Experimental evaluation of substrate's particle size of wheat and rice straw biomass on methane production yield

