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Improved Efficiency and Stable Digestion of Biomass in Nonmixed Upflow Solids Reactors

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ABSTRACT

A nonmixed upflow solids reactor (USR), which permitted longer solids than hydraulic retention times, was used to study the anaerobic digestion performance of sea kelp (*Macrocystis pyrifera*). The performance of the USR was compared to that of the continuously stirred tank reactor (CSTR) at different organic loading rates in terms of methane yield, methane production rate, and process stability. Results showed that, although digester performance was markedly affected by kelp compositional variability, methane yields and production rates in the USR were significantly higher than those observed with the CSTR. Results also showed that volatile acid concentrations, which are generally inversely related to digester stability, were significantly lower in the USR than in the CSTR.

Index Entries: Anaerobic digestion; sea kelp; upflow solids reactor; methane yield improvement; digestion stability.

INTRODUCTION

Biomass may be defined as vegetation from land and water and the residues and wastes created by utilizing this vegetation. Biomass, which contains about 10 to 18 GJ of energy/dry t, represents a significant energy resource. By some accounts, worldwide biomass production is almost 10

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times the 1980 energy consumption (*1*). Depending on production and conversion efficiencies, biomass can be technically and economically competitive with conventional nonrenewable energy sources. Development of renewable biomass resources requires concurrent research on growth, harvesting and collection, and conversion techniques.

Marine biomass offers a potentially vast renewable energy resource for countries with substantial coastal regions. In the United States, for example, the area available for growth of marine plants has been estimated to be about 2.3 million km^2 (*2*). If one assumes a growth yield of 5 $kg/m^2/yr$ and a heating value of about 10 MJ/kg, that area could produce a biomass gross energy equivalent of about 10 hexajoules (quads). However, the success of a large-scale energy-from-marine biomass system will be determined by the technical and economic feasibility of ocean farming and biogasification processes for conversion to methane and other valuable products.

The most effective method for converting biomass to usable energy forms depends to a large extent upon the physical and chemical composition of the feedstock. Widely used processes for recovering usable energy from biomass include direct combustion, anaerobic digestion, fermentation, thermal liquefaction, and thermal gasification. Because marine biomass contains almost 90% moisture, anaerobic digestion is particularly suited to this material for producing methane.

Methane production by anaerobic digestion is a process occurring widely in nature. It involves first the conversion of the organic components of biomass into simple products such as acetate, CO_2, and H_2 by a mixed population of nonmethanogenic bacteria. These products are then utilized by a mixed population of methanogenic bacteria for the production of CH_4, CO_2, and H_2O. The nonmethanogenic bacteria are a relatively hearty and fast-growing group of microorganisms, whereas the methanogens are fastidious and slow-growing. Because at least two very distinct groups of microorganisms are involved in anaerobic digestion, some investigators have proposed separating these organisms into two phases, each phase promoting the predominant activity of one group of organisms (*3*). Whether methane production is performed with these phases combined or separated, the process must be strictly anaerobic.

Controlled anaerobic digestion for the purpose of methane production and recovery is performed in specially constructed digesters. A major objective of anaerobic digestion of kelp is to produce methane gas at a low cost. Low costs require high methane yields and high methane production rates. Generally, higher methane yields are achieved through longer solids and microorganism retention times. Higher organic loading rates and resultant short hydraulic retention times (HRTs) result in higher methane production rates, provided high methane yields are maintained. Long solids retention times (SRTs) can be attained by reducing the loading rate or by retaining the solids for longer than the liquid at a high loading rate. This latter procedure permits both long SRTs and short HRTs, thereby allowing maximum methane production rates without adversely affecting the methane yield.

The Institute of Gas Technology (IGT) has developed a simple solids concentrating digester, referred to as a nonmixed upflow solids reactor (USR), which, by virtue of its design and operating technique, promotes longer solids than hydraulic retention times. This paper describes the novel digester design, operating technique, and the results obtained using different lots of sea kelp (*Macrocystis pyrifera*). The paper also compares the performance of the USR to that of the continuously stirred tank reactor (CSTR) in terms of methane yields, methane production rates, process stability, and liquid effluent characteristics.

MATERIALS AND METHODS

Upflow Solids Reactor Design

The USR developed at IGT was investigated for anaerobic digestion of sea kelp as a means of enabling efficient digestion at high loading rates. The design of USR, illustrated in Fig. 1, prolonged the retention of microorganisms and unreacted solids through passive settling. The reactor was fed from a bottom port, and the effluent was removed from a

