

Research Article

Two-Stage Dry Anaerobic Digestion of Beach Cast Seaweed and Its Codigestion with Cow Manure

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Two-stage, dry anaerobic codigestion of seaweed and solid cow manure was studied on a laboratory scale. A methane yield of 0.14 L/g VS_{added} was obtained when digesting solid cow manure in a leach bed process and a methane yield of 0.16 L/g VS_{added} and 0.11 L/g VS_{added} was obtained from seaweed and seaweed/solid manure in a two-stage anaerobic process, respectively. The results showed that it was beneficial to operate the second stage methane reactor for the digestion of seaweed, which produced 83% of the methane, while the remainder was produced in the first leach bed reactor. Also, the two-stage system was more stable for the codigestion for seaweed and manure when compared to their separate digestion. In addition, the initial ammonia inhibition observed for manure digestion and the acidification of the leach bed reactor in seaweed digestion were both avoided when the materials were codigested. The seaweed had a higher Cd content of 0.2 mg Cd/kg TS than the manure, 0.04 mg Cd/kg TS, and presents a risk of surpassing limit values set for fertiliser quality of seaweed digestate. Evaluation of the heavy metal content of seaweed or a mixture of seaweed and manure digestate is recommended before farmland application.

1. Introduction

Eutrophication of the Baltic Sea results in large deposits of microalgae along the coastlines in the south eastern coast of Sweden [1]. The deposited seaweed poses a pollution problem due to its smell and the prevention of beach access for recreational purposes. The collection of the piles of seaweed in turn leads to a waste management problem for the municipality of Trelleborg, Sweden. Anaerobic digestion can be a suitable waste management technique for the collected seaweed since it also leads to the production of bioenergy in the form of biogas [2].

Seaweed can be a potential feedstock for biogas production, with a biomass yield greater than land biomass [3] and which also does not compete with agricultural land. It is easily hydrolysable and has a low lignin content [4]. The C/N ratio reported for seaweed ranges between 7 and 31 [5], which is close to the ratio of about 16 to 25 needed for efficient anaerobic digestion [6]. Seaweed adsorbs nutrients from the sea and has been used to stabilise a pilot-scale anaerobic process digesting milk waste [7]. These advantages together

with the need to replace fossil fuel with renewable alternatives have led to the cultivation of both algae for the production of multiple biofuels in addition to the extraction of high value chemicals [8]. Seaweed, however, contains compounds, such as NaCl, sulphate, heavy metals, polyphenols, and tannins, which are potential inhibitors of methanogens [9–11].

The two-stage dry anaerobic digestion can be used for the digestion of seaweed and this dry digestion process is present at commercial scale for the digestion of municipal solid waste [12]. In a two-stage anaerobic digestion system, hydrolysis/solubilisation of solid organic materials mostly occurs in the first (leach bed) reactor, which generates a leachate with low pH and soluble organic compounds, mainly as volatile fatty acids (VFA). This leachate can be subsequently treated in a controlled manner in a high-rate methane reactor, in order to achieve high methane productivities under stable operational conditions. Alternatively, methane production can also occur in the leach bed reactor, especially during the latter part of the digestion phase, when hydrolysis becomes rate-limiting, or in the digestion of organic materials, which can generate sufficient buffer capacity [13]. Hence, only

a one-stage dry digestion process is needed for the digestion of such organic materials, representing a lower investment and reduced operational costs [14]. The main advantages of using a two-stage dry digestion system include high methane yields, low energy demands, the application of high organic loading rates (OLR), process stability, less foaming, and the fact that the methane reactor is less sensitive to toxic shocks and variations in the feedstock [15–18]. However, the high initial investment required is the major disadvantage of using two-stage systems.

Continuous stirred tank reactor (CSTR) is an alternative one-stage anaerobic digester, widely used because of its simple construction and operation and low initial investment cost [19]. The CSTR is designed for the treatment of waste streams with low TS content (TS < 10%), such as sewage sludge and liquid manure [17, 20]. Conversely, the disadvantages of the one-stage CSTR are the high energy demands and handling costs of dealing with large volumes of liquid [17]. Problems associated with the one-stage CSTR anaerobic digestion of seaweed include accumulation of sand and the potential of acidification of the easily hydrolysable fraction of seaweed [11, 21].

