Evaluation of Biogas Through Chemically Treated Cottonseed Hull in Anaerobic Digestion With/Without Cow Dung: an Experimental Study

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Abstract
Cow dung is generally used as the feedstock material for the anaerobic digestion to produce biogas. A selection of alternate biomass material is needed to reduce the consumption or to eliminate the use of cow dung. Recently, cottonseed hull has been considered as the primary substrate to produce biogas. In this paper, the effect of biogas production on anaerobic co-digestion of CD with pre-treated CSH using sulfuric acid, hydrochloric acid, hydrogen peroxide, and acetic acid is investigated. The concentration of each acid has been varied as 1%, 2%, and 3%. In addition, the two alkaline, namely, sodium hydroxide and calcium hydroxide, are used at different concentrations of 4%, 6%, and 8%. The biogas yield obtained from the mono-digestion of pre-treated CSH and the co-digestion of CD with chemically treated CSH at the ratio of 75:25 (CD: CSH) using the experimental results are compared. The enhancement of biogas production from the batch reactors at mesophilic temperature where the cow dung is mono- and co-digested with acid-treated and alkaline-treated cotton seed hull are observed and compared. The maximum biogas yield is achieved for the treated CSH at the concentration of 6% NaOH that offers 13-fold improvement over untreated CSH during mono-digestion. Whereas in co-digestion, it achieved a 6-fold improvement over untreated CSH with the ratio of 75:25 at the concentration of 6% Ca(OH)₂.

Keywords Biogas · Chemical pre-treatment · Anaerobic digestion · Cow dung · Cottonseed hull

Introduction
In the present world, the increase in the human population is proportional to the increase in energy demand. Energy extracted from fossil fuel is mostly used which creates issues such as scarcity, expensive in price, and causes air pollution which mainly affects the environment [1]. Previous studies also suggested using biogas as a clean energy source for power generation, cooking, and heating. Furthermore, anaerobic digestion for biogas production is a potential option that may both augment and reduce the use of non-renewable energy sources like fossil fuels [2]. Cotton production is predicted to climb 4.7% globally by 2021/2022, according to a forecast by the US Department of Agriculture. However, there is a 6.5% reduction in comparison to 2019/2020. China is predicted to be the largest producer, with 29.0 million bales of cotton, the highest level in the last 6 years, while India is estimated to produce roughly 475 kg/hectare, a 1% decrease from the previous year. India was first in cotton-producing countries in 2015, and second in 2019 and 2020, followed
by the USA, Brazil, and Pakistan [3]. In India, surplus crop residue is composted, which takes up a lot of space, and then burned. Crop residues produce greenhouse gases when burned, contributing to increased air pollution [4]. Agricultural crop residues are used to produce biogas via anaerobic digestion to address this problem [5]. Agricultural crop residue such as cotton waste was generated around 11.4 Mt in India [6]. Appropriate technologies are employed for the production of clean energy to properly utilize waste and meet current energy requirements by reducing pollution. For the maximum degradation of organic waste, anaerobic digestion is the best technique opted for the generation of energy (methane) in a more economical and environment-friendly manner [7–9].

The anaerobic biodegradability has been enhanced with the aid of treatment methodologies such as mechanical, thermal, chemical, ultrasonic, biological, and microwave approaches through the anaerobic digestion process [10, 11]. Biogas is produced through an anaerobic digestion process on various biomass materials such as wheat straw [12], pearl millet straw [13], corn stover [14, 15], rice straw [16], yard waste, and leaves [17], and also with other wastes such as food waste with cow dung [18], food waste with fresh septic tank sludge [19], and sewage sludge with food waste [20].

Anaerobic co-digestion is a promising technique to enhance the digestion performance and biodegradability of lignocellulose biomass [21]. Among all the pre-treatment processes of biomass, the chemical pre-treatment process has been reported to offer maximum methane yield through the anaerobic digestion process with the effective breaking of chemical bonds among cellulose, hemicellulose, and lignin through microorganisms [22]. In the chemical treatment methods, the following chemicals are commonly used such as H2SO4, HCl, H2O2, CH3COOH, NaOH, and Ca(OH)2 for the biodegradability of lignocellulosic biomass materials through an anaerobic digestion process [23]. NaOH and Ca(OH)2 are used as pre-treatment chemicals on giant reed materials for the enhancement of biogas production through anaerobic digestion [24]. Three plant species such as hay, straw, and bracken were pre-treated using Ca(OH)2, maleic acid, and ammonium carbonate, and subsequent anaerobic digestion was carried out under mesophilic temperature for 40 days in a batch digester [25]. The highest methane production was achieved by pre-treating corn stalk with Ca(OH)2 through an anaerobic co-digestion process with levulinic acid wastewater [26]. Pre-treated grass silage with NaOH increases biodegradability as well as biogas production through anaerobic digestion [27]. Sunflower stalks are pre-treated using various chemicals like NaOH, H2O2, Ca(OH)2, HCl, and FeCl3 to enhance methane production through anaerobic digestion [28]. Anaerobic co-digestion of cattle manure and corn stover was compared with that of ammonia solution and NaOH pre-treated samples which also results in higher methane yield under mesophilic conditions [29]. Pre-treatment of corn stalk using H2SO4 and H2O2 yields higher biogas production on the anaerobic co-digestion with swine manure [30]. Anaerobic co-digestion of cocoa pod husk with swine manure yields maximum biogas production where cocoa pod husk was pre-treated by using H2SO4 and H2O2 [31]. It was reported that methane production is directly proportional to the enzymatic degradation of the lignocellulose biomass, whereas methane potential is inversely related to the lignin content present in the lignocellulose biomass [17]. Remarkable biogas production was achieved on pre-treating NaOH with corn stover [14, 15, 32] and asparagus stover [33] in the anaerobic digestion process. Pre-treatment of rice straw with H2O2 used in biodegradation enhances biogas production [34]. Co-digestion of wheat straw with chemicals like KOH, Ca(OH)2 results in higher biodegradability with the increase in biogas yield [35]. The main advantage of chemical pre-treatment on lignocellulosic biomass is to improve the effective biodegradability and upsurge the bioenergy production [23].