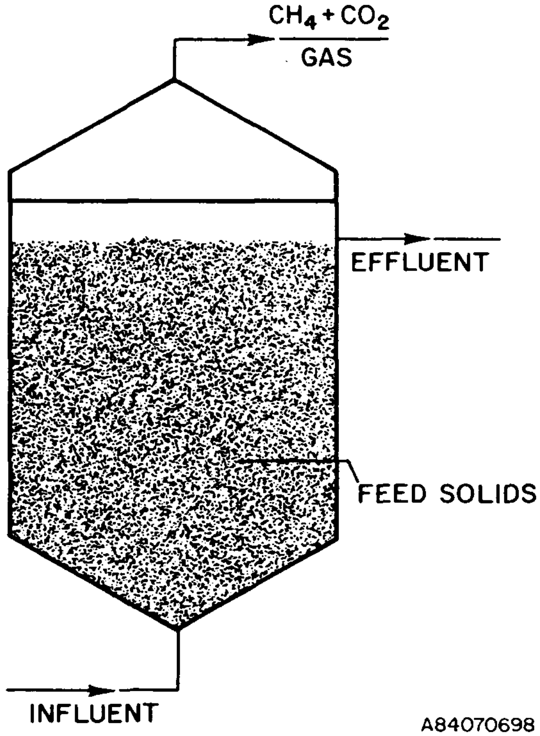

Fig. 1. Schematic diagram of non-mixed upflow solids reactor.

port located near the top of the reactor. Several peripheral rings were installed in the reactor to prevent feed short-circuiting. Using this configuration, the kelp feed moved upward through microorganisms that were attached to unreacted solids. Because these solids were denser than water, their settling promoted increased SRTs at shorter HRTs.

The methane production rate in the USR can be increased by increasing the feed loading rate, without sacrificing the methane yield, by promoting longer SRTs but shorter HRTs. The USR is suited for feeds with both low and high solids contents and differs from the upflow sludge blanket digester (widely applied to the anaerobic digestion of soluble feeds) in that the feedstock contains higher concentrations of nonhomogeneous particulate matter, and the bed, which is not expanded, contains unreacted solids and microorganisms. This reactor concept was successfully applied to a relatively low-biodegradable/low-solids biomass feed, water hyacinth (*4*), and also to a relatively high-biodegradable/high-solids biomass feed, sorghum (*5*).

Continuously Stirred Tank Reactor

CSTRs, such as the one illustrated in Fig. 2, are widely used and are considered conventional for sewage sludge digestion. Because these reactors provide completely mixed contents, the SRTs and HRTs are the same. Consequently, increases in SRT to promote higher methane yields also require longer HRT, thereby requiring larger reactor sizes and resultant capital costs. Although CSTR digesters can be modified to include solids settling and recycling of the effluent back to the digester, conventional CSTR digester designs, without solids recycle, were used in this

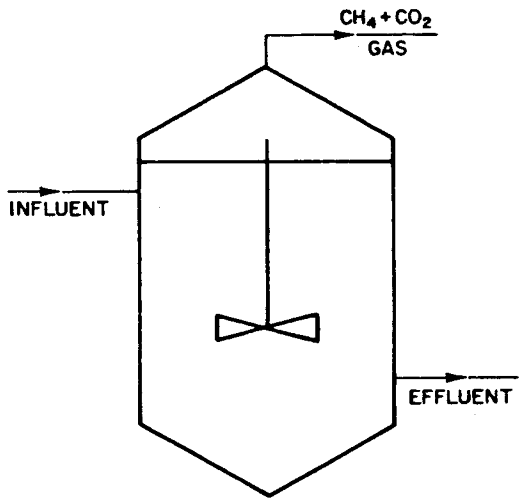

Fig. 2. Schematic diagram of continuously stirred tank reactor.

study as a basis for evaluating the performance of novel USR digester designs.

Digester Operation

Start-Up

Digesters were inoculated with a culture originally derived from a mixture of effluents from an IGT pilot-scale digester that was receiving municipal solid waste and sewage sludge, from a municipal high-rate digester, that had been gradually converted to raw kelp and operated for about 10 yr under a variety of operating conditions. Before inoculation, each digester was pressure-tested for leaks at 21 kPa for about 10 to 24 h. When no leaks were detected, air was voided from the system by an oxygen-free water displacement pump. The temperature was adjusted to the experimental level (35°C) using water in the digester, and the gas-collecting system was filled with an acid-salt solution and checked for gas leaks. The head-space in the digester was filled with helium and, under continuous helium out-gassing, the inoculum was introduced to the digester.

Feeding

Digesters were fed on a once-a-day basis. Ground kelp was fed into the reactor through the feed port, and an equal volume of digester content was withdrawn from the effluent port. Digester loading rates were gradually increased to minimize digestion imbalance during start-up. Before feeding, gas production was measured at atmospheric pressure, and room temperature and barometric pressure were recorded. The effluent volume at a specified loading rate was withdrawn, and the temperature and pH of this effluent were measured and recorded.

Sampling and Performance Monitoring

Digester performance was evaluated by monitoring digester gas production, pH, volatile acids, and gas composition. Gas production and pH were determined daily. Gases were analyzed at least once a week to evaluate digester performance. Digester effluents were sampled for volatile acids on a weekly basis, and for total and volatile solids, total suspended solids, soluble and total carbon, as required, during stable performance. These samples were analyzed immediately or were preserved as described in *Standard Methods* (6).