The current laboratory-scale investigation evaluated the dry anaerobic digestion of seaweed and solid cow manure separately, in addition to their codigestion. Solid cow manure was codigested with seaweed to provide a better leach bed structure for easy liquid and bacterial biomass circulation. The two-stage system used was a leach bed reactor combined with an upflow anaerobic sludge blanket (UASB) reactor. The leach bed reactor alone (without the UASB reactor) was used to digest the solid cow manure. Biochemical methane potential (BMP) batch tests were also performed on these materials for comparison.

2. Materials and Methods

2.1. Feedstocks. Solid cow manure was collected from a farm in the east of Scania, Sweden, in February 2009 and stored at -20°C until use. The TS of the manure was 20.6%, the volatile solid (VS) proportion was 82.4% of the TS, and the $\text{NH}_4^+ - \text{N}$ content was 1.3 g/L. Seaweed was collected from a beach near Trelleborg, Sweden, in May 2008. It was reduced by grinding to 2–3 cm pieces and stored at -20°C until use. The TS of the seaweed was 31.2%, the VS was 30.0% of the TS, and the $\text{NH}_4^+ - \text{N}$ content was 0.02 g/L.

2.2. Dry Anaerobic Digestion Systems. Anaerobic dry digestion was performed using a one-stage leach bed reactor or a two-stage system combining a leach bed reactor with a UASB reactor. Seaweed and seaweed/solid cow manure combined were digested using a two-stage system. Solid cow manure on its own was digested using only a leach bed reactor. Duplicate digestion systems were used in the experiments.

The leach bed reactor was a 1.2 L plastic reactor, 30 cm in height, with an internal diameter of 7.5 cm. The UASB reactor had a volume of 1 L, with an active liquid volume of 0.85 L. Both reactors were operated under mesophilic (37°C) conditions. The remaining reactor set-up and operation were

similar to that previously described [13]. Internal recirculation of the liquid reactor content was achieved using peristaltic pumps at 5 mL/min for both the leach bed and UASB reactors. The recirculation was performed from bottom to top for the leach bed reactor but from top to bottom for the UASB reactor. Liquid exchange between the reactors of the two-stage system was accomplished using a multichannel peristaltic pump and a timer switch. The effluent from the UASB reactor was also recirculated into the leach bed reactor. Prior to the start of the experiments, the leach bed reactors were flushed with nitrogen to create anaerobic condition.

The volume and composition of the gas, total chemical oxygen demand (tCOD), and pH were monitored throughout the course of the experiments.

2.2.1. Methane Production from Solid Cow Manure Using a One-Stage Leach Bed Reactor. At the start of the experiment, 94 g (16.0 g VS) solid cow manure and 200 mL tap water were placed in the leach bed reactor. The leachate was recirculated over the hydrolysis bed as described in Section 2.3. The experiment was conducted for a period of 60 days.

2.2.2. Methane Production from the Codigestion of Seaweed and Solid Cow Manure Using an Anaerobic Two-Stage Process. Seaweed and solid cow manure were codigested using a mixture ratio of approximately 1:1 grams VS. Consequently, 84 g seaweed (7.9 g VS), 46 g cow manure (7.8 g VS), and 200 mL tap water were added in the leach bed reactor. The experiment lasted 36 days, with an initial organic loading rate (OLR) of 1.5 g COD/L·day applied to the UASB reactor, and corresponded to a varying hydraulic retention time (HRT) of 1–9 days. The objective of the operation was to avoid organic overload of the UASB reactor, especially during the initial phase when a rapid hydrolysis rate was expected.

2.2.3. Methane Production from Seaweed Using an Anaerobic Two-Stage Process. At the start of the experiment, 200 g (15.5 g VS) seaweed (TS = 24.1%; VS = 32.1% TS) and 200 mL tap water were added in the leach bed reactor. Care was taken when adding the seaweed to the leach bed, so as not to pack the bed and cause clogging. The experiment was conducted for 24 days at a constant HRT of 3 days. The OLR decreased progressively from 3.2 to 0.3 g COD/L·day; as the hydrolysis and solubilisation became rate-limiting the soluble organics were transferred and converted into methane in the UASB reactor. The liquid transfer from the leach bed reactor into the UASB reactor was initiated after 1 day of hydrolysis. Seaweed hydrolysis in one-stage leach bed process under mesophilic and thermophilic temperatures, which resulted in the acidification of the leach bed, has been reported in another study [22].

2.3. Biochemical Methane Potential Tests. Biochemical methane potential (BMP) tests were performed in batches in order to validate the methane potentials obtained in the two-stage system and the leach bed reactor. Methane production from seaweed, solid cow manure, and seaweed/solid cow manure combined (1:1 based on grams VS) was evaluated.