Naturally, agricultural biomass waste like cotton stalks was generally burnt and lead to air pollution. Cotton stalks can be effectively converted into useful energy through anaerobic digestion by various treated chemicals such as KOH, NaOH, Ca(OH)2, alkali hydrogen per-oxide (AHP), H2SO4, H3PO4, and steam explosion method [36]. Wheat straw was pre-treated with H2O2 and also co-digested with cattle manure for the enhancement of biodegradability and also methane yield [37]. Cotton wastes such as cotton stalks, cottonseed hull (CSH), and cotton oil cake can be effectively converted for biogas production in the presence of basal medium through anaerobic digestion [38]. For sustainable environments, energy extraction has been done by performing effective pre-treatment studies to improve energy production [39].

Biochemical methane potential (BMP) test was conducted in an anaerobic co-digestion of cow dung (CD) with cottonseed hull (CSH) at different ratios (CD:CSH), i.e., 0:100, 50:50, 25:75, 75:25, and 100:0. Maximum biogas yield was obtained from the anaerobic co-digestion at the ratio of 75:25 among other proportions. Mono-digestion of CSH results in less biogas yield compared to the co-digestion of CD and CSH at the ratio of 75:25. From the previous studies, it is found that the optimum biogas yield is obtained from the anaerobic co-digestion of CD with CSH at the ratio of 75:25, and verified both experimentally [40] and using kinetic studies [41].
From the above literature review, it is found that the importance of chemical treatments on different biomass and the triggering of biogas generation through anaerobic digestion. Besides, the chemicals used for treatment break the bonding between the complex biomass structures in generating the anaerobes at a rapid rate. The CSH has the potential to generate biogas during mono- and co-digestion with CD. Very few literatures have reported on the biogas generation from anaerobic mono- and co-digestion of CD with chemically treated CSH. The performance of the digester with CD and CSH in the ratios of 75:25 and 0:100 with pre-treatment with various chemicals such as sulfuric acid, hydrochloric acid, hydrogen peroxide, acetic acid, sodium hydroxide, and calcium hydroxide at different concentrations for the enhancement of biogas yield has been investigated in this paper. The main objective of this paper is to find out the maximum biogas yield among all chemically pre-treated CSH and the best concentration in each acid and alkaline. The best-treated chemical for CSH for the complete replacement of CD in the existing gobar gas plant is also suggested.

Materials and Methods

Feedstock Material

Feedstock material such as CD and CSH was collected from a local village in Karur city, Tamil Nadu, India (latitude—10.69°N, longitude—78.42°E). Before the usage of CSH material, air drying and shredding were done to make it into small particles with a spice pulverizer (Vikrem commercial heavy-duty pulverizer, India, Vik-9A model). Then, the material was sieved for 10 min through a particle sieve analyzer (maker: Versatile Equipment Private Limited, India) which ranges from 0.5 to 0.75 mm. Fresh CD was collected from a small household located in the same village. The inoculum was taken from the batch anaerobic digester where CD was used as the main feedstock material at the same location. Prior to the BMP test, the collected feedstock material was kept at a temperature of 4°C. The effluent was maintained at a temperature of 37°C for 7 days and diluted with water [40]. The physical and chemical characteristics of the feedstock material are listed in Tables 1 and 2. CSH substrates consist of 32 ± 2.1% cellulose, 18 ± 0.9% hemicellulose, and 20 ± 1.7% lignin found using sequential extraction and weighing method [13].

Pre-treatment

A 500-ml conical flask is filled with 300 ml of distilled water and 100 g of CSH sample. Based on the weight/weight basis, acids and alkaline are added to the conical flask. From the previous study, the concentration of each acid and alkaline was chosen for the pre-treatment of CSH [23]. Acids are mixed with distilled water of proportions 1%, 2%, and 3%, whereas alkaline is mixed with distilled water of proportions 4%, 6%, and 8%, respectively. The conical flask was kept inside the incubator at a temperature of 25 ± 2°C for 7 days. After the incubation period, all the samples were kept in the electric oven for 2 days at a temperature of 80°C [23]. Then, the dried samples were taken out without washing and again maintained at a temperature of 4°C in the refrigerator until the start of the BMP test.

Anaerobic Digestion Experiments

Biogas production was determined through anaerobic digestion in a batch process with two sets of experiments. Each pre-treated CSH was used as the feedstock material, where untreated CSH was used as the control. In the first set of experiments, mono-digestion of acid- and alkaline-treated CSH was carried out at different concentrations. In the second set of experiments, co-digestion of CD and treated CSH at the ratio of 75:25 was carried out with the corresponding pre-treated CSH using early

| Table 1 Physical characteristics of the feedstock materials used |
| Samples used | Moisture present (%) | Total solid (TS) (%) | Volatile solid (VS) (%) | Fixed solid (FS) (%) | Reported |
|---------------|----------------------|----------------------|------------------------|----------------------|----------|
| Cow dung      | 86 ± 1               | 14 ± 1               | 68 ± 4                 | 32 ± 4               | [40]     |
| Cotton seed hull | 11 ± 0.1          | 90 ± 0.1             | 90 ± 0.1               | 10 ± 0.1             |          |
| Inoculum      | 92 ± 0.1             | 9 ± 0.1              | 62 ± 0.2               | 38 ± 0.2             |          |

± denotes the standard deviation values for triplicate observation

| Table 2 Chemical characteristics of the feedstock materials used |
| Feedstock materials | Total C (%) | Total H (%) | Total N (%) | Total S (%) | C/N ratio | Reported |
|---------------------|-------------|-------------|-------------|-------------|-----------|----------|
| Cow dung            | 39.64 ± 1.25| 1.85 ± 0.01 | 1.21 ± 0.02 | 2.24 ± 0.03 | 32.76     | [40]     |
| Cotton seed Hull    | 38.31 ± 0.3 | 2.24 ± 0.25 | 1.05 ± 0.01 | 1.47 ± 0.01 | 36.38     |          |
| Inoculum            | 30.36 ± 1.5 | 0.88 ± 0.02 | 1.53 ± 0.01 | 1.37 ± 0.02 | 19.91     |          |
mentioned chemicals. All the experiments were conducted in a 0.5-L conical flask of which 0.3 L was taken as working volume. Each conical flask was filled with 0.3 L of inoculum, and feedstock material was added based on a final concentration of 1.5 g volatile solid (VS) per liter, the main reason for using inoculum from the anaerobic digestion process, which stimulates the methanogenic activity inside the batch reactors. Initially, all the conical flasks were stirred well and incubated under the mesophilic condition at a temperature of 35 ± 2 °C for the digestion period of 45 days [42]. All the flasks were flushed with nitrogen, then closed by using a septa cap and kept in the incubator to create favorable conditions for generating anaerobes. Each flask was stirred manually for 1 min before measuring the biogas yield at the interval of 5 days. All the BMP tests with each sample were performed in duplicate.

