The Open Environmental Engineering Journal, **2013**, *6*, 32-39

Enhanced Methane Production from Pilot-Scale Anaerobic Digester Loaded with Rice Straw

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Abstract: A novel co-digestion approach was evaluated to determine if agricultural and industrial waste residues could efficiently degrade straw without pretreatment. Untreated rice straw was co-digested with pig wastewater and anaerobic sludge from the pulp and paper mill treatment process in a pilot-scale digester (1 m^3) operated in dry, mesophilic conditions. The total weight ratio of dry straw to pig wastewater to sludge was 1 to1.25 to 0.5. The experiment was performed for a total of 153 days, however, the optimum period to balance the maximum energy output with the minimum retention time was determined to be 93 days. The addition of paper mill sludge accelerated VFA formation and gas production when compared to another pilot-scale digester operated under the same conditions without the sludge material. The straw in the pilot-scale digester with the sludge yielded 231 LCH_4/kg VS within a 93-day digestion cycle compared to 189 days without the sludge. Daily leachate recirculation (0.2m^3/m^3 straw-day), however, was not adequate for internal mixing and homogenization of the digester material. With adequate mixing, this co-digestion approach could enhance methane production and reduce the digestion time for untreated rice straw in a farm-scale digester.

Keywords: Anaerobic digestion, rice straw, methane, pilot-scale, paper mill.

1. INTRODUCTION

Energy production from lignocellulosic waste is advantageous because there is an abundant supply of agricultural waste residues available, it does not interfere with the provision of valuable food sources, and it offers a potential reduction of greenhouse gas emissions by removing these residues from the field and capturing the methane. Energy from rice straw can be produced from thermochemical processes such as pyrolysis, combustion or gasification [1-4]; however, these processes are energy intensive. Bioethanol production from rice straw via fermentation is also an option but this process is expensive and relatively low yields have been observed [5]. As in anaerobic digestion, the hydrolysis of cellulose is inhibited by lignin and pretreatment is required to enhance ethanol production [5, 6]. Biogas production from rice straw via anaerobic digestion is considered to be one of the most environmentally friendly processes for converting biomass into energy [7, 8].

The challenge associated with the utilization of lignocellulosic wastes for energy recovery is that the lignin acts as a barrier and can inhibit microbial populations that perform hydrolytic conversion of cellulose [9]. Several studies have investigated pretreatment strategies that enhance microbial degradation of lignocellulosic wastes in the context of anaerobic digestion [10-13]. The major goal of this research is to avoid design complications and energy inputs by removing the pretreatment step and use a novel co-digestion approach with waste products. Co-digestion with other wastes has been shown to enhance methane production from lignocellulosic wastes [14], and co-digestion is a simpler and more feasible approach for farm-scale applications. Co-digestion of rice straw with animal manure provides an appropriate balance of nutrients for anaerobic systems [15], and increased biogas yields from rice straw co-digested with both cattle manure and piggery wastewater have been demonstrated [16, 17]. An existing farm-scale system (15,000 m^3) in Northern Italy converts rice straw into electricity using piggery wastewater alone to promote microbial fermentation in dry conditions (*i.e.* ≥ 20% total solids (TS) concentration) [18]. However, a long acclimation period (200 days) and slow digestion cycle (422 days) was observed. A practical option for improvement is to add an acclimated microbial population to reduce the start-up cycle and improve methane yields.

Sludge generated in the pulp and paper mill industry likely contains microbial populations that are already acclimated to lignin-containing waste material. *Clostridium cellulovorans*, for example, originate in wood chips [19] and they produce enzymes that are capable of degrading rice straw in

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1874-8295/13

Table 1. Total and Volatile Solids Concentrations of Raw Materials in Digester

	Rice Straw	Piggery Wastewater	Paper Mill Sludge
TS (%)	64.4	1.1	17.0
VS (%TS)	88.7	40.2	62.4

10 days [20]. To test this hypothesis, sludge was collected from an upflow anaerobic sludge blanket (UASB) reactor that is part of the initial stage of treatment for pulp and paper mill effluent. This effluent is generated from five different pulping facilities that employ different operational practices. An initial laboratory study demonstrated that co-digestion of rice straw with both piggery wastewater and UASB paper mill sludge could accelerate formation of volatile fatty acids (VFA) and produce higher methane yields (302 to 340 L_NCH_4/kgVS) than those generated with the piggery wastewater alone [21]. In the present work, a pilot-scale digester (1 m^3) was operated with the same straw-inocula mixture and digestion conditions tested in previous lab-scale experiments to determine if this co-digestion approach could improve methane production and reduce digestion cycles for farm-scale systems. The purpose of this work is to increase the scale of the laboratory experiments in order to simulate farm-scale conditions and determine if this co-digestion approach is an appropriate solution for large-scale applications. The premise of this work is unique because it proposes a co-digestion approach with not only piggery wastewater (tested previously in a pilot-scale system) but also with anaerobic sludge from the pulp and paper mill treatment process to enhance methane production from untreated rice straw.