The methane potential tests were performed in triplicate, for 38 days under mesophilic conditions (37°C) in a shaking water bath. The inoculum to substrate ratio was set at 2:1, based on grams VS. The experiment was performed in 0.5 L E-flasks and the active reactor volume was 300 mL. At the start of the batch test, anaerobic condition was created by flushing the head of the flasks with N₂ for 3 minutes. The flasks were then sealed with butyl rubber stopper that had an outlet for gas collection in aluminium gas tight bags. The experimental set-up matched that previously described [23]. The volume and composition of the biogas were analysed and the temperature was measured throughout the course of the experiments. The recorded room temperature was used for normalising the biogas volume to 273 K and 1 atm.

2.4. Analytical Methods. TS, VS, and tCOD were analysed according to standard methods [24]. The biogas composition was analysed using a gas chromatography, 6890N Agilent Technologies, CA, USA, and it was equipped with a thermal conductivity detector, Hay Sep N 80/100, and a molecular sieve column (5A 60/100) as previously described [1]. The biogas volume was measured with a 100 mL gas tight glass syringe (Fortuna, Germany) that was in turn connected to a three-way valve. NH₄⁺-N was analysed on filtered (0.45 µm) samples using Dr. Lange test kit, LCK 303, and a Lasa 100 spectrometer (Dr. Bruno Lange GmbH, Germany). Elemental analyses of seaweed and solid cow manure were performed by LMI AB, Helsingborg, Sweden. Elemental analyses of nitrogen and carbon were undertaken, from which C/N ratios were calculated. Fe, Al, B, Cu, P, S, Zn, Mn, Na, Mg, Ca, K, and Si were analysed by means of inductive coupled plasma atomic emission spectrometry (ICP-AES), while Mo, Cr, W, Se, Ni, Cd, Co, As, Hg, and Pb were analysed using inductive coupled plasma mass spectrometry (ICP-MS). Kjeldahl-nitrogen (Kj-N) analyses were performed on the solid cow manure. Gas volumes were normalised to 0°C and 1 atmosphere. Free NH₃ concentrations were calculated using the formula previously described by Hansen et al. [25]:

$$\frac{[\text{NH}_3]}{[\text{NH}_4^+-\text{N}]} = \left(1 + \frac{10^{-\text{pH}}}{10^{-(0.09018+(2729.92/T(K)))}} \right)^{-1}, \quad (1)$$

where [NH₃] is the concentration of free NH₃ in mg/L, [NH₄⁺-N] is the concentration of ammonium-nitrogen in mg/L, and *T* is the temperature in Kelvin.

3. Results and Discussion

3.1. Elemental Composition of Solid Cow Manure and Seaweed. The nutrient compositions of the solid cow manure and seaweed were comparable, as demonstrated in Table 1. Key micronutrients, such as Fe, Co, Ni, Mo, Se, and W, were all present in concentrations suitable for biogas production [26]. The concentration of Fe was in excess in the seaweed, being about five times higher than in the manure. The C/N ratio for the seaweed was low, although codigestion with manure can improve this ratio, increasing it to a level close to that recommended for biogas production [6].

TABLE 1: Elemental composition of solid cow manure and seaweed.

Metal	Solid cow manure (mg/kg)	Seaweed (mg/kg)
Fe	110	530
Al	40	178
B	5.2	13.1
Mo	0.39	0.14
Hg	0.007	0.012
Cu	4.7	1.4
Cr	0.23	0.78
As	0.04	0.87
W	0.01	0.02
Se	0.24	7.49
Co	0.33	0.20
Pb	0.12	0.99
P	830	265
S	630	1841
Zn	27	14
Cd	0.04	0.20
Mn	34	5.3
Ni	0.31	1.21
Na	1200	1872
Mg	930	562
Ca	2000	5616
K	5800	1092
Si	206	79
C	105	52
N		5.6
N-kj	0.62	
C/N	16.9	9.3
TS (%)	20.6	24.1–31.2
VS (% of TS)	82.4	30.0–32.1

The concentration of P in the seaweed was also lower than in the manure. The manure (0.04 mg Cd/kg TS) satisfied Swedish fertiliser quality guidelines (less than 2 mg Cd/kg TS), while the seaweed (0.2 mg Cd/kg TS) was 5 times higher when compared to manure [27]. The digestion of seaweed and the removal of organic compounds can result in even higher Cd concentrations. Hence, there is risk of surpassing this limit when seaweed digestate is applied as a fertiliser. The use of macroalgae as a fertiliser on agricultural land for nonfood crops has been recommended [28]. In a recent study of the brown algae *Fucus vesiculosus*, the concentrations of heavy metals (Cd, 0.7; Pb, <1; Cr, 1; Cu, 4; Ni, 7; Hg < 0.04; and Zn, 87 mg/kg TS) were comparable to that of maize and the digestate was recommended for land application as a fertiliser [29]. Evaluation of the heavy metal content of seaweed is therefore recommended before application of seaweed or a mixture of seaweed and manure digestate as a fertiliser.