Raw feeds and digester feed slurries were analyzed for total and volatile solids, heating value, elements, organics, and anaerobic biogasification potential (ABP), as required, for feed characterization and mass balance calculations, Calculations for gas production, gas yield, methane yield, volatile solids reduction, CSTR digester contents replacement, HRT, SRT, and rate of digester feed addition are described elsewhere (7).

RESULTS AND DISCUSSION

Biochemical Characteristics of Kelp

Chemical Characteristics

Table 1 shows the chemical composition and other values of several lots of kelp that were harvested on different occasions. The total solids content ranged from 11.1% to 12.9%, whereas the volatile solids content ranged from 53.8% to 63.9% of the total solids. Other characteristics, such as the carbon-to-nitrogen (C/N) and carbon-to-phosphorus (C/P) ratios, heating value, stoichiometric methane yield, and mannitol content, showed much greater variation. The C/N ratio varied between 11.7–24.0, and C/P varied between 85.7–148. Previous experiments conducted with kelp have shown that a C/N ratio of 15 and a C/P ratio of 100 were required for stable digestion (7), which suggests that Lot 42, for example, was deficient in nitrogen and Lots 42 and 59 were deficient in phosphorus.

Biological Characteristics

The two major organic components of sea kelp—mannitol, a highly biodegradable component, and algin, a less biodegradable component, varied in percentage very significantly and appeared to be inversely related, as shown in Fig. 3. The mannitol concentrations ranged widely

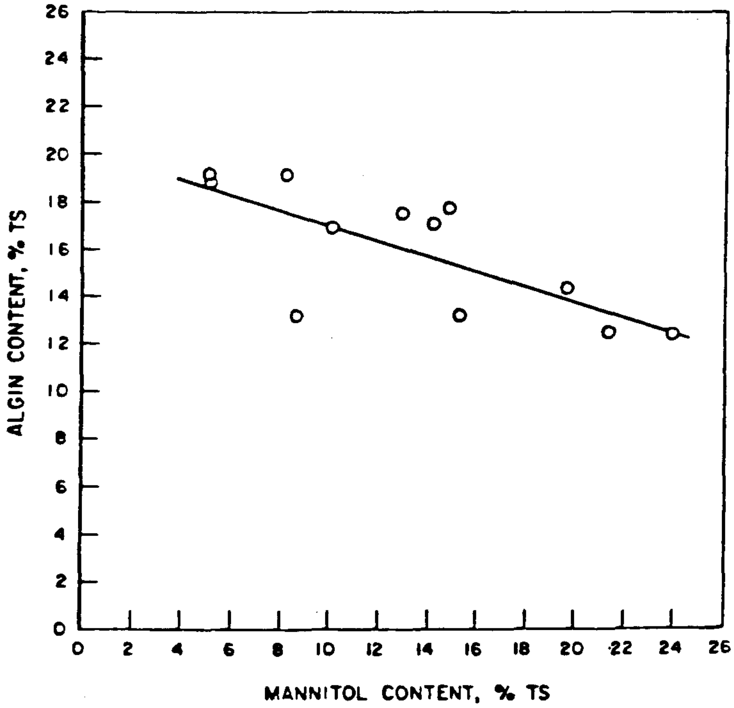

Fig. 3. Relationship between algin and mannitol in kelp lots used in anaerobic digestion.

Table 1
Characteristics of a Few Lots of Sea Kelp (*Macrocystis Pyrifera*) Feed

Kelp Lot No.	42	48	50	53	54	59
TS, %	11.9	11.1	11.7	12.6	11.8	12.9
Moisture, %	88.1	88.9	88.3	87.4	88.2	87.1
VS, % of TS	62.9	53.8	56.3	60.2	57.9	63.9
Ash, % of TS	37.1	46.2	43.7	39.8	42.1	36.1
Elements, % of TS						
Carbon	28.3	25.2	26.5	29.8	25.7	29.7
Hydrogen	3.6	3.4	3.5	4.0	3.3	4.2
Nitrogen	1.2	1.9	1.8	2.0	2.2	1.7
Phosphorus	.2	—[a]	.3	.3	.3	.2
Sulfur	1.4	1.0	1.1	.9	1.2	.2
C/N	24.0	13.4	14.7	14.9	11.7	17.5
C/P	128	—[a]	88.3	99.3	85.7	148
Mannitol, % of TS	13.0	9.1	8.3	21.4	15.4	18.7
Algin, % of TS	19.5	17.0	13.2	12.4	13.7	14.4
Heating value, kJ/kg dry wt	10,560	9,470	9,960	11,300	10,090	11,420
Stoichiometric methane yield, SCM/kg VS added	.44	.51	.50	.52	.44	.48

[a]Not determined.