**Analysis and Calculations**

The volume of biogas produced from the digester was determined by using the water displacement method as mentioned in the previous paper [41]. The measured volume of biogas was finally calculated by subtracting measured biogas in each digester from the volume of biogas collected in the inoculum. Physical characteristics like total solid, volatile solid, fixed solid, and moisture content were found using standard methods [43]. Chemical characteristics like carbon and nitrogen were calculated using Vario EL III- Germany Elementar analyzer. C/N ratio was calculated as the ratio of total carbon to total nitrogen. pH values were determined using a pH meter (pH 827 modules, Metrohm India Ltd.). The composition of cellulose, hemicellulose, and lignin presented in CSH substrate was measured using sequential extraction and weighing method on a dry weight basis [13]. CSH samples were mixed in 75 ml of water and boiled for 1 h. Residing hot water was removed after an hour by adding fresh water and boiled for one more hour. Then, the CSH samples were cleaned with cold water, and the sample was dried in an oven for 15 h at a temperature of 60 °C and weighed. The dried CSH sample was again mixed with 30 ml of water, 2 ml of acetic acid (i.e., 10%), and 0.6 g of sodium chlorite, and heated at 75 °C for 1 h to calculate the lignin content. Similar steps were followed one more time and heated for 2 h. Distilled water, acetic acid, and ether were used to wash the CSH samples 5 times, 2 times, and 1 time, respectively. After that, the same CSH sample was dried at a temperature of 105 °C for 1.5 h and weighed the sample. Hemicellulose content was calculated by appending 24% KOH, i.e., 20 ml, and left in air at a temperature of 20 °C. Then, the sample was soaked 5 times with water and one time into 5% acetic acid. Again, the same sample was bathed one more time with water, acetone, and ether. After bathing, the CSH sample was maintained at a temperature of 105 °C for 1.5 h and weighed the same. The left-over weight of the CSH sample was considered as the weight of the cellulose content.

**Results and Discussion**

**Effect of Pre-treatment on pH**

Before anaerobic digestion, the initial pH values from all the mixture inside the reactors ranged from 7.21 to 7.44 which is mainly responsible for microbial growth and gives a positive impact on biogas production [44]. Since micro-organisms are more sensitive to pH, methanogenic bacteria perform maximum reproduction over the pH range of 6.6 to 7.8 for biogas generation. After anaerobic digestion, the final pH values were from 7.08 to 7.48 for all the digesters at the end of 45 days. The pH values at the end of the anaerobic digestion process were stable when it lies within 7.5 [45]. pH values for the pre-treated acid and alkaline at various concentrations before and after the anaerobic digestion process are shown in Figs. 1 and 2.

**Effect of Chemical Pre-treatment on Mono-digestion**

Table 3 describes the cumulative biogas production of untreated CD and CSH at the ratio of 100:0, 0:100, 75:25 along with the treated CSH, 0:100, and 75:25.

**Effect of H$_2$SO$_4$-Treated CSH on Biogas Generation with Mono-digestion**

Maximum biogas yield of 120 ± 9 ml/g VS was observed at 3% pre-treated H$_2$SO$_4$ with CSH. There was no significant difference in biogas yield between 1 and 2% H$_2$SO$_4$-treated CSH as the final yield was 106 ± 11 and 106 ± 9 ml/g VS. Biogas yield was 3- to 4-fold higher than untreated CSH. The difference in biogas yield between treated CSH and untreated CSH was observed as 73 ml/g VS, 73 ml/g VS, and 87 ml/g VS at the concentration of 1%, 2%, and 3% H$_2$SO$_4$. Results produced are consistent in the previous study as the cumulative methane yield lies nearer range 176 ml/g VS for the 2% H$_2$SO$_4$-treated corn straw [23]. The maximum biogas difference was observed as 34 ml/g VS between 3% pre-treated H$_2$SO$_4$ and co-digestion of CD with untreated CSH at 75:25 (CD: CSH). A higher concentration of...
pre-treated CSH with H$_2$SO$_4$ leads to maximum bioconversion which could improve biogas production.

**Effect of HCl-Treated CSH on Biogas Generation with Mono-digestion**

Different concentration of HCl pre-treated CSH offers different biogas yields as compared to untreated CSH. A higher biogas yield of 116 ± 9 ml/g VS was observed at 1% HCl pre-treated CSH. 73 ±13 ml/g VS and 87 ±11 ml/g VS of biogas yield were observed for 2% and 3% HCl-treated CSH. Results produced are persistent in the previous study as the cumulative methane yield lies nearer range 163 ml/g VS for the 2% HCl-treated corn straw [23]. The difference in biogas yield between treated at the concentration of 1%, 2%, and 3% and raw CSH was 83, 40, and 54 ml/g VS. 30 ml/g VS was observed as the difference in biogas yield at the 1% HCl-treated CSH and untreated CSH at the ratio of 75:25 (CD:CSH). Cumulative biogas production from the treated HCl on CSH was 2- to 4-fold greater than untreated CSH. A lower concentration of HCl on pre-treated CSH also improves biodegradability.

**Effect of H$_2$O$_2$-Treated CSH on Biogas Generation with Mono-digestion**

H$_2$O$_2$ pre-treated CSH substrate offered cumulative biogas production of 91± 12 ml/g VS, 183 ±11 ml/g VS, and 171 ± 10 ml/g VS respectively for 1%, 2%, and 3% under hydraulic retention time (HRT) of 45 days. The cumulative methane yield reported in the previous study for the 3% H$_2$O$_2$ pre-treated corn straw was observed as 217 ml/g VS [23]. It was observed that the difference of biogas yield between H$_2$O$_2$ treated at the concentration of 1%, 2%, and 3% and raw CSH was 58, 150, and 138 ml/g VS. The maximum difference in biogas yield of 97 ml/g VS was observed between the 2% H$_2$O$_2$-treated CSH and CD with untreated CSH at the ratio of 75:25 (CD:CSH). More than 3 to 6 times higher biogas yield was observed over untreated CSH. Increasing the loading of pre-treated H$_2$O$_2$ with CSH upsurge the bioconversion during anaerobic digestion.