2. MATERIAL AND METHODS

2.1. Experimental Set-up

A single pilot-scale digester (1 m^3) equipped with a leachate recirculation system was used for this experiment. The specific components and dimensions of the digester are described in a previous study [22]. The digester was operated as a batch reactor and initially filled with 50 kg of dry straw, 75 kg of piggery wastewater, and 25 kg of anaerobic sludge from the pulp and paper mill treatment process. This substrate to inocula ratio was determined to be the optimum ratio based on methane yields obtained in laboratory-scale digesters [21] and feasible application for a farm-scale system. The digester was operated in dry (20% TS), mesophilic conditions for a total of 153 days. Dry conditions are advantageous since they require significantly less water that wet conditions (*i.e.* $\leq$ 10% TS) and the farm-scale system is currently operated in dry conditions [18]. Mesophilic temperatures were chosen since optimal gas production from rice straw is within 35 to 40°C [15], and much less energy input is required than thermophilic conditions. The entire volume of excess liquid, or leachate, was recirculated daily. The leachate recirculation served as the primary means of mixing since there was no mechanical stirrer. On two occasions (Day 62 and Day 99) the digester was opened and the biomass was manually stirred. The digester was flushed with nitrogen gas after each mixing event to reestablish anaerobic conditions. The biogas production volume, biogas quality (*i.e.* % CH_4, %CO_2, and %O_2), and digester temperature was also measured and recorded daily.

The rice straw was harvested from a rice field in the Pavia Province of Italy approximately two weeks prior and stored in a dry location. No pretreatment, drying, cutting or milling activities were applied to the rice straw. The straw was collected directly from the field and added to the digester in lengths ranging from 0.2 to 0.6 m. Raw piggery wastewater was collected from a preliminary holding tank at a pig farm in the Pavia Province of Italy. Anaerobic granular sludge was collected from a treatment facility in Eerbeek, the Netherlands, which processes a combined wastewater from five different pulp and paper mill plants.

2.2. Analytical Methods

TS and volatile solid (VS) concentrations were measured on the rice straw, piggery wastewater and paper mill sludge prior to placement in the digester. Solids concentrations were also measured on the digestate at the end of the experiment. These analyses were conducted in triplicate and measured according to American Public Health Association (APHA) Standard Methods 2540 [23]. The results of the solids concentrations are summarized in Table **1**. Biochemical methane potential (BMP) assays were also conducted for the seed mixture (*i.e.* piggery wastewater and paper mill sludge) in mesophilic conditions to determine if the fraction of methane production coming from the wastewater was significant [24].

A leachate sample was collected daily and analyzed for pH, VFA, carbonate alkalinity (C_T), and total ammonia nitrogen (TAN). The leachate analyses were completed as a single sample within two hours of the collection time. The pH was analyzed with a Hamilton Filltrode probe and was conducted in accordance with the APHA Standard Methods [23]. VFA and C_T were analyzed by a titration method using 0.1 M hydrochloric acid (HCl) and acidifying the sample to pH of 2.2, while continually recording pH and using a computer modulation to calculate the results [25]. The TAN concentration (NH_3-N and NH_4^+-N) was analyzed using a spectrophotometer (SPT-500) with a Carlo Erba reagent kit (0800.05405). Free ammonia (NH_3-N) was calculated from TAN using an equation from Anthonisen et al. that incorporates pH and temperature [26].

A permanent temperature probe was placed inside the digester and connected to a Gefran digital meter for temperature readings. Biogas volume was measured with an Elster volumetric flow meter (Q_{max} – 4m^3/h, Q_{min} – 0.005m^3/h) and the gas composition was measured with a Geotech biogas analyzer.