The amount of S in the seaweed, 1, 841 mg/kg, was very high when compared to the manure, 630 mg/kg. Although S is an important element for anaerobic digestion, excess amounts are inhibitory, since it results in competition between sulphate-reducing bacteria and also the production

TABLE 2: Methane production in batch tests (BMP), leach bed reactor, and anaerobic two-stage processes.

Substrate	Process	Duration (days)	Methane yield (l/g VS _{added})	Methane content (%)
Seaweed	BMP	38	0.17 ± 0.01	49
Solid cow manure	BMP	38	0.09 ± 0.01	38
Seaweed/solid cow manure	BMP	38	0.13 ± 0.01	48
Seaweed	Two-stage process	24	0.16 ± 0.02	41 ^a , 65 ^b
Seaweed/solid cow manure	Two-stage process	30	0.11 ± 0.01	42 ^a , 43 ^b
Solid cow manure	Leach bed process	77	0.14 ± 0.01	48

^aThe methane content in the leach bed reactor.

^bThe methane content in the UASB reactor.

Ratio of substrate mix: 1:1 based on g VS.

of H₂S, which inhibits methanogens [10]. The concentration of Na⁺ ions was higher in the seaweed (1.87 mg/kg) than in the manure (1200 mg/kg), which could also inhibit the biogas process. However, both substrates can be diluted to some extent, in order to attain the required TS content prior to anaerobic digestion. Dilution can therefore reduce concentrations below inhibitory levels, favouring an efficient biogas process.

Comparison of the chemical compositions of the seaweed and manure suggested that seaweed may be an alternative cosubstrate for anaerobic digestion. However, care must be taken not to exceed heavy metal concentration limits when using the digestate as a fertiliser. Furthermore, the utilisation of both land- and marine-based biomass for anaerobic digestion and the subsequent return of the digestate to farmland is crucial for the sustainability of the agricultural sector. In fact, since key nutrients, such as P, are near depletion, research efforts should be focused on nutrient recycling not only from land biomass but also from marine biomass, where a greater amount of nutrients is lost.

3.2. Methane Production from Solid Cow Manure in a One-Stage Leach Bed Reactor. A methane yield of 0.14 L/g VS_{added} (0.09 L/g TS_{added} or 0.02 L/g_{added}) was obtained when solid cow manure was digested in a leach bed reactor for 77 days. Table 2 summarises the methane production from solid cow manure, seaweed, and their codigestion performed in methane potential batch tests, leach bed, and two-stage processes. The methane yield was low, whether expressed per gram TS or per gram wet weight, due to the high water content of the solid manure. Hence, efficient transportation of the raw materials is vital if biogas production costs are to be kept low. The methane yield of 0.12 L/g VS_{added} obtained after 38 days in the leach bed reactor was similar to that acquired after 38 days from the BMP test. This indicates that digestion for an extended period would result in higher methane yields.

Methane represented 48% of the total gas produced in the leach bed reactor. The methane production rate was insignificant during the first 6 days of digestion but increased subsequently, to reach a maximum on day 20 (Figure 1). A gradual decrease in the methane production rate was then observed until the termination of the experiment on day 77. Furthermore, 83% of the methane was produced during the first 35 days of digestion. The work in [30] reported a methane

yield of 0.08 L/g VS from dairy cow manure in a two-stage anaerobic digestion lasting 70 days, which is similar to the results presented here. In another study, the digestion of cow manure in a CSTR resulted in a high methane yield of 0.21 L/g VS, with a HRT of 30 days and OLR of 1.3 g VS/L·day [31]. No starter culture or inoculum was added during the present study. A faster start-up time and a shortened digestion period can be achieved by recycling part of the digestate to act as an inoculum for the next batch [32].