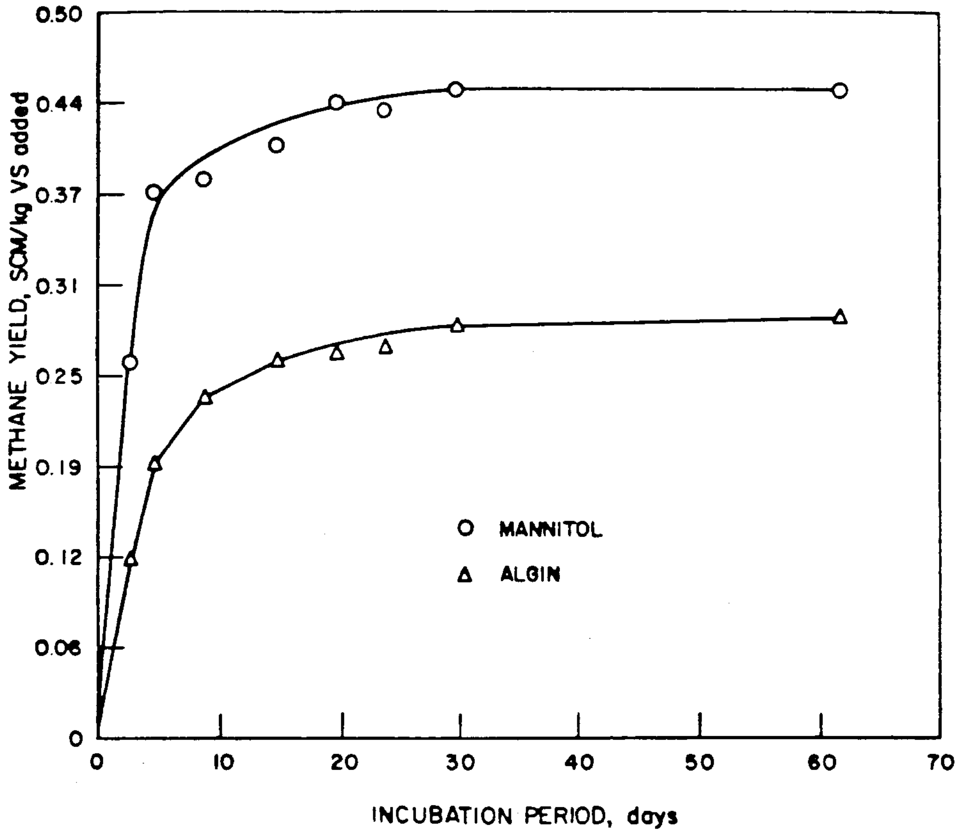

Fig. 4. Biodegradability of mannitol and algin (60 days at 35°C).

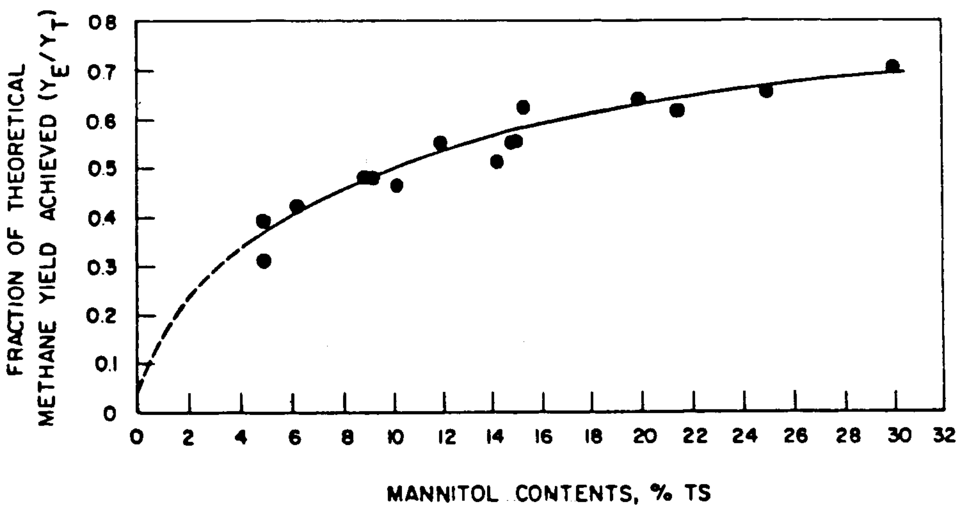

Fig. 5. Fraction of theoretical methane yield achieved experimentally at different kelp mannitol concentrations.

from 5.2–24% of TS, whereas the algin concentrations ranged from only 12.4–19.5% of TS. The relative biodegradability of mannitol and algin was also evaluated using a 60-d batch ABP assay. Figure 4 shows that both the rate of methane production and the ultimate methane yield were higher for mannitol than for algin.

Since both the rate and efficiency of mannitol conversion were higher than algin, and the mannitol concentration varied considerably more than algin, a study was conducted to determine the effect of mannitol concentration on the digestion of kelp, using the CSTR at a baseline loading rate of 1.6 kg VS/m^3-day, a retention time of 15–18 d, and a digester temperature of 35°C. The results, shown in Fig. 5, demonstrated that the mannitol concentration in each kelp lot was related to the fraction of the theoretical (or stoichiometric) methane yield that was achieved experimentally.