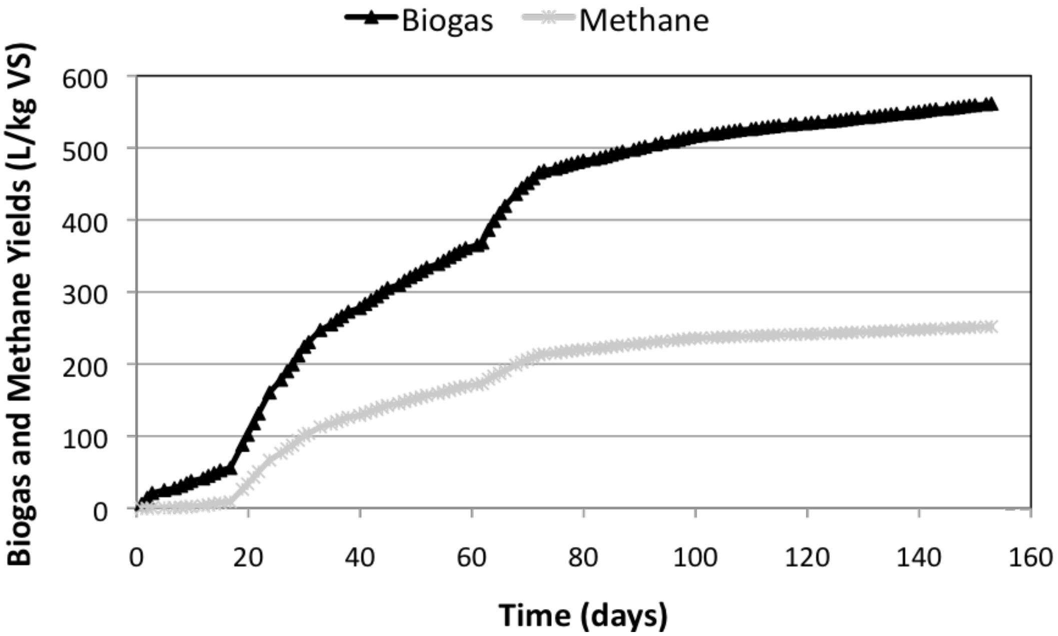

Fig. (1). Specific Biogas and Methane Yields from Digester as a Function of Time.

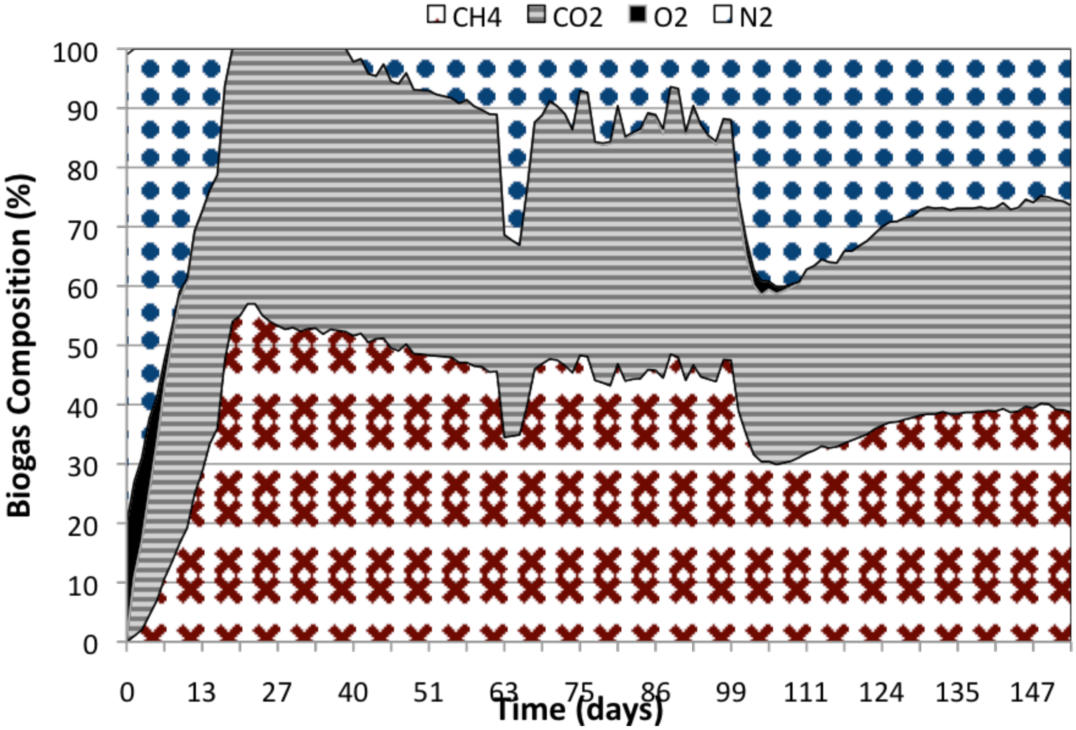

Fig. (2). Biogas Composition from Digester as a Function of Time, Red X (CH_4) and Blue dot (N_2).