The pH was 8.4 at the start of the experiment and therefore above the neutral pH of 7 that represents suitable conditions for methanogens during efficient biogas production [33]. The initial concentration of free NH₃ (139 mg/L) was high and thereby close to the inhibitory range of 200 to 468 mg/L reported for methanogens [34]. However, NH₃ inhibition is also dependent on methanogenic sludge adaptability [34, 35]. In this study, there was a correlation between initial inhibitory levels of free NH₃ and the 6-day period of insignificant biogas production, indicating ammonia inhibition. The slow start could also have been a lag phase, where the anaerobic sludge adapts to the substrate. Subsequently, pH and NH₃ concentrations decreased as the solid cow manure was solubilised, indicated by an increase in tCOD, which reached a maximum of 12.2 g/L on day 3. In turn, the soluble organic matter was efficiently converted into biogas as conditions became favourable for its production, reflected by the low tCOD concentration (2.7 g/L) at the termination of the experiment. The pH increased during the latter period, resulting in a progressive increase in free NH₃ concentrations from 68 mg/L (day 24) to 103 mg/L (day 77). This may indicate the possibility of long-term NH₄⁺-N accumulation and ammonia inhibition following several rounds of operation.

The adjustment of pH with dilute acid or codigestion with a carbon-rich organic material is recommended strategies to avoid lengthy start-up times and the expected long-term ammonia inhibition [36]. Moreover, [32] reported that start-up times can be shortened by the addition of 20–30% of inoculum, which introduces buffering compounds and microorganisms.

Anaerobic digestion of the manure in the current study resulted in biogas production together with a digestate suitable of application on farm land as a fertiliser. Thus, the technique is suitable for replacement of the present current conventional storage of manure in Sweden. Other aspects that have to be considered when manure is used for anaerobic

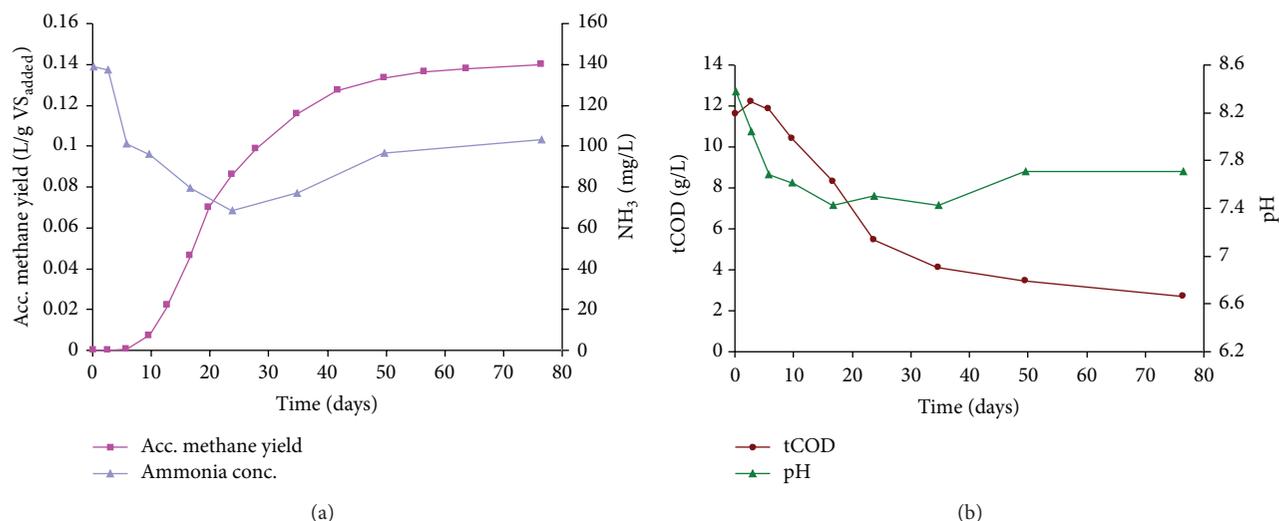


FIGURE 1: (a) Cumulative methane production and ammonia concentration in the anaerobic digestion of solid cow manure in leach bed reactors, (b) pH, and tCOD variation in the leach bed reactor.

digestion are the transportation cost. Small farm-scale one-stage dry digestion units can be installed to reduce the transport of the manure for digestion in a centralised biogas plant. In the case of liquid manure that is suitable for digestion in wet processes, pipeline exchange of manure and digestate (fertiliser) between a centralised biogas plant and animal farms could be considered in order to keep the transport cost low [37].

