	37	351	-	-	-	-	[15]
15	50%S13+50%M15	37	416	382	9	-	-	[15]
15	100%M15	37	349	-	-	-	-	[15]
16	100%S14	37	363±68	-	-	-	-	[16]
16	90%S14+10%M16	37	400 ± 22	360	11			[16]
16	100%M16	37	331 ± 76	-	-	-	-	[16]
17	100%S15	37	449±17	-	-	-	-	[16]
17	90%S15+10%M16	37	560±24	437	28	-	-	[16]
18	100% S16	35	86[f]	-		-	-	[17]
18	95%S16+5%M17	35	96[f]	98	-2	-	-	[17]
18	90%S16+10%M17	35	122[f]	110	11	-	-	[17]
18	75%S16+25%M17	35	209[f]	147	43	-	-	[17]
18	60%S16+40%M17	35	307[f]	183	68	-	-	[17]
18	50%S16+50%M17	35	317[f]	207	53	-	-	[17]
18	25%S16+75%M17	35	275[f]	268	3	-	-	[17]
18	100%M17	35	328[f]	-				[17]

[d] the unit of the measurement results are not clear, [f] values read from graph - = data not available

Table 3. Results of batch tests at thermophilic conditions.

Batch test nr	Substrate [% of VS content]	Temp. [°C]	Meas. BMP [Ncm^3 CH_4 gVS^{-1}]	Calc. BMP [Ncm^3 CH_4 gVS^{-1}]	Enhanced yield [%]	Theor. BMP [Ncm^3 CH_4 gVS^{-1}]	Conv. Effi. [%] Meas./ Theor.	Ref.
19	100 % S1	55	363±6	-	-	521	70	[8]
19	88% S1+ 12% M1	55	388±75	358	8	519	75	[8]
19	75% 1+25% M1	55	338±65	352	-4	516	65	[8]
19	63% S1+ 37% M1	55	321±15	356	-10	514	62	[8]
19	100 % M1	55	317±53	-	-	503	63	[8]
20	88% S1+ 12% M2	55	323±8	337	-4	512	62	[8]
20	75% S1+25% M2	55	298±55	307	-3	502	58	[8]
20	63% S1+37% M2	55	276±10	281	-2	494	54	[8]
20	100 % M2	55	150±13	-	-	447	34	[8]
21	100 % S6	50	464±4	-	-	-	-	[10]
21	75 % S6+25% M7	50	420	403	4	-	-	[10]
21	50 % S6+50% M7	50	340	342	-1	-	-	[10]
21	25 % S6+75% M7	50	259	280	-8	-	-	[10]
21	100 % M7	50	219±10	-	-	565	39	[10]
22	75 % S6+25% M8	50	370	386	-4	-	-	[10]
22	50 % S6+50% M8	50	286	308	-7	-	-	[10]
22	25 % S6+75% M8	50	201	230	-13	-	-	[10]
22	100 % M8	50	152±6	-	-	624	24	[10]