3. RESULTS AND DISCUSSION

3.1. Gas Production

The specific biogas and methane yields were calculated as the volume of biogas and methane produced per kg of rice straw VS added, and any contribution of gas production from the inocula mixture was subtracted. The methane produced from the inocula mixture was determined during preliminary biochemical methane potential (BMP) assays containing both piggery wastewater and paper mill sludge. Based on these results, approximately 5% of the overall methane produced (*i.e.* 515 L out of 11,325 L) was from the inocula mixture. After subtracting any influence of gas production from the inocula mixture, the specific biogas and methane yields were calculated to be 561 and 252 L/kg VS straw added, respectively, for the 153-day digestion cycle. Cumulative yields are shown as a function of time in Fig. (**1**).

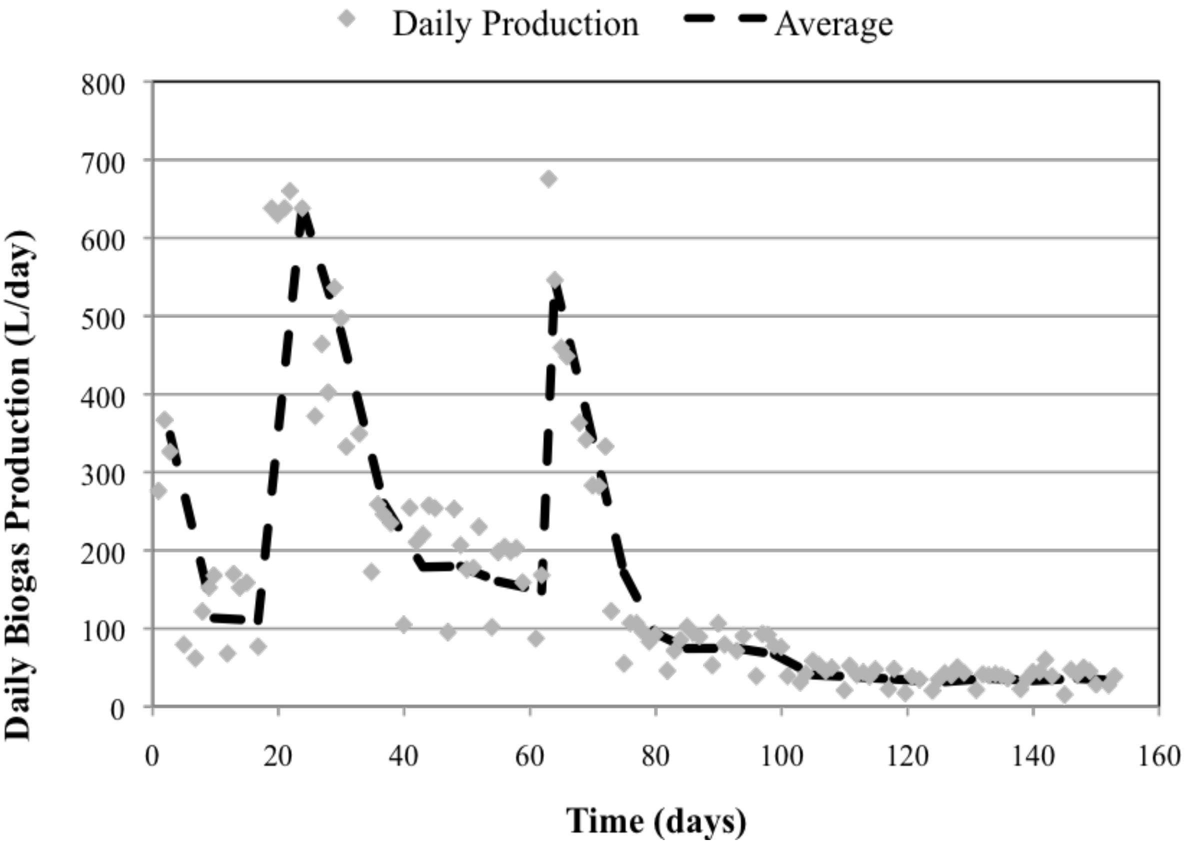

Fig. (3). Daily Biogas Production Rate Measured in Digester.