3.3. Methane Production from the Codigestion of Solid Cow Manure and Seaweed Using an Anaerobic Two-Stage Process.

The methane yield obtained after 30 days of solid cow manure and seaweed codigestion in a two-stage anaerobic process was 0.11 L/g VS_{added} (0.06 L CH₄/g TS_{added} or 0.02 L/g_{added}), which was similar to the yield of 0.13 L/g VS_{added} obtained after 38 days in the BMP test (Table 2). The methane yield obtained was low. A longer digestion time or posttreatment of the slowly degradable fraction would be required to extract the remaining energy bound in the material. A total of 83% of the methane was collected from the UASB reactor, while only 17% was obtained from the leach bed reactor, indicating that the second stage methanogenic reactor was required for the rapid conversion of the soluble organics into biogas. Figure 2(a) shows the cumulative methane production in two-stage anaerobic digestion of seaweed and solid cow manure and the ammonia concentration in the leach bed reactor; Figure 2(b) shows pH and tCOD variation in the leach bed reactor. Recycling the effluent from the UASB reactor into the leach bed reactor resulted in the transfer of some buffering species and microorganisms from the former into the latter. As a result, the pH of the leach bed reactor increased to about 7 after 7 days, providing pH conditions suitable for methanogens and leading to the onset of biogas production after about 10 days.

During the experiment, tCOD concentrations in the leach bed reactor increased to a maximum of about 10 g/L

and then gradually decreased to about 1 g/L by the end of the experiment as the organics were converted into biogas, mainly in the UASB reactor (Figure 2). At the start of the experiment, leachate transfer to the UASB reactor was not as efficient as under the operational conditions due to clogging. Consequently, the initial methane production rate in the pH-neutral UASB reactor was low. Interestingly, conditions in the leach bed reactor were favourable for methane production at this time. It was suggested, therefore, that codigestion of seaweed and solid cow manure in the correct proportions can lead to efficient biogas production in a one-stage leach bed reactor, without the need for a second methanogenic reactor. Hence, the investment and operating costs of having two reactors can be avoided [14]. The work in [21] reported a methane yield of 0.17 L CH₄/g VS_{added} and content of 55% when a 1:1 ratio of algae and manure was codigested.

The tCOD concentration in the UASB reactor was low and was 1.12 g/L on day 4 and 0.96 g/L on day 23 and it was due to the efficient conversion of the transferred soluble organics into biogas (results not shown). The pH ranged from 7.4 to 7.7, presenting good conditions for methanogenesis. The concentration of NH₄⁺-N was fairly constant (323 mg/L; corresponding to 21 mg/L of free NH₃ at pH 7.3 and 37°C) throughout the entire experimental period.

The codigestion of seaweed and solid cow manure provided better leach bed structure than was observed during the digestion of seaweed alone, thereby improving liquid percolation. Today, the codigestion of seaweed and manure is not recommended due to the high content of heavy metals such as Cd in the seaweed and the limited practical knowledge of their removal, which is in a bid to produce a digestate that can satisfy fertiliser quality. Efficient, fast, and cheap methods of cadmium removal have been reported, which employed materials such as chitosan and activated carbon [38, 39]. In addition, the removal of Cd has been reported by the use of supermacroporous cryogel carriers and