**Effect of CH$_3$COOH-Treated CSH on Biogas Generation with Mono-digestion**

A total of 295 ± 9 ml/g VS of biogas yield was observed at 3% CH$_3$COOH, whereas 202 ± 9 ml/g VS and 158 ± 9
ml/g VS were observed at 1% and 2%, respectively. Previous results obtained cumulative methane yield as 145 ml/g VS for the 4% CH₃COOH-treated corn straw [23]. Biogas yield obtained at the difference between treated 1%, 2%, and 3% CH₃COOH and raw CSH was 169, 125, and 262 ml/g VS. Remarkable difference in biogas yield around 209 ml/g VS was observed between 3% CH₃COOH and untreated CSH at the ratio of 75:25 (CD:CSH). The maximum difference of 102 ml/g VS in yield was also observed between 3% CH₃COOH and CD alone. More than 5- to 9-fold higher biogas yield was observed with untreated CSH. The higher concentration of CH₃COOH was directly related to the bioconversion of CSH.

**Effect of NaOH-Treated CSH on Biogas Generation with Mono-digestion**

Cumulative biogas yield of 212 ± 11, 430 ± 11, and 155 ± 13 ml/g VS was observed respectively at 4%, 6%, and 8% pre-treated NaOH with CSH. It was obvious from data that 5- to 13-fold greater biogas yield obtained raw CSH during the anaerobic digestion process. Eight percent NaOH-treated corn straw produced a cumulative methane yield of 164 ml/g VS [23]. The difference in biogas yield between the NaOH-treated CSH at the concentration of 4%, 6%, and 8% and untreated CSH was observed as 179, 397, and 122 ml/g VS. The maximum difference in biogas yield was observed as 344, 237 ml/g VS with the 6% treated NaOH between untreated CSH at the ratio of 75:25 (CD:CSH) and CD. Medium concentration (6%) of NaOH offered maximum biogas generation as compared to too low and too high concentrations.

**Effect of Ca(OH)₂-Treated CSH on Biogas Generation with Mono-digestion**

Maximum biogas of 279 ± 14 ml/g VS was produced for the 6% Ca(OH)₂ pre-treated CSH, whereas 100 ± 9 ml/g VS and 150 ± 8 ml/g VS were observed for 4% and 8% Ca(OH)₂ pre-treated CSH, respectively. This was 3- to 8-fold greater biogas yield compared to the mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23]. Four percent, 6%, and 8% Ca(OH)₂-treated CSH produces a difference in biogas yield compared to mono-digestion of raw CSH. Eight percent Ca(OH)₂ pre-treated corn straw produced a cumulative methane yield of 207 ml/g VS [23].
Acidic vs Alkaline Treatment Effect on Mono-digestion

With mono-digestion of pre-treated CSH, the obtained biogas yield was found to follow the order, 6% NaOH > 3% CH₃COOH > 2% H₂SO₄ > 3% H₂O₂ > 1% HCl, where the obtained cumulative biogas yields respectively were 430 ± 11 ml/g VS, 295 ± 9 ml/g VS, 279 ± 14 ml/g VS, 183 ± 11 ml/g VS, 120 ± 9 ml/g VS, and 116 ± 9 ml/g VS. This finding implies that in acid pre-treatment of CSH, 3% CH₃COOH appears to be the most effective at increasing biogas yield as concentration increases, whereas in alkaline pre-treatment of CSH, 6% NaOH appears to be the most effective. A previous study also reports that the maximum concentration of alkaline added to lignocellulose material does not produce any effect on chemical links between lignin and hemicellulose, which only reduces the lignin solubilization [46]. The difference in maximum biogas yield between acid- and alkaline-treated CSH during mono-digestion of CSH, 3% CH₃COOH appears to be the most effective at increasing biogas yield as concentration increases, whereas in alkaline pre-treatment of CSH, 6% NaOH appears to be the most effective. A previous study also reports that the maximum concentration of alkaline added to lignocellulose material does not produce any effect on chemical links between lignin and hemicellulose, which only reduces the lignin solubilization [46]. The difference in maximum biogas yield between acid- and alkaline-treated CSH during mono-digestion of CSH, 3% CH₃COOH appears to be the most effective at increasing biogas yield as concentration increases, whereas in alkaline pre-treatment of CSH, 6% NaOH appears to be the most effective. A previous study also reports that the maximum concentration of alkaline added to lignocellulose material does not produce any effect on chemical links between lignin and hemicellulose, which only reduces the lignin solubilization [46]. The difference in maximum biogas yield between acid- and alkaline-treated CSH during mono-digestion of CSH, 3% CH₃COOH appears to be the most effective at increasing biogas yield as concentration increases, whereas in alkaline pre-treatment of CSH, 6% NaOH appears to be the most effective. A previous study also reports that the maximum concentration of alkaline added to lignocellulose material does not produce any effect on chemical links between lignin and hemicellulose, which only reduces the lignin solubilization [46].
mono-digestion is around 135 ml/g VS. Pre-treatment on lignocellulose biomass was reported to improve biogas production by accelerating the growth of the micro-organisms at a rapid reaction rate through an anaerobic digestion process [47]. Effective alkaline treatment had a high potential to increase the biogas yield since it degrades the biomass completely by reducing the lignin content during anaerobic digestion [48, 49].