A log curve demonstrated with $r^2 = 0.92$ is plotted in Fig. 3. The equation illustrating the relationship between mannitol concentration and methane yield is

$$Y_E = Y_T\,(0.055 + 0.19\ \ln X_m) \tag{1}$$

where

Y_E = experimental methane yield, SCM/kg VS added
Y_T = theoretical methane yield, SCM/kg VS added
X_m = mannitol concentration, % dry wt

The fraction of the theoretical methane yield achieved experimentally increased logarithmically with the mannitol content.

In summary, the biochemical analyses of kelp feed presented here demonstrate significant compositional variation in different kelp lots, which may be related to variations in genetic makeup, growth conditions, methods of harvesting, handling, and storage. Results also suggest that such variations can have a dramatic effect on performance and stability of a conventional CSTR digester.

Anaerobic Digestion Process Development

Methane Production

Several experiments were conducted at 35°C at different organic loading rates in USR and in CSTR digesters to evaluate the performance of the USR in terms of conversion rates, efficiencies, and process stability relative to those of the CSTR. Table 2, which summarizes the methane yields obtained from USR and CSTR digesters receiving kelp (Lot 53) at loading rates of 1.6, 4.8, 6.4, 8.0, and 9.6 kg VS/m^3-d, shows that the improvement in methane yields of the USR over those of the CSTR varied from 10% at lower loading rates (1.6 and 4.8 kg VS/m^3-d) to 22% at a high loading rate (9.6 kg VS/m^3-d). Figure 6 illustrates the effect of loading rates on methane yields in USRs and CSTRs. The methane yield in the USR dropped only by 10% (from 0.38–0.34 SCM/kg VS added) as com-

Table 2
Methane Yields for USR and CSTR Digesters Receiving Sea Kelp at Different Loading Rates
(Kelp Lot-53, Feed TS 12.6% wet wt)

Types of digesters	Loading rates, kg VS/m³-d					Methane yield, SCM/kg added				
USR	1.6	4.8	6.4	8.0	9.6	.38	.35	.36	.35	.34
CSTR						.35	.32	.31	.30	.28
Improvement in USR over CSTR, %						10	10	16	17	22

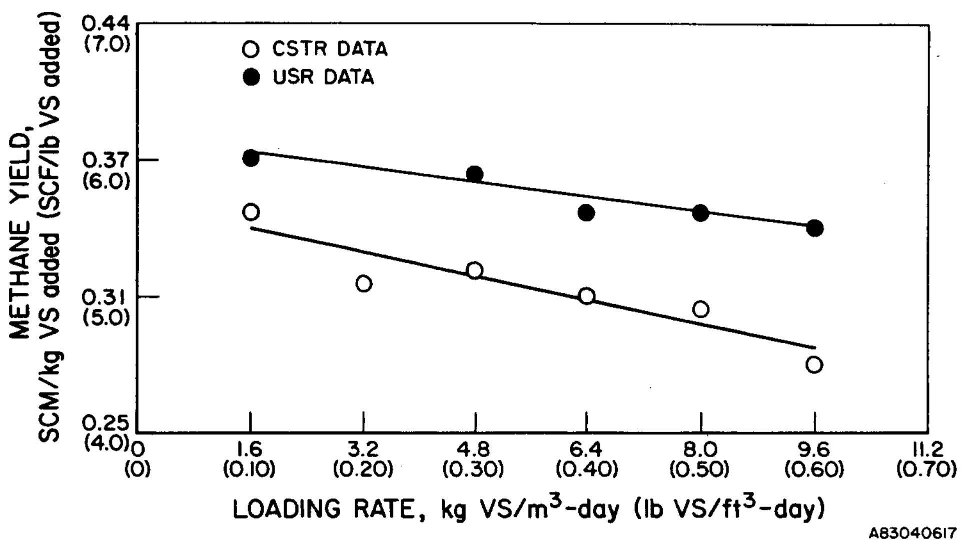

Fig. 6. Methane yield in CSTR and USR digesters receiving kelp lot 53, at several loading rates.

pared to 20% in the CSTR when the loading rate was increased from 1.6–9.6 kg VS/m^3-d. The methane production rates of the two digester types compared at the several loading rates studied are depicted in Fig. 7. The methane production rate in the USR digesters increased from .61–3.3 vol/vol culture-day, while that of the CSTR digesters increased from