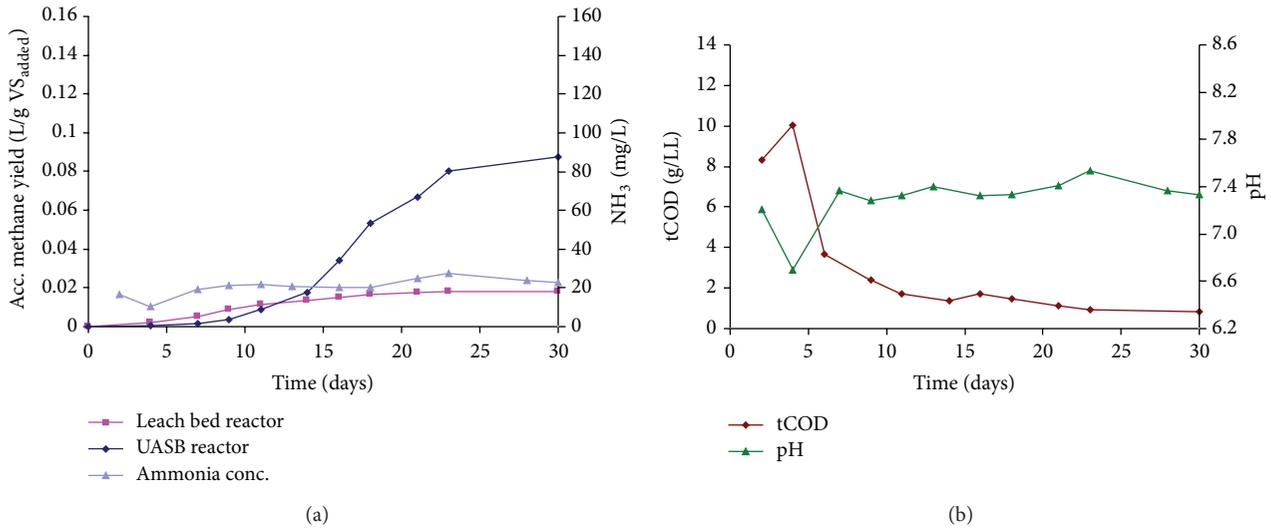


FIGURE 2: (a) Cumulative methane production in two-stage anaerobic digestion of seaweed and solid cow manure and the ammonia concentration in the leach bed reactor, (b) pH and tCOD variation in the leach bed reactor. Seaweed/solid cow manure 1:1 based on g VS in the digestion.

a suitable metal binding ligand, which permits the circulation of liquid with particulate matter under high flow [1, 40]. Despite the available methods of heavy metal removal, more research is needed for the practical applicability prior to the use of seaweed digestate as a fertiliser.

3.4. Methane Production from Seaweed in an Anaerobic Two-Stage Process. A methane yield of 0.16 L CH₄/g VS_{added} (0.04 L CH₄/g TS_{added} or 0.01 L CH₄/g_{added}) was obtained from the anaerobic digestion of seaweed in a two-stage system over 24 days (Table 2), which is similar to that obtained in the BMP test. This demonstrates that the two-stage system had a suitable process configuration for the dry digestion of seaweed. The methane proportion of the total gas produced during the process was 41% in the leach bed reactor and 65% in the UASB reactor. The soluble organics transferred into the UASB reactor were in a more reduced state, resulting in higher methane content than in the leach bed reactor, where hydrolysis was dominant. Higher pH increases the solubility of CO₂; thus the higher pH in the UASB also contributed to the higher methane content in the gas phase.

Approximately 75% of the total methane produced in the two-stage system was collected within the first 10 days (Figure 3). In other words, the two-stage process produced methane yields comparable to the seaweed BMP test in a short time. In addition, 80% of the methane was produced in the UASB reactor and only 20% in the leach bed reactor. Moreover, the methane production rate in the UASB reactor attained a maximum on day 3 and then decreased gradually as the organics were converted into biogas.

Acidification of the leach bed was reported when seaweed was digested alone. Consequently, methane production would take longer if only a leach bed reactor was used [1]. It is, therefore, advantageous to include a second (UASB) reactor,

combined with liquid recycling, in a two-stage digestion of seaweed under the operating conditions applied in this study.

Comparable methane yields of 0.13–0.15 L CH₄/g VS_{added} and contents of 65–80% were obtained when water hyacinth was digested in a two-stage anaerobic reactor [41, 42]. In another study, this time concerned with the anaerobic digestion of marine algae in a two-stage system, 30% of the biogas was produced from the acidogenic and 70% from the methane reactor [43], comparable with the results of the present study. High methane yields have also been reported in the anaerobic two-stage process due to phase separation [15, 44]. The reactors in a two-stage process are optimised to suit the condition of the acidogens and methanogens [17, 44].

Seaweed was efficiently solubilised and hydrolysed in the leach bed reactor, producing a leachate with a high organic content (9.7 g tCOD/L) during the initial phase of the experiment (Figure 3). The soluble organics were then efficiently converted into biogas in the UASB reactor, as reflected in the low tCOD concentration (1.2 g tCOD/L) and neutral pH in the effluent from this reactor (results not shown). The digestion of seaweed in the two-stage process was incomplete and thus more time or posttreatment of the recalcitrant fraction would be needed to recover the remaining energy bound in the material. The work in [43] reported similarly high initial COD concentrations (5.3–6.8 g/L) in the hydrolytic reactor prior to methane production in an upflow anaerobic filter during the anaerobic digestion of marine algae. Furthermore, the work in [15] also described comparable COD concentrations (<1 g/L) in the effluent of a batch two-stage anaerobic digestion of grass silage.