The average methane content in the biogas was 51% upon digester stabilization through Day 62. The biogas quality exceeded 50% CH_4 by Day 19 and reached a maximum of 57% on Day 22. The biogas quality was compromised, however, each time the digester was opened for manual stirring (Days 63 and 99), resulting in decreasing CH_4 and increasing N_2. Slight concentrations of O_2 (0.2 to 3.0%) persisted in the digester for 10 days following the second mixing event. The biogas composition (%CH_4, %CO_2, %O_2, and %N_2) is shown as a function of time in Fig. (**2**).

The daily biogas production trend shows that 45% of the biogas was produced within the first 35 days, with an initial peak of 660 L/day on Day 22 (see Fig. **3**). Biogas production gradually declined until Day 62. A second peak of 676 L/day occurred on Day 63, immediately following the first mixing event in which the digester was opened and manually stirred. The initial mixing event stimulated biogas production for 10 days (through Day 72) followed by a stable decline. The second mixing event on Day 99 had no stimulating effect on gas production, and the residual oxygen generated from opening the digester may have had a detrimental effect. Though the digestion cycle was carried out for 153 days for data collection purposes, the average daily gas production was less than 40 L/day for the last 50 days. Therefore, 90% of the overall biogas production and 92% of the overall methane production was completed by Day 93. For comparison purposes, a 93-day digestion cycle would have resulted in specific biogas and methane yields of 505 and 231 L/kg VS straw added, respectively.

3.2. VFA Formation and System Stability

Leachate was recirculated at a rate of $0.2 m^3/m^3$ straw-day and chemical analysis was performed daily on the leachate samples. The accumulation of VFAs was evident during the first 20 days of the experiment. An initial peak VFA concentration of 6178 mg HAc/L occurred on Day 8, and a second smaller peak of 3387 mg HAc/L was observed on Day 14. By Day 22, the formation of VFAs was moderate with concentrations ranging from 112 to 739 mg HAc/L and averaging 405 mg HAc/L for the remainder of the experiment. Although gas production significantly increased as a result of the mixing event on Day 63, there was no corresponding accumulation of VFAs indicating system stability and microbial acclimation.

The pH and alkalinity were impacted by the initial accumulation of VFAs, but the overall stability of the system was not compromised. During the initial VFA peak on Day 8, the lowest pH value (6.25) and alkalinity concentration (0 mg $CaCO_3$/L) were observed. The pH completely recovered by Day 12 and remained stable, ranging from 7.38 to 8.08, with an average of 7.78 for the duration of the experiment. The alkalinity also showed signs of recovery through Day 12, but a sudden decrease in alkalinity corresponded with the second VFA peak on Day 14. By Day 22, the alkalinity had completely recovered to 3698 mg $CaCO_3$/L and it remained above 2000 mg $CaCO_3$/L for the rest of the digestion cycle. Fig. (**4**) shows the trend of VFA concentrations, alkalinity and pH values measured during the digestion cycle.