Effect of Chemical Pre-treatment on Co-digestion

**Effect of H\textsubscript{2}SO\textsubscript{4}-Treated CSH on Biogas Generation with Co-digestion of CD**

Seventy-five percent of cow dung was co-digested with 25% pre-treated H\textsubscript{2}SO\textsubscript{4} through anaerobic digestion process yield cumulative biogas of 197 ± 8, 106 ± 9, and 126 ± 9 ml/g VS for the concentration of 1%, 2%, and 3% H\textsubscript{2}SO\textsubscript{4}, respectively. This was 3- to 6-fold greater biogas yield over raw CSH, whereas 1- to 2-fold greater yield was obtained over co-digestion of CD with raw CSH at the same ratio. One hundred sixty-four, 73, and 93 ml/g VS were observed as the difference in biogas yield between 1%, 2%, 3% H\textsubscript{2}SO\textsubscript{4}-treated and untreated CSH. The maximum biogas difference of 111, 4 ml/g VS was observed with the 1% H\textsubscript{2}SO\textsubscript{4}-treated CSH between untreated CSH at the ratio of 75:25 (CD:CSH) and CD. A lower concentration of pre-treated H\textsubscript{2}SO\textsubscript{4} itself enhances the maximal biodegradability of CSH.

Effect of HCl-treated CSH on Biogas Generation with Co-digestion of CD

200 ± 9, 170 ± 8, and 173 ± 9 ml/g VS of biogas were generated during the co-digestion (75:25) of CD with HCl pre-treated for the concentration of 1%, 2%, and 3%, respectively. This was a 5- to 6-fold increment achieved over mono-digestion of untreated CSH and also 2-fold greater than co-digestion of CD with untreated CSH at the same ratio. One hundred sixty-seven, 137, and 140 ml/g VS were obtained as the biogas yield difference between 1%, 2%, 3% HCl-treated and raw CSH. One percent HCl-treated CSH resulted in maximum biogas difference as 114, 7 ml/g VS between untreated CSH at the ratio of 75:25 (CD:CSH) and CD. Results revealed that a lower concentration of HCl produced maximum biogas generation.
Effect of H$_2$O$_2$-Treated CSH on Biogas Generation with Co-digestion of CD

The co-digestion (75:25) of CD with pre-treated H$_2$O$_2$ on CSH yielded cumulative biogas of 139 ± 8, 195 ± 9, and 145 ± 7 ml/g VS for 1%, 2%, and 3% concentrations, respectively, which was 4- to 6-fold higher than mono-digestion of untreated CSH. Similarly, this yield was 2-fold greater than the one obtained with co-digestion of CD with untreated CSH at the same ratio. The biogas yield difference was observed as 106, 162, 112 ml/g VS between the 1%, 2%, 3% H$_2$O$_2$-treated and untreated CSH. A remarkable biogas yield difference was noticed as 109, 2 ml/g VS between untreated CSH at the ratio of 75:25 (CD:CSH) and CD at the 2% H$_2$O$_2$-treated CSH. The medium concentration of treated H$_2$O$_2$ on CSH leads to maximum biogas generation.

Effect of CH$_3$COOH-Treated CSH on Biogas Generation with Co-digestion of CD

277 ± 14, 171 ± 9, and 345 ± 9 ml/g VS of biogas were produced during the co-digestion (75:25) of CD with CH$_3$COOH pre-treated CSH for the concentration of 1%, 2%, and 3% which was 5- to 10-fold greater than the yield obtained with mono-digestion of untreated CSH, and 2- to 4-fold greater than the yield obtained with co-digestion of CD with untreated CSH for the same ratio. The biogas yield difference was observed between 1%, 2%, 3% CH$_3$COOH-treated and untreated CSH was observed as 244, 138, and 312 ml/g VS. At 3% CH$_3$COOH-treated CSH, the maximum biogas yield difference was observed as 259, 152 ml/g VS between the untreated CSH at the ratio of 75:25 (CD:CSH) and CD. A higher concentration of CH$_3$COOH-treated CSH leads to maximum biogas generation.

Effect of NaOH-Treated CSH on Biogas Generation with Co-digestion of CD

During the anaerobic co-digestion (75:25) of CD with pre-treated NaOH on CSH yielded cumulative biogas of 166 ± 8, 395 ± 16, and 104 ± 9 ml/g VS for the concentrations of 4%, 6%, and 8%, respectively, which was 3- to 12-fold higher than mono-digestion of untreated CSH, and 1- to 5-fold greater than the yield achieved during the co-digestion of CD with untreated CSH at the same ratio. The biogas yield difference was observed as 133, 362, 71 ml/g VS between the 4%, 6%, 8% NaOH-treated and untreated CSH. A remarkable biogas yield difference was noticed as 309, 202 ml/g VS between untreated CSH at the ratio of 75:25 (CD:CSH) and CD at the 6% NaOH-treated CSH. The medium concentration of treated CSH with NaOH yielded maximum biogas generation.

Effect of Ca(OH)$_2$-Treated CSH on Biogas Generation with Co-digestion of CD

151 ± 11, 489 ± 12, and 431 ± 12 ml/g VS of biogas were generated during anaerobic co-digestion (75:25) of CD with treated Ca(OH)$_2$ for the concentrations of 4%, 6%, and 8%, respectively. It was observed that 5- to 15-fold greater yield was achieved over the mono-digestion of untreated CSH, and a 2- to 6-fold higher yield was achieved over the co-digestion of CD with untreated CSH at the same ratio. The biogas yield difference between 4%, 6%, 8% Ca(OH)$_2$-treated and untreated CSH was observed as 118, 456, and 398 ml/g VS. At 3% Ca(OH)$_2$-treated CSH, the maximum biogas yield difference was observed as 403, 296 ml/g VS between the untreated CSH at the ratio of 75:25 (CD: CSH) and CD. The medium concentration of treated CSH with Ca(OH)$_2$ yielded maximum biogas generation.

Acidic vs Alkaline Treatment Effect on co-digestion

The co-digestion of CD with pre-treated CSH at the ratio of 75:25 resulted in the cumulative biogas production of 489 ± 12 ml/g VS, 395 ± 16 ml/g VS, 345 ± 9 ml/g VS, 200 ± 9 ml/g VS, 197 ± 8 ml/g VS, 195 ± 9 ml/g VS (ranked in the order of 6% Ca(OH)$_2$ > 6% NaOH > 3% CH$_3$COOH > 1% HCl > 1% H$_2$SO$_4$ > 2% H$_2$O$_2$). This means that in acid pre-treatment of CSH, 3% CH$_3$COOH appears to be the most effective at increasing biogas yield, whereas in alkaline pre-treatment of CSH, 6% Ca(OH)$_2$ appears to be the most effective. The maximum difference in biogas yield of 144 ml/g VS is observed during co-digestion of CD with acid- and alkaline-treated CSH (75:25). The cumulative biogas production on both untreated CD and CSH at different ratios were observed to be 193 ± 6 ml/g VS (100:0), 33 ± 2 ml/g VS (0:100), and 86 ± 7 ml/g VS (75:25) after 45 days [40].