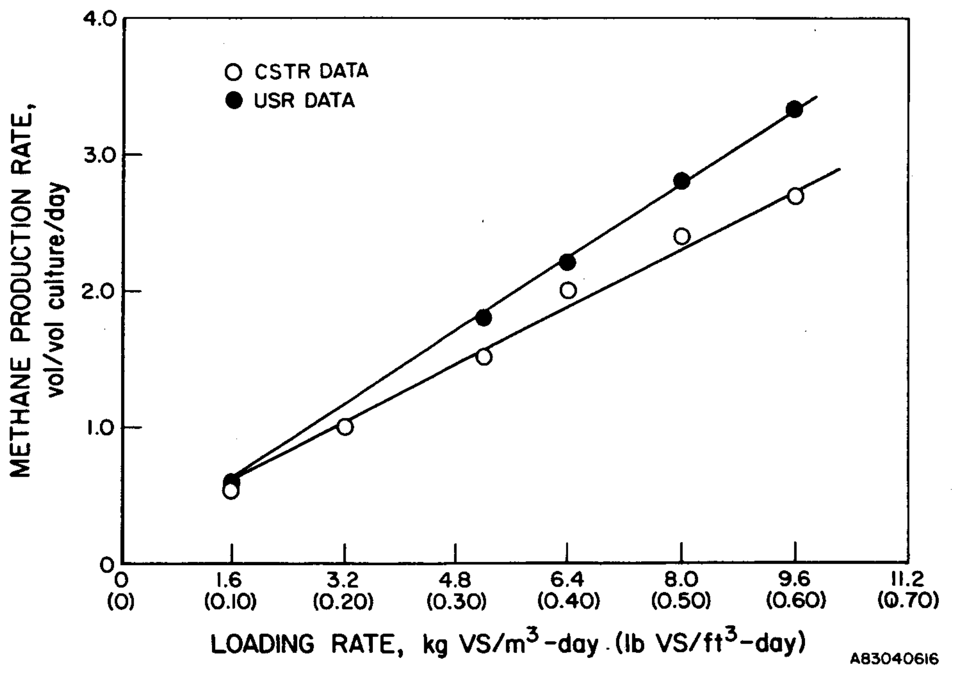

Fig. 7. Methane production rate in CSTR and USR digesters receiving kelp lot 53, at several loading rates.

Table 3
Solids and Hydraulic Retention Times in USR and CSTR Digesters at Several Loading Rates Using Kelp Lot 53

Loading rate, kg VS/m^3-d	HRT, USR and CSTR	days	SRT, USR and CSTR
1.6	50	—[a]	50
3.2	25	—[a]	25
4.8	17	66	17
6.4	12	45	12
9.6	10	28	10
11.2	8.5	23	8.5

[a]Not measured.

56–2.7 vol/vol culture-day when the loading rate was increased from 1.6 to 9.6 kg VS/m^3-d. The methane production rate in the USR digesters at the highest loading rate studied exceeded that of the CSTR digesters by about 22%.

The reason for improved performance of the USR at every loading rate studied is believed to be the USR design and operating technique, which promotes the retention of feed solids and the microorganisms associated with these solids. The higher SRTs in the USR digesters improved the conversion. Table 3 presents the SRT data for USR and CSTR at several different loading rates. The SRTs in the USR were 2.7–3.8 times higher than the HRTs at loading rates ranging from 4.8–9.6 kg VS/m^3-d.

The passive settling that occurred in the USRs promoted longer SRTs than HRTs. The relationship between the SRT and the methane yield in both CSTR and USR is shown in Fig. 8. Increasing the SRTs up to about 30 d had an important effect on improving the methane yield in both digester types. However, beyond about 30 d, increases in the SRT had only marginal improvement in the methane yield. At an SRT of about 200 d, a methane yield as high as .42 SCM/kg VS added was achieved.

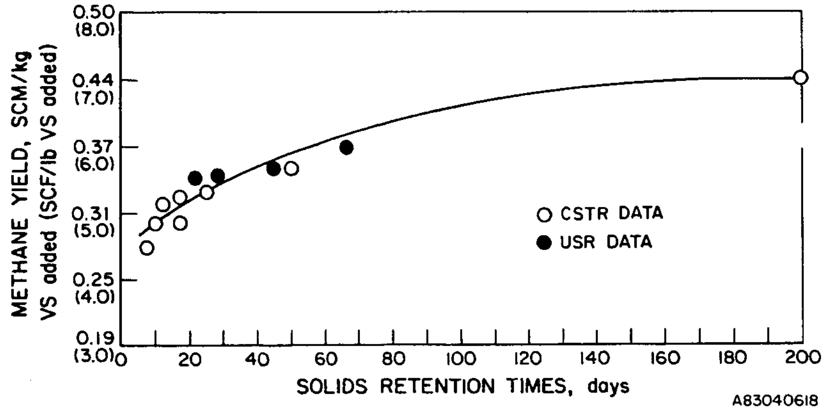

Fig. 8. Relationship between SRT and methane yield in digesters receiving kelp lot 53 with one-a-day feeding.

These data indicate that long SRTs are probably more important to high methane yields than the reactor design. However, in the CSTRs, the SRT was the same as the HRT, whereas the SRT exceeded the HRT in USRs. This highlights the advantage of the USR over the CSTR digester in that long SRTs can be achieved without correspondingly larger reactor volumes (2–3 times larger for CSTRs requiring increased capital expenditures).