- = data not available

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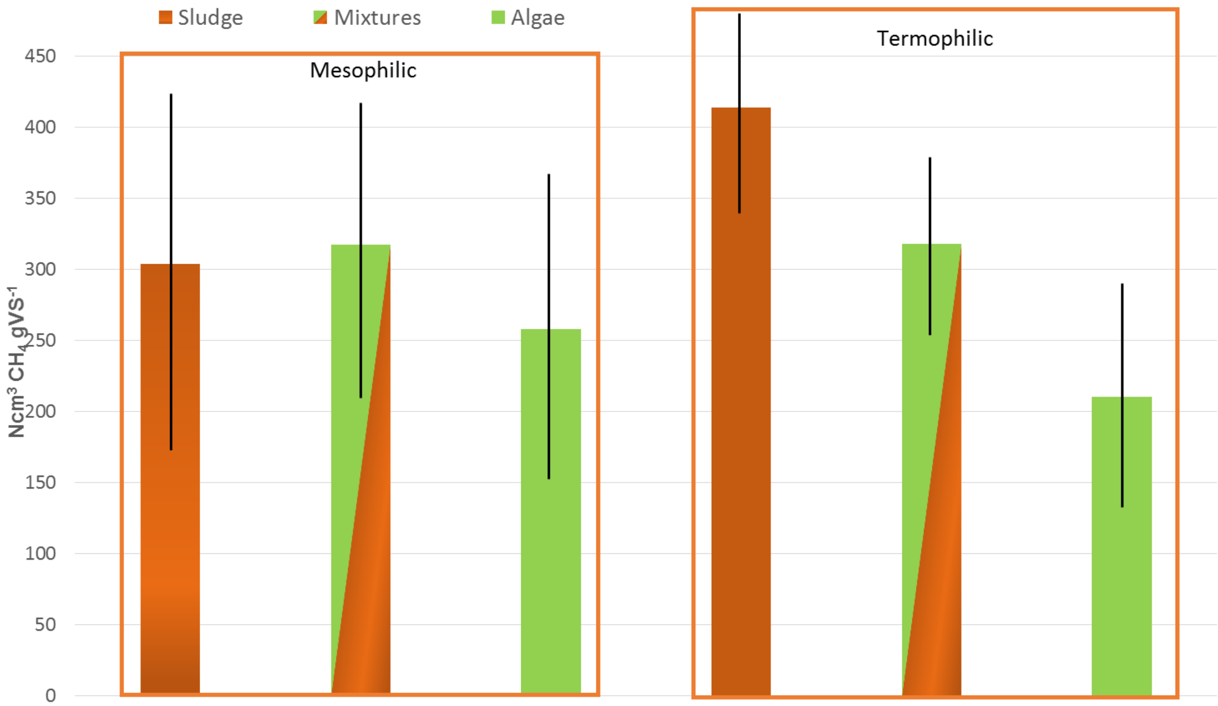

Figure 1. Average methane production in the batch tests. The lines indicate the standard deviation.

The results of the calculation of the enhanced yield for the co-digestion tests on mixtures of microalgae and sludge are presented in Table 2 and 3 and also illustrated in Figure 2 and 3. The majority of the tests in mesophilic conditions indicate enhanced methane production, with enhancements up to almost 70%, when microalgae and sewage sludge are co-digested. However, the results are uncertain since standard deviations for some of