The cumulative biogas yield from the treated CSH with the chemical concentration of 1% CH$_3$COOH, 3% CH$_3$COOH, 4% NaOH, 6 % NaOH, 6 % Ca(OH)$_2$ produces the maximum results as compared with the CD alone. All other untreated CD with chemically pre-treated CSH produces extraordinary cumulative biogas production when compared to the untreated CD with CSH for the ratio of 75:25. Untreated CSH offered only very low cumulative biogas production as compared with both chemically treated CSH and untreated CD. In the 100% pre-treated CSH, the maximum biogas generation was seen through the mono-digestion process, especially in 6% pre-treated NaOH, whereas in the co-digestion of...
CD with pre-treated CSH, it was observed for the 6% of Ca(OH)$_2$.

Remarkably, biogas production was enhanced through co-digestion of CD with pre-treated CSH when compared with mono-digestion of CD and CSH. Previous studies were also reported that maximum biogas production achieved through the co-digestion process which indicates the greater solubility and the biodegradability of hemicellulose, cellulose, and lignin. This in turn shows the importance of anaerobic bacteria [37].

**Comparison of Acid and Alkaline pre-treated CSH on Biogas Production**

The biodegradability of lignocellulosic material mainly depends on the degradation of cellulose, hemicellulose, and lignin. Lignin plays a major role in biodegradation in anaerobic conditions [50]. For higher biodegradability, lignin content present in the lignocellulosic material must be lower. If lignin content is more in the lignocellulosic material, the solubilization rate will be low, and special chemical treatment will create a positive effect on biodegradability [17, 25, 44]. Alkali treatments are best in maximum solubilization of hemicellulose and lignin since they broke the chemical bonded linkages on ester bonds between them presented on the cell wall [11, 51]. Maximum methane yield was observed when there was greater enzymatic degradation, and contents of cellulose and hemicellulose with less lignin in the biomass [17, 47, 52]. Saturated lignocellulose presented in biomass samples sinks the biogas production, whereas alkaline pre-treatment upsurge the biogas production through the increase of microbial fermentative organism available in the soluble organic substance [37, 47, 52, 53].

In the acid pre-treatment of CSH, the maximum biogas production was observed in the 3% CH$_3$COOH as shown in the Figure 3, whereas, in the alkaline pre-treatment of CSH, maximum biogas production was observed in the 6% NaOH from the mono-digestion of CSH as shown in the Fig. 4. For the co-digestion of 75% CD with 25% of pre-treated CSH, the maximum biogas was produced in the 3% CH$_3$COOH in the acid pre-treatment and 6% Ca(OH)$_2$ in the alkaline pre-treatment as depicted in the Figures 3 and 4. During mono-digestion of treated CSH, 13-fold improvement was observed at 6% NaOH over untreated CSH, whereas in co-digestion of CD with treated CSH, it achieved 15-fold improvement over untreated CSH at 6% Ca(OH)$_2$ which is
The variation of biogas production on anaerobic digestion of chemically treated mono-digestion of cottonseed hull and co-digestion of cow dung with treated cottonseed hull was studied under batch digester conducted for 45 days. Remarkable biogas production was achieved in the co-digestion of cow dung with treated cottonseed hull at the ratio of 75:25 when compared with the treated mono-digestion of cottonseed hull. Among all digesters, it was observed that 153.4% of biogas production in the co-digestion of 75% cow dung and 25% cottonseed hull treated with 6% calcium hydroxide as compared to 100% cow dung. It is suggested that pre-treated 25% cottonseed hull at 6% calcium hydroxide will replace 25% of cow dung consumption in the existing biogas plant with increased biogas production. Among various acid pre-treatments, 3% acetic acid was best for biodegradability of cottonseed hull and enhancement of biogas yield and in alkaline pre-treatments, 6% calcium hydroxide was best. Chemical pre-treatment on cottonseed hull enhances biogas production with reduced duration of digestion time compared with untreated cottonseed hull.

Conclusions

The variation of biogas production on anaerobic digestion of chemically treated mono-digestion of cottonseed hull and co-digestion of cow dung with treated cottonseed hull was studied under batch digester conducted for 45 days. Remarkable biogas production was achieved in the co-digestion of cow dung with treated cottonseed hull at the ratio of 75:25 when compared with the treated mono-digestion of cottonseed hull. Among all digesters, it was observed that 153.4% of biogas production in the co-digestion of 75% cow dung and 25% cottonseed hull treated with 6% calcium hydroxide as compared to 100% cow dung. It is suggested that pre-treated 25% cottonseed hull at 6% calcium hydroxide will replace 25% of cow dung consumption in the existing biogas plant with increased biogas production. Among various acid pre-treatments, 3% acetic acid was best for biodegradability of cottonseed hull and enhancement of biogas yield and in alkaline pre-treatments, 6% calcium hydroxide was best. Chemical pre-treatment on cottonseed hull enhances biogas production with reduced duration of digestion time compared with untreated cottonseed hull.

Declarations

Conflict of Interest The authors declare no competing interests.