Process Stability

One important measure of digester stability is the volatile acid concentration in the digester effluent. Higher volatile acids concentrations indicate that these products of kelp hydrolysis and acetogenesis are not being converted to methane as rapidly as they are produced. Thus, a high volatile acids concentration suggests an imbalance between the populations of acid- and methane-forming bacteria and greater digester instability.

The volatile acids concentrations in the USR and CSTR at kelp loading rates ranging from 1.6–9.6 kg VS/mg^3-d are shown in Fig. 9. At the

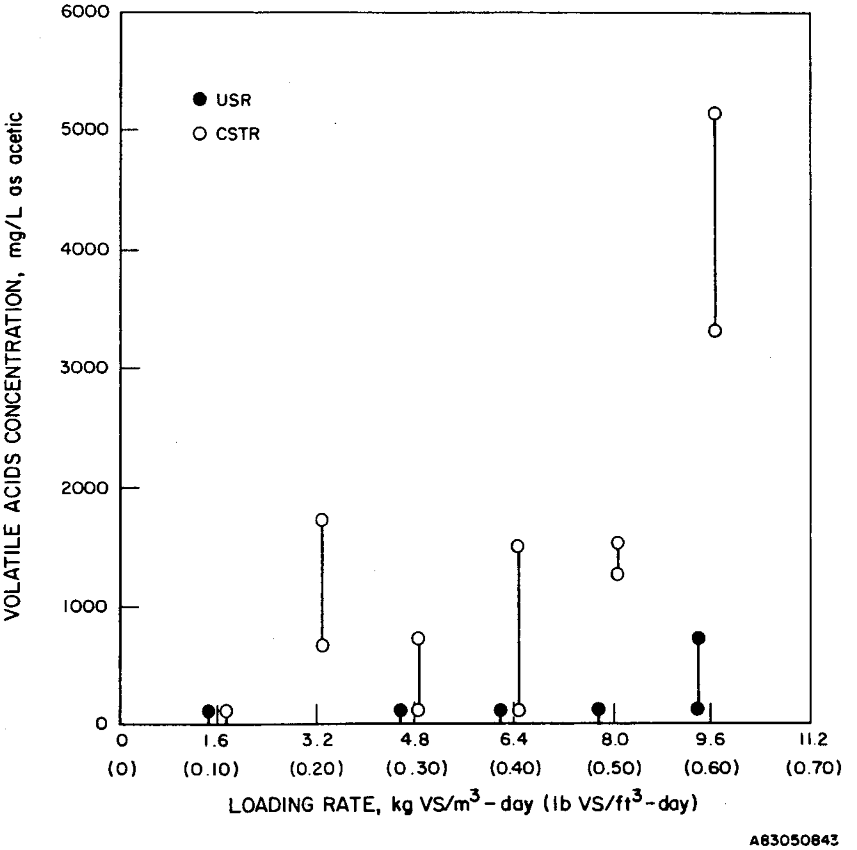

Fig. 9. Volatile acids concentration in USR and STR digesters receiving kelp lot 53 at several loading rates.

lowest loading rate, the volatile acids concentration in both the USR and CSTR was 100 mg/L as acetic. As the loading rate in each digester was increased to 8.0 kg VS/m^3-d, the volatile acids concentration increased in the CSTR, but not in the USR. The upper limit volatile acids concentrations ranged from 800–1800 mg/L as acetic in the CSTR, but did not exceed 100 mg/L as acetic in the USR. At the highest kelp loading rate, the volatile acids concentrations in the USR increased to an upper limit of 800 mg/L as acetic, but in the CSTR this level was as high as 5200 mg/L. These data clearly indicate that at loading rates above 1.6 kg VS/m^3-d, the performance of the USR was more stable than that of the CSTR. Furthermore, although some destabilization was observed in the USR at the highest kelp loading rate of 9.6 kg VS/m^3-d, significant instability occurred under similar conditions in the CSTR.

Liquid Effluent Characteristics

Reactors that promote longer SRTs have lower cell synthesis requirements and, consequently, lower energy and nutrient needs. Figure 10 presents the ammonia nitrogen (NH_3-N) concentration in the effluent from both USRs and CSTRs operated at 35°C, SRTs ranging from 7–200 d, and at loading rates ranging from .4–9.6 kg VS/m^3. The NH_3-N concentration in the effluent of a CSTR operated at an SRT of approximately 200