the BMP tests are in the same order of magnitude as the identified enhancement. High values of enhanced methane production are found for tests (no 2, 9, 13 and 17), where sewage sludge with high BMP values are co-digested with microalgae with low BMP values. This might be due to a higher importance of enhanced hydrolysis of algae biomass by sludge microorganisms, as mentioned in [7], for those cases. However, also test no 11 and 12 with slighlty higher BMP values for the microalgae, even though still lower than the BMP for the sludge, show high values of

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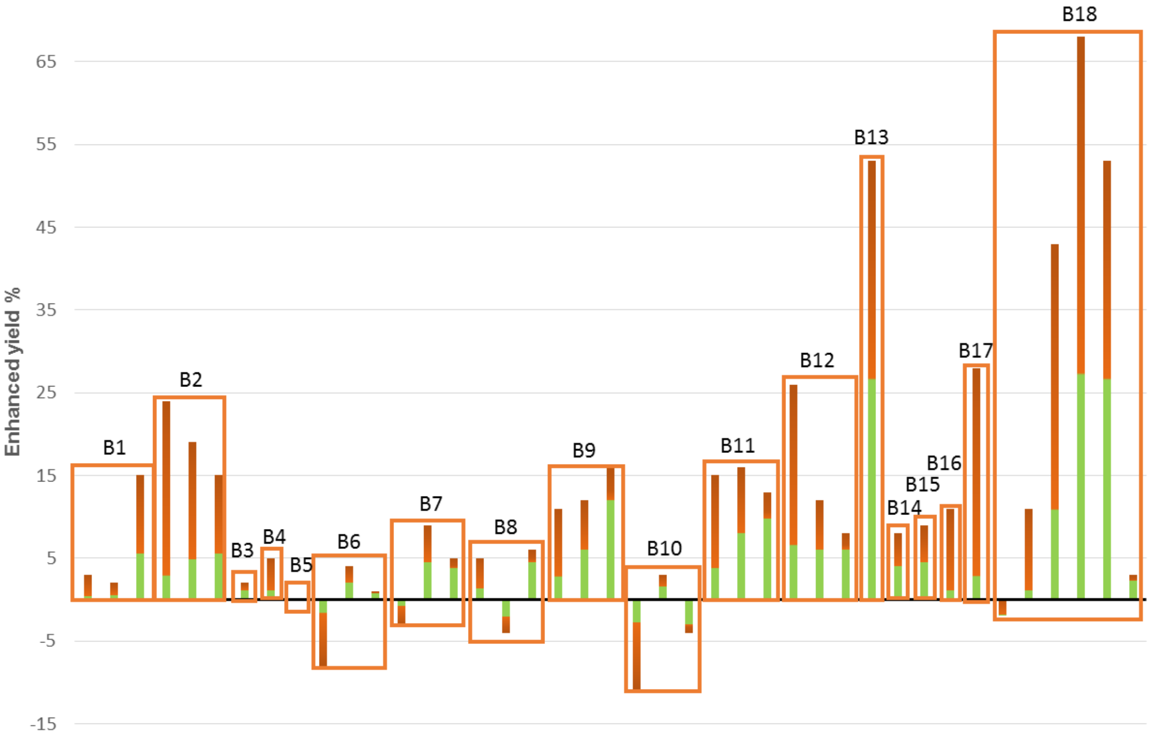