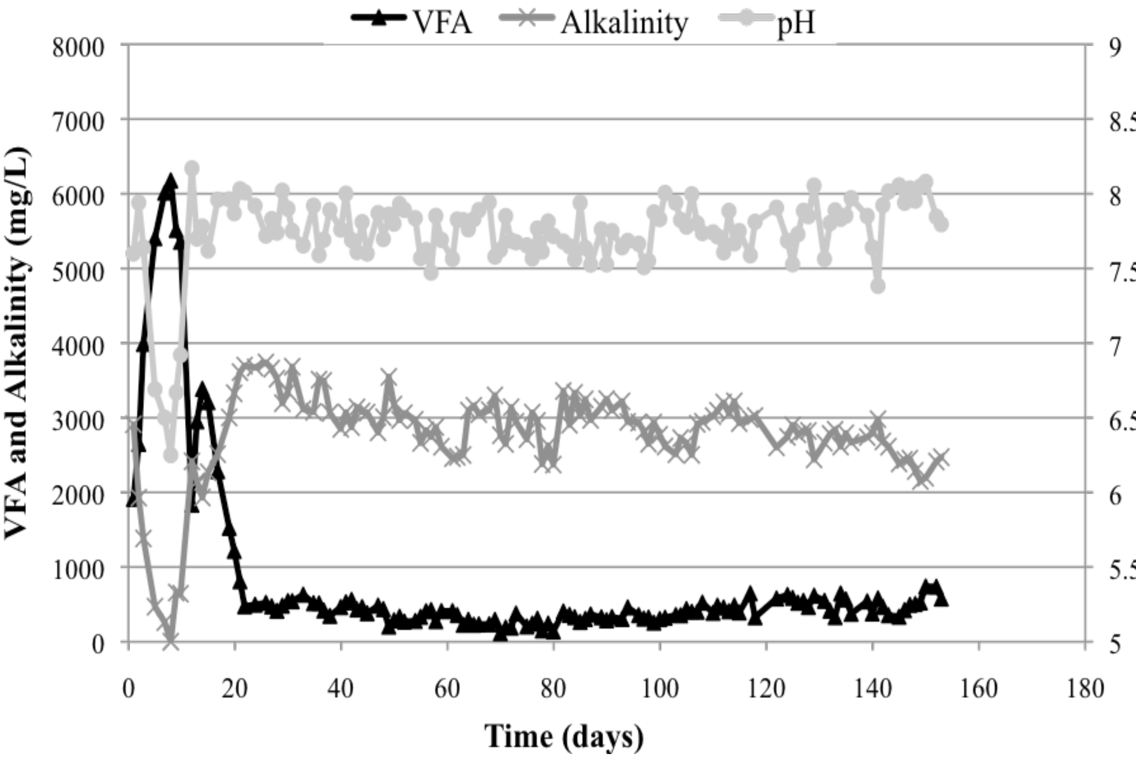

Fig. (4). VFA Concentration (as mg HAc/L), Alkalinity (as mg $CaCO_3$/L) and pH Measured in Leachate Samples as a Function of Time.

The ideal temperature range for the anaerobic digestion of rice straw is between 35 and 40°C [15]. Excluding the first 24 hours, the digester temperature ranged from 35.2 to 41.0°C with an average digester temperature of 37.2°C.

3.3.Ammonia Nitrogen Concentrations

The TAN (NH_3 + $NH4^+$-N) and free ammonia (NH_3) trends are shown in Fig. (**5**). Upon mixing the straw with the inocula, the leachate from the digester had an initial TAN concentration of 805 mgN/L. TAN was consumed during the peak gas production phase, resulting in a concentration of 613 mgN/L on Day 22. Following Day 22, TAN concentrations remained fairly stable between 525 and 626 mg N/L with an average concentration of 580 mgN/L. Although some variability was observed from day to day, a distinct oscillation (rise-fall-rise-fall) occurred during the 10 days following the initial mixing event (*i.e.* Day 63 to 72). The NH_3 concentration varied based on the slight changes in temperature and pH, but it remained below 100 mgN/L except on one occasion. The maximum NH_3 concentration (129 mgN/L) occurred on Day 12, which corresponded with the minimum pH value.

4. DISCUSSION

The experiment was carried out for a total of 153 days resulting in a specific methane yield of 252 L/kgVS. However, after 93 days, over 90% of the methane production was complete and a specific methane yield of 231 L/kgVS was calculated. A comprehensive summary of methane yields obtained for rice straw are reported in a previous literature review [15]. For large-scale applications and economic feasibility, it is important to balance maximum energy outputs and minimum biomass retention times. In the current design, a 93-day digestion cycle would be most appropriate to achieve this balance.

The addition of the anaerobic sludge from the pulp and paper mill treatment process resulted in much faster digestion than without sludge. Another pilot-scale system with the same quantity of dry rice straw (50kg), twice as much piggery wastewater (150L) but no paper mill sludge, and the same operational design parameters (20% TS, mesophilic temperature, leachate recirculation) resulted in the same specific methane yield (231 L/kgVS) in 189 days [22].

The acclimation period for the digester without the sludge was much longer with a daily peak gas production on Day 112 [22] versus Day 22 with the sludge, resulting in an overall digestion time that was twice as long. Another major advantage of using the paper mill sludge is that less volume of inocula is required, which reduces costs for acquiring and transporting wastewater. In the current design, the substrate to inocula weight ratio (dry rice straw to piggery wastewater to paper mill sludge) is 1 to 1.25 to 0.5 while the other pilot-scale digester was 1 to 3 to 0 [22].