References

1. McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresour Technol 83:37–46. https://doi.org/10.1016/S0960-8524(01)00118-3
2. Obileke K, Nwokolo N, Makaka G et al (2021) Anaerobic digestion: technology for biogas production as a source of renewable energy—A review. Energy Environ 32:191–225. https://doi.org/10.1177/0958530X20923117
3. Johnson J, MacDonald S, Meyer L, Soley G (2021) The world and united states cotton outlook. http://www.usda.gov/sites/default/files/documents/cotton-outlook.pdf. Accessed 18-19 Feb 2021
4. Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning. Glob Biogeochem Cycles 15:955–966. https://doi.org/10.1029/2000GB001302
5. Nguyen VH, Topno S, Balasingh C et al (2016) Generating a positive energy balance from using rice straw for anaerobic digestion. Energy Rep 2:117–122. https://doi.org/10.1016/j.egyrep.2016.05.005
6. Devi S, Gupta C, Jat SL, Parmar MS (2017) Crop residue recycling for economic and environmental sustainability: the case of India. Open Agric 2:486–494. https://doi.org/10.1515/opag-2017-0053
7. Paritosh K, Yadav M, Chawade A et al (2020) Additives as a support structure for specific biochemical activity boosts in anaerobic digestion: a review. Front Energy Res 8:88. https://doi.org/10.3389/fengr.2020.00088
8. Chandra R, Takeuchi H, Hasegawa T (2012) Methane production from lignocellulosic agricultural crop wastes: a review in context to second generation of biofuel production. Renew Sust Energ Rev 16:1462–1476. https://doi.org/10.1016/j.rser.2011.11.035
9. Glivin G, Kalaiselvan N, Mariappan V et al (2021) Conversion of biowaste to biogas: a review of current status on techno-economic challenges, policies, technologies and mitigation to environmental impacts. Fuel 302:121153. https://doi.org/10.1016/j.fuel.2021.121153
10. Paritosh K, Yadav M, Mathur S et al (2018) Organic fraction of municipal solid waste: overview of treatment methodologies to enhance anaerobic biodegradability. Front Energy Res 6:75. https://doi.org/10.3389/fengr.2018.00075
11. Sun S, Sun S, Cao X, Sun R (2016) The role of pretreatment in improving the enzymatic hydrolysis of lignocellulosic materials. Bioresour Technol 199:49–58. https://doi.org/10.1016/j.biortech.2015.08.061
12. Paritosh K, Vivekanand V (2019) Biochar enabled syntrophic action: solid state anaerobic digestion of agricultural stubble for enhanced methane production. Bioresour Technol 289:121712. https://doi.org/10.1016/j.biortech.2019.121712
13. Paritosh K, Balan V, Vijay VK, Vivekanand V (2020) Simultaneous alkaline treatment of pearl millet straw for enhanced solid state anaerobic digestion: experimental investigation and energy analysis. J Clean Prod 252:119798. https://doi.org/10.1016/j.jclepro.2019.119798
14. Zheng M, Li X, Li L et al (2009) Enhancing anaerobic biogasification of corn stover through wet state NaOH pretreatment. Bioresour Technol 100:5140–5145. https://doi.org/10.1016/j.biortech.2009.05.045

15. Zhu J, Wan C, Li Y (2010) Enhanced solid-state anaerobic digestion of corn stover by alkaline pretreatment. Bioresour Technol 101:7523–7528. https://doi.org/10.1016/j.biortech.2010.04.060

16. Chen G-Y, Cao H-N, Fan X-Q et al (2021) Investigating the effect of compaction on the anaerobic digestion process of rice straw. Bioenergy Res. https://doi.org/10.1016/j.biorenew.2021.100715

17. Liew LN, Shi J, Li Y (2012) Methane production from solid-state anaerobic digestion of lignocellulosic biomass. Biomass Bioenergy 46:125–132. https://doi.org/10.1016/j.biombioe.2012.09.014

18. Kesharwani N, Bajpai S (2021) Pilot scale anaerobic co-digestion at tropical ambient temperature of India: digester performance and techno-economic assessment. Bioresource Technol Rep 15:100715. https://doi.org/10.1016/j.biteb.2021.100715

19. Kesharwani N, Bajpai S (2020) Batch anaerobic co-digestion of food waste and sludge: a multi criteria decision modelling (MCDM) approach. SN Appl Sci 2:1467. https://doi.org/10.1007/s42452-020-03265-1

20. Zheng Y, Wang P, Yang X et al (2021) Process performance and microbial communities in anaerobic co-digestion of sewage sludge and food waste with a lower range of carbon/nitrogen ratio. Bioenergy Res. https://doi.org/10.1016/j.biorenew.2021.100715

21. Kumar S, Paritsosh K, Pareek N et al (2018) De-construction of major Indian cereal crop residues through chemical pretreatment for improved biogas production: an overview. Renew Sust Energ Rev 90:160–170. https://doi.org/10.1016/j.rser.2018.03.049

22. Song Z, GaieYang LX et al (2014) Comparison of seven chemical pretreatments of corn straw for improving methane yield by anaerobic digestion. PLoS One 9:e93801. https://doi.org/10.1371/journal.pone.0093801

23. Jiang D, Ge X, Zhang Q et al (2017) Comparison of sodium hydroxide and calcium hydroxide pretreatments of giant reed for enhanced enzymatic digestibility and methane production. Bioresour Technol 244:1150–1157. https://doi.org/10.1016/j.biortech.2017.08.067

24. Fernandes TV, Klaasse Bos GJ, Zeeman G et al (2009) Effects of thermo-chemical pre-treatment on anaerobic biodegradability and hydrolysis of lignocellulosic biomass. Bioresour Technol 100:2575–2579. https://doi.org/10.1016/j.biortech.2008.12.012

25. Yang F, Bai L, Li P et al (2019) Improved methane production and sulfate removal by anaerobic co-digestion corn stalk and lesvinlic acid wastewater pretreated by calcium hydroxide. Sci Total Environ 691:499–505. https://doi.org/10.1016/j.scitotenv.2019.07.172

26. Xie S, Frost JP, Lawlor PG et al (2011) Effects of thermo-chemical pre-treatment of grass silage on methane production by anaerobic digestion. Bioresour Technol 102:8748–8755. https://doi.org/10.1016/j.biortech.2011.07.078

27. Monlau F, Baraka A, Steyer JP, Carrere H (2012) Comparison of seven types of thermo-chemical pretreatments on the structural features and anaerobic digestion of sunflower stalks. Bioresour Technol 120:241–247. https://doi.org/10.1016/j.biortech.2012.06.040

28. Wei Y, Li X, Yu L et al (2015) Mesophilic anaerobic co-digestion of cattle manure and corn stover with biological and chemical pretreatment. Bioresour Technol 198:431–436. https://doi.org/10.1016/j.biortech.2015.09.035

29. Venturin B, Frumi Camargo A, Scapini T et al (2018) Effect of pretreatments on corn stalk chemical properties for biogas production purposes. Bioresour Technol 266:116–124. https://doi.org/10.1016/j.biortech.2018.06.069