Figure 2. Enhanced yield for the different mesophilic batch tests on mixtures of microalgae and sludge. The green color indicate the proportion of algae and the boxes indicate results from the same batch test (B1-B18 in Table 2).

the enhancement. Test no 18 also show high enhancements even though the microalgae in this case has much higher BMP value than the sludge used in the co-digestion.

The majority of the co-digestion tests at thermophilic conditions show negative enhancement values down to about -10%.

The conversion efficiency is higher than 50% for most co-digestion cases, for which the conversion efficiency can be evaluated, in both mesophilic and thermophilic conditions. However, for the pure microalgae the conversion efficiency is lower than 50% in most cases with typical values around 40%.

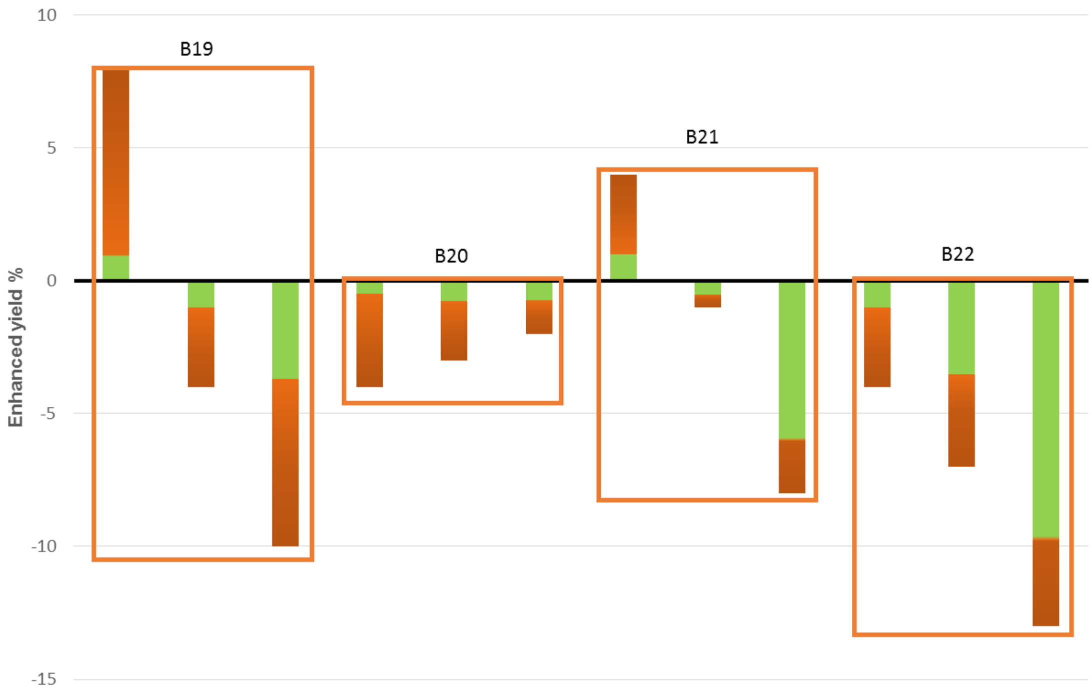

Figure 3. Enhanced yield for the different thermophilic batch tests on mixtures of microalgae and sludge. The green color indicate the proportion of algae and the boxes indicate results from the same batch test (B19-B22 in Table 3).

3.3. Continuous tests

The results of the continuous tests are presented in Table 4. The working volumes in the continuous tests are 5, 7 and 1.5 dm^3 for test 1, 2 and 3, respectively [8, 5, 12]. In the continuous test no 2 a two-stage system is used including one stage of 2 $dm^3$and a second stage of 5 dm^3 [5]. The HRT used are similar in the different tests in a range from 10 to 20 days. The organic loading rates are different for the different tests with low loading rates below 1 $kgVSm^{-3}d^{-1}$ for the two-step process (the second test) and a range from 1.5 to 6 $kgVSm^{-3}d^{-1}$ for the first and third tests. The yields for the co-digestion cases show high variation with an average of 290±115 Ncm^3 $gVSin^{-1}$. The methane yield per reduced VS show a lower variation with an average of 682±76 Ncm^3 $gVSred^{-1}$,

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Table 4. Results of continuous tests.

Cont. test nr	Substrate (% of VS content)	Temp. [°C]	OLR [$kgVSm^{-3}d^{-1}$]	HRT [days]	CH_4 prod. [$Ncm^3\ dm^{-3}\ d^{-1}$]	Normalized CH_4 yield [$Ncm^3\ gVS_{in}^{-1}$]	CH_4 /VS conv. [$Ncm^3\ gVS_{red}^{-1}$]	Ref.
1	40% S2+60% S3	37	2.5	15	305±55	200±33	393±69	*
			3.5	10	388 ± 39	177 ±21	371±58	
1	22 % S2+51% S3 + 37% M3	37	2.5	15	260 ± 35	172±26	607±165	*
			3.5	10	353 ± 31	158±15	568±62	
2	100% S5	36	0.7**	14	270	386	643	[5]
2	67% S5+ 33% M6	36	0.64**	14	295	461	738	[5]
2	100 % M6	36	0.54**	14	179	332	498	[5]
3	100% M11	35	1.5	20	310	310	733	[12]
			3.0		370	190	725	
			4.5		510	170	688	
			6		620	160	661	
3	9.3% S10 + 90.7% M11	35	3.2	20	690	310	701	[12]
3	32.7% S10+67.3% M11	35	4.4	20	820	280	731	[12]
3	49.4% S10+ 51.6% M11	35	5.8	20	1410	360	748	[12]
3	100% S10	35	2.8	20	640	330	721	[12]

* tests described in [8] but data not previously published,** OLR based on the total volume of the two-stage process.

where the standard deviation is similar to the reported standard deviations for the first test.

Varol and Urgulu [5] report lower variations in pH for the co-digestion test compared to digestion of the single substrates. This could be due to providing higher buffer capacity when co-digesting with microalgae as observed in [23], where microalgae and corn silage were co-digested. The results from the second and third continuous tests indicate a synergetic effect of the co-digestion and methane yield per reduced VS increase for the co-digestion case for the first continuous test. The influence of OLR and HRT on the biogas production and process stability cannot clearly be seen. None of the studies report on any major process instabilities.