The current pilot-scale digester is an upscale of a previous lab-scale digester (1 L) with the same substrate to inocula ratio and operational parameters. The lab-scale digester (D4) had a specific methane yield of 302 L/kgVS in a 92-day digestion cycle [21], which is significantly higher than the results obtained in the pilot-scale digester. The primary reason for this difference is the lack of mixing capacity in the pilot-scale reactor. Lack of mixing typically results in less methane production and incomplete digestion since

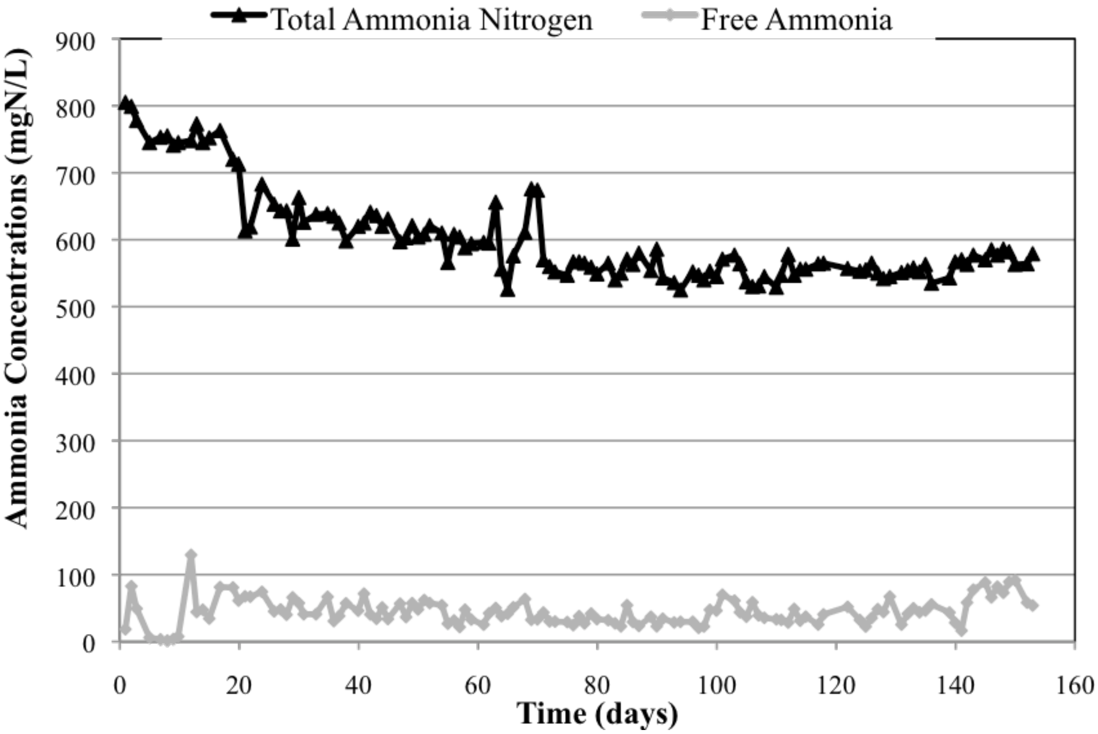

Fig. (5). TAN and Free Ammonia Measured in Leachate Samples as a Function of Time.

there is no uniform distribution of substrate, inocula and enzymes [27]. Internal mixing components for dry digestion systems require lots of energy and maintenance since the material is heavy and immobile. In the lab-scale digester, the contents were stirred by hand to create a homogenous mixture prior to digestion since the volume was manageable and leachate recirculation was not possible. The pilot-scale digester was designed to emulate the farm-scale system in which leachate recirculation is currently the only mechanism used for mixing [18]. The leachate recirculation in the pilot-scale digester, however, did not provide adequate mixing and therefore gas production was hindered. This limitation is evident based on the peak in gas production observed after the digester was manually opened and mixed on Day 62 (see Fig. **3**) as well as the visual observation when the digester was opened. The black granules of the paper mill sludge were clustered on the top of the straw material, rather than being evenly distributed throughout the digester. Manual mixing to redistribute the sludge material resulted in an immediate increase in gas production in the following days. If the digester contents would have been adequately homogenized at the beginning of the experiment, complete digestion would likely have occurred within a 92-day digestion cycle as observed in the lab-scale digesters [21].