30. Dahunsi SO, Osuwe CO, Olayanju TMA, Lawal AI (2019) Co-digestion of Theobroma cacao (Cocoa) pod husk and poultry manure for energy generation: effects of pretreatment methods. Bioresour Technol 283:229–241. https://doi.org/10.1016/j.biortech.2019.03.093

31. Pang YZ, Liu YP, Li XJ et al (2008) Improving biodegradability and biogas production of corn stover through sodium hydroxide solid state pretreatment. Energy Fuel 22:2761–2766. https://doi.org/10.1021/ef800001n

32. Sun C, Liu R, Cao W et al (2019) Optimization of sodium hydroxide pretreatment conditions to improve biogas production from asparagus stover. Waste Biomass Valor 10:121–129. https://doi.org/10.1007/s12649-017-0202-0

33. Song Z, Yang G, Feng Y et al (2013) Pretreatment of rice straw by hydrogen peroxide for enhanced methane yield. J Integr Agric 12:1258–1266. https://doi.org/10.1016/S2095-3119(13)60355-X

34. Shen J, Zheng Q, Zhang R et al (2019) Co-pretreatment of wheat straw by potassium hydroxide and calcium hydroxide: methane production, economics, and energy potential analysis. J Environ Manag 236:720–726. https://doi.org/10.1016/j.jenvman.2019.01.046

35. Zhang H, Ning Z, Khalid H et al (2018) Enhancement of methane production from cotton stalk using different pretreatment techniques. Sci Rep 8:3463. https://doi.org/10.1038/s41598-018-21413-x

36. Song Z, Zhang C (2015) Anaerobic co-digestion of pretreated wheat straw with cattle manure and analysis of the microbial community. Bioresour Technol 186:128–135. https://doi.org/10.1016/j.biortech.2015.03.028

37. Isci A, Demirer GN (2007) Biogas production potential from cotton wastes. Renew Energy 32:750–757. https://doi.org/10.1016/j.renene.2006.03.018

38. Dale BE, Ong RG (2012) Energy, wealth, and human development: why and how biomass pretreatment research must improve. Biotechnol Prog 28:893–898. https://doi.org/10.1002/btpp.1575

39. Venkateshkarumar R, Shammugam S, Veerappan AR (2021) Experimental investigation on the effect of anaerobic co-digestion of cotton seed hull with cow dung. Biomass Conv Bioref 11:1255–1262. https://doi.org/10.1007/s13205-019-00523-0

40. Venkateshkarumar R, Shammugam S, Veerappan AR (2020) Anaerobic co-digestion of cow dung and cotton seed hull with different blend ratio: experimental and kinetic study. Biomass Conv Biofer. https://doi.org/10.1007/s12649-020-01066-3

41. Paritsosh K, Mathur S, Pareek N, Vivekanand V (2018) Feasibility study of waste (d) potential: co-digestion of organic wastes, synergistic effect and kinetics of biogas production. Int J Environ Sci Technol 15:1009–1018. https://doi.org/10.1007/s13762-017-1453-5

42. APHA (1995) Standard methods for the examination of water and waste water. American Public Health Association, Washington

43. Jash T, Ghosh DN (1996) Studies on the solubilization kinetics of solid organic residues during anaerobic biomethanation. Energy 21:725–730. https://doi.org/10.1016/0360-5442(95)00123-9

44. De Rossi E, Lindino CA, Cremonez PA et al (2017) Biogas production with co-digestion of sugarcane straw. MEQ 28:94–106. https://doi.org/10.1108/MEQ-07-2015-0142

45. Şenol H (2020) Anaerobic digestion of hazelnut (Corylus colurna) husks after alkaline pretreatment and determination of new important points in Logistic model curves. Bioresour Technol 300:122660. https://doi.org/10.1016/j.biortech.2019.122660

46. Jaffar M, Pang Y, Yuan H et al (2016) Wheat straw pretreatment with KOH for enhancing biomethane production and fertilizer value in anaerobic digestion. Chin J Chem Eng 24:404–409. https://doi.org/10.1016/j.cjche.2015.11.005

47. Weiland P (2010) Biogas production: current state and perspectives. Appl Microbiol Biotechnol 85:849–860. https://doi.org/10.1007/s00253-009-2246-7
49. You Z, Zhang S, Kim H et al (2018) Effects of corn stover pretreated with NaOH and CaO on anaerobic co-digestion of swine manure and corn stover. Appl Sci 9:123. https://doi.org/10.3390/app9010123
50. Komilis DP, Ham RK (2003) The effect of lignin and sugars to the aerobic decomposition of solid wastes. Waste Manag 23:419–423. https://doi.org/10.1016/S0956-053X(03)00062-X
51. Xiao B, Sun XF, Sun R (2001) Chemical, structural, and thermal characterizations of alkali-soluble lignins and hemicelluloses, and cellulose from maize stems, rye straw, and rice straw. Polym Degrad Stab 74:307–319. https://doi.org/10.1016/S0141-3910(01)00163-X
52. Zhou S, Zhang Y, Dong Y (2012) Pretreatment for biogas production by anaerobic fermentation of mixed corn stover and cow dung. Energy 46:644–648. https://doi.org/10.1016/j.energy.2012.07.017
53. Nizami A-S, Korres NE, Murphy JD (2009) Review of the integrated process for the production of grass biogas. Environ Sci Technol 43:8496–8508. https://doi.org/10.1021/es901533j
54. Yu Q, Liu R, Li K, Ma R (2019) A review of crop straw pretreatment methods for biogas production by anaerobic digestion in China. Renew Sust Energ Rev 107:51–58. https://doi.org/10.1016/j.rser.2019.02.020
55. Dai B, Guo X, Yuan D, Xu J (2018) Comparison of different pretreatments of rice straw substrate to improve biogas production. Waste Biomass Valor 9:1503–1512. https://doi.org/10.1007/s12649-017-9950-9
56. Liew LN, Shi J, Li Y (2011) Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment. Bioresour Technol 102:8828–8834. https://doi.org/10.1016/j.biortech.2011.07.005
57. Reilly M, Dinsdale R, Guwy A (2015) Enhanced biomethane potential from wheat straw by low temperature alkaline calcium hydroxide pre-treatment. Bioresour Technol 189:258–265. https://doi.org/10.1016/j.biortech.2015.03.150

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