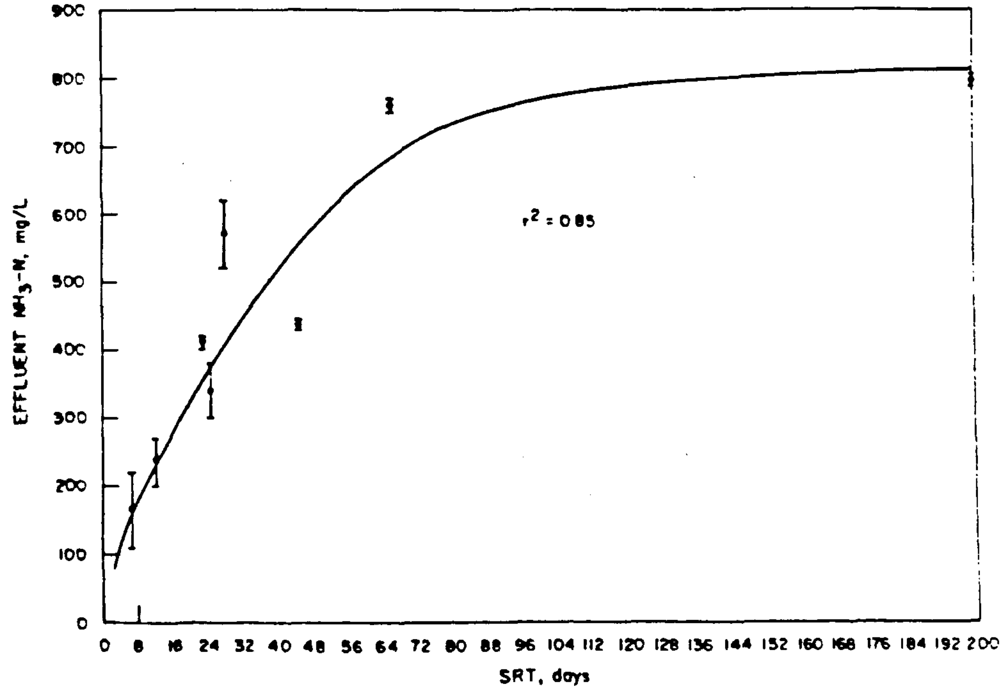

Fig. 10. Relationship between SRT and ammonia nitrogen in kelp digester effluent.

d was approx. 790–810 mg/L in the effluent. A nitrogen balance performed on a USR operated at a loading rate of 6.4 kg VS/m^3-d and a 12-d HRT, for example, showed that virtually all of the feed nitrogen was accounted for in the digester effluent and gas. Almost 98% of the feed nitrogen was accounted for in the digester affluent.

These data indicate that the ammonia in this digester was derived from sources within the feed, and suggest that either the nitrogen requirements for anaerobic digestion can be reduced or additional bound NH_3-N is made available by increasing the SRT. Higher NH_3-N concentrations reportedly increase alkalinity and digester stability (*8*). It is also indicative that a lower carbon-to-nitrogen ratio may be required in feeds that are digested in reactors such as USRs that promote longer SRTs.

CONCLUSIONS

Kelp is an abundant, highly biodegradable biomass that can be used in anaerobic digestion to produce methane. Long SRTs are probably more important to high methane yields than reactor design. For example, at long SRTs of 200 days under mesophilic conditions, 81% of the theoretical methane yield is attainable with kelp in CSTRs. However, longer SRTs are achievable in USRs, by virtue of their design, than in CSTRs because the solids are passively retained longer than the liquid portion of the feed. Thus, utilization of USR designs will enable smaller reactor sizes and resultant lower capital costs.

Methane yields of 0.37 SCM/kg VS added can be achieved in stable digestion of sea kelp. Using USRs and organic loading rates of as high as 9.6 kg VS/m^3-d, methane production rates of more than 3.3 vol/vol-d can be achieved. The performance of kelp digestion presented here, in terms of loading rates, methane yields, methane production rates, and process stability, is among the best ever reported for particulate forms of biomass.

The organic composition of kelp can vary substantially, depending on the conditions of growth and harvest. Mannitol and algin are two important organic components of sea kelp whose concentrations in kelp are somewhat inversely related. Since the methane yield of mannitol is substantially higher than that of algin, kelp lots that have higher concentrations of mannitol relative to algin can be expected to have higher methane yields. These observations emphasize the importance of controlling the growth of kelp to be used for methane production in order to maximize the mannitol and minimize the algin content. Achieving the most cost effective algin-to-mannitol ratio requires establishing the optimum systems costs than can be achieved using the value of both the energy and byproducts from the process.

In addition to improved performance in terms of methane yields and process stability, longer SRTs promote higher concentrations of ammonia–nitrogen in the digester effluent. The data suggest that the cell synthesis requirements for digesters decrease or that additional ammonia is released at longer SRTs.

Sea kelp (*Macrocystis pyrifera*) is a very promising species for large-scale methane production from renewable biomass. Although considerable progress has been demonstrated in the anaerobic digestion of kelp, further research is needed. The design of the upflow solids reactor and a second-stage reactor needs further evaluation and optimization. These studies should include large-scale demonstration reactors to enable the evaluation of materials handling, process control, and effluent utilization options. Further work is needed on the effect of feed composition and inocula development on anaerobic digestion. In addition, different operating conditions, including two-phase digestion, may affect process performance and stability, and methods for process control need further study.

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