4. Discussion and identified knowledge gaps

As can be seen in Figure 1 the variation in BMP for microalgae is large. In [7] it is mentioned that different species and growth conditions can cause variations in methane yield and Passos et al [25] show that the methane yield from microalgae biomass cultivated in a waste water treatment plant varies during the year due to variations in the dominant microalgae species. This shows the need for more studies also of co-digestion of sludge and microalgae on a system level related to the conditions for microalgae cultivation and variations in sludge quality to better understand the overall biomethane production potential for the system during the year. Also the proportions of sludge and microalgae needs to be related to the overall system. In most of the cases (40 of 55) investigating the methane production of mixtures of sludge and microalgae presented in Table 2, 3 and 4 the proportions of sludge are 50% or more. In a system with cultivation of microalgae utilizing carbon also from CO_2 in the air, in a waste water treatment plant with integration of microalgae cultivation, the microalgae biomass production might be larger than other sludge production and more studies on co-digestion of microalgae and sludge where the proportion of microalgae are more than 50% are of high relevance. Investigations on system level to find optimal conditions for overall biogas production, and quantifying captured nutrients (C, N, P) in comparison to the traditional activated sludge process are needed.

The low conversion efficiency for many of the batch tests on pure microalgae indicates that pretreatment of the microalgae could be a way to increase the biogas production also for the co-digestion of microalgae and sludge. Good results, concerning increased biogas production, in anaerobic digestion of thermally pretreated microalgae, are reported in for example [24] and [11]. However, as shown in table 2 the VS content of wastewater derived microalgae cultures is rather low compared to mono-microalgae cultures. The lower VS content reduces the potential of organic material that can be released by pretreatment. Anbarasan et al [26] give an indication that thermal pretreatment of wastewater grown microalgae has rather a slight effect on the degradation kinetics than on the final yield. Mendez et al [27] also show that the pretreatment effect is dependent on the microalgae species. Further, the energy balance of the whole process needs to be considered. Passos et al [18] show that both thermal and microwave pretreatment methods can have negative energy balances and that further development are necessary for decreasing the energy demand of the pretreatment processes.

The different batch tests have been run for different times in the interval 20 to 55 days, with 55 days for batch tests 1, 2, 19 and 20, 42 days for test 13, 35 days for batch test 3, 6 and 7, 32 days for batch test 8, 28 days for batch test 9 and 11, 27 days for batch tests 12, 16, 17, 21 and 22, 25 days for test 14 and 15, 23 days for batch test 10, and 20 days for batch tests 4, 5 and 18. This introduces an uncertainty in comparing the reported biogas potentials. In [8] the batch test results have been correlated to a kinetic model of the biogas production, the modified Gompertz equation presented by Zhu et al [28]. The Gompertz model gives the biogas yield potential that might be a better value for evaluation of the full biogas potential than the measured accumulated biogas volume in the experiment.

Ward et al [29] report on several continuous studies on digestion of microalgae. They conclude that the focus in most of those studies was on concentrating and dewatering the substrate to avoid too low concentration of digestible substrate. They also report on several studies indicating that a two-step process is favorable for digestion of microalgae resulting in a more stable process and higher biogas yields. Very few continuous studies on co-digestion of microalgae and sludge have been found. Also the available continuous studies are scarce in process data. To better understand the process it is of interest to follow other parameters than the biogas production, such as volatile fatty acids, ammonia and alkalinity.

5. Conclusions

Available investigations of co-digestion of sewage sludge and microalgae mostly concern batch tests at mesophilic conditions while investigations at thermophilic conditions and of semi-continuous processes are scarce. For the microalgae, mesophilic conditions is favourable for high methane production while thermophilic conditions

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give higher methane production for sewage sludge. Tests on co-digestion with high proportions of sludge dominates in the studies found. Synergetic effects of co-digestion of microalgae and sewage sludge at mesophilic conditions are indicated in both batch and semi-continuous tests. The available test results clearly show the possibility for co-digestion of sewage sludge and microalgae. The variations in conditions and presented results between different studies are large and including kinetic models of the test results in more studies might make it easier to compare different experimental results. Further investigations are needed to find operation conditions (proportions, loading rates and retention times) for optimal methane production and studies on using higher proportions of microalgae in the co-digestion are especially of interest. For better understanding of the process, more studies following process parameters such as volatile fatty acids, ammonia and alkalinity as well as more analysis of the substrate and digestate composition are needed. In addition, the effect of microalgae implementation on waste water treatment has to be evaluated on a system perspective to identify the total mass balance of substrate, resulting biogas production and nutrient recovery considering also variations during the year.

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