In the current study, the digestion of seaweed in a two-stage process was stable, owing to the neutral pH and low tCOD concentrations in the UASB reactor. Blockage of the leach bed reactor was experienced during the experiment,

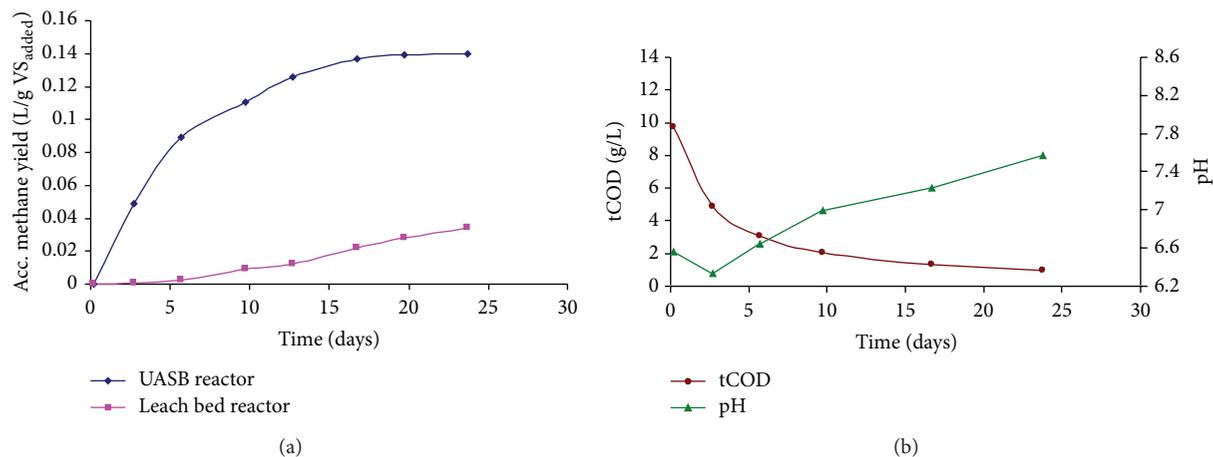


FIGURE 3: (a) Cumulative methane production in two-stage anaerobic digestion of seaweed; (b) pH and tCOD variation in the leach bed reactor.

which could represent a serious problem in large-scale implementation of these processes, since it may limit contact between the bacterial biomass and the substrate. Although the seaweed was digested under stable operational conditions in the two-stage system, not all the material was digested. Efficient seaweed hydrolysis strategies, such as dilution of the leach bed reactor content and alkaline and autoclave treatments, which thus improve the overall efficiency of methane production, have been described previously [22]. In addition, several leach bed reactors could be operated in parallel, in order to provide a sufficient, constant leachate supply to the UASB reactor, thus maximising its optimum OLR capacity and also maintaining constant methane production. In a previous study, the treatment of seaweed leachate in a UASB reactor at a high OLR of 20.6 g tCOD/L-day has been reported [1]. However, the resultant biogas quality could be poor, due to high H₂S concentration, which can be corrosive to engines if not removed, especially when the biogas is upgraded and used as a fuel.

The treatment of seaweed deposits by anaerobic digestion produced renewable energy in the form of biogas; however, the residue contained high levels of heavy metals, limiting its use as a fertiliser. Posttreatment of the residue has been reported to lead to increase biogas production, thus limiting the amount of residues with high heavy metal content [22].

4. Conclusions

Seaweed and manure were codigested in a dry anaerobic two-stage system using a leach bed reactor for hydrolysis and a UASB reactor for methane production. The benefits of codigestion of these materials in a two-stage system were stable operational conditions at neutral pH, low tCOD, and low NH₃ concentrations in the digestion system liquids. Although most of the methane was produced in the second stage UASB reactor, the process can also be optimised such that the codigestion can be performed in only a one-stage leach bed dry digestion system, since methanogenic

conditions also prevailed in the latter. Another aspect to consider is the Cd concentration in seaweed, which is higher than the maximum levels permissible in fertiliser in Sweden. Thus, application of the seaweed digestate as a fertiliser is not recommended in the present study. This study demonstrates that biogas production from beach cast seaweed can be a source of renewable energy and the removal from the sea shore can also add recreational value of beaches.

Abbreviations

BMP: Biochemical methane potential test
 CSTR: Continuous stirred tank reactor
 HRT: Hydraulic retention time
 OLR: Organic loading rate
 tCOD: Total chemical oxygen demand
 TS: Total solids
 VS: Volatile solids.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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