Typically, untreated lignocellulosic material is very difficult to degrade and thus hydrolysis of this material is considered the rate limiting step in the anaerobic digestion process [9, 28]. However, the production of VFAs in the current pilot-scale digester peaked very quickly within the first two weeks of the digestion cycle followed by peak gas production on Day 22. Two definitive VFA peaks were observed on Day 8 and Day 14, representing the hydrolysis of the piggery wastewater followed by the hydrolysis of the rice straw. Similar VFA trends were observed in the lab-scale digesters (specifically in D3 and D4), where the initial VFA concentration began to decrease rapidly followed by a second peak in production [21]. In the lab-scale digesters, the second peak was associated with the hydrolysis of the straw material, which occurred faster in the digesters containing a higher ratio of paper mill sludge [21]. Based on these observations as well as the increased gas production that followed, it is reasonable to assume that the straw degradation in the pilot-scale digester was occurring by Day 14 of the digestion cycle. Following VFA accumulation, concentrations settled around 400 mgHAc/L which is within the optimum range of 50 to 500 mgHAc/L for anaerobic digestion [27], signifying stable digester performance.

The VFA production and specific methane yield observed in this experiment with untreated rice straw in mesophilic conditions are very similar to the results obtained from a pilot-scale digester with pretreated rice straw in ambient conditions [29]. The VFA peak production for the digester with pretreated rice straw occurred on Day 10 [29], while the VFA peak with untreated rice straw occurred on Day 14. A specific methane yield of 240 $LCH_4/kgVS$ was achieved after 89 days for the pretreated straw, which is comparable to the results for the untreated straw co-digested with piggery wastewater and paper mill sludge (231 $LCH_4/kgVS$ in 93 days).

While the paper mill sludge accelerated VFA formation and gas production, the presence and routine recirculation of the piggery wastewater provided sufficient buffer and nutrients to maintain system stability. The digester leachate was slightly acidic (6.25) during peak VFA production but quickly recovered within a couple days. The alkalinity supplied by the piggery wastewater was sufficient (approximately 3,000 mg$CaCO_3$/L) to prevent an extreme drop in pH, and the TAN concentrations were adequate but not inhibitory for the anaerobic digestion process [27, 30].

5. CONCLUSIONS

The addition of paper mill sludge with piggery wastewater in a pilot-scale digester of untreated rice straw operated in dry, mesophilic conditions accelerated VFA formation and gas production. The untreated rice straw with the sludge yielded 231 LCH_4/kg VS within a 93-day digestion cycle compared to 189 days without the sludge. Although the digestion cycle was initially carried out to 153 days, the 93-day digestion cycle was determined to be the optimum time period to balance the maximum energy output with the minimum retention time. Daily leachate recirculation ($0.2m^3/m^3$ straw-day) was not adequate for internal mixing and homogenization of the digester material, which is necessary to achieve maximum gas production within the shortest time period. This co-digestion approach is feasible for application to the farm-scale digester, as it would improve methane production, reduce the retention time of the straw, and reduce the quantity of piggery wastewater needed for the optimum digestion conditions.

Future studies should focus on improving the mixing capacity in the existing system as well as the potential for using continuous anaerobic reactor configurations for dry systems such as Dranco, Valorga or Kompogas. To better understand the microbial consortium responsible for the improved digestion with the paper mill sludge, microbiological evaluations should be conducted on samples collected at the beginning and throughout the digestion process to identify the specific microorganisms present in the mixture.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

This research was funded by the Erasmus Mundus Joint Doctorate program ETeCoS^3 (Environmental Technologies for Contaminated Solids, Soils and Sediments) under the EU grant agreement FPA n2010-0009 and also by the company Acqua e Sole s.r.l. as an associate member of the ETeCoS^3 consortium. Representatives from Acqua e Sole provided the basis of the study design, all the necessary equipment to carry out the experiments, laboratory support for the analyses, and assistance in the data interpretation. The authors would like to thank Erasmus Mundus for funding for this research program and Acqua e Sole s.r.l. for their help and support throughout the project. A special thanks to Filip ("Pippo") Pitu for the digester set-up, Fabrizio Boari for his machine operator skills and Yuri Lazzarini for his consistent help and support.

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Received: September 26, 2013 Revised: November 15, 2013 Accepted: November 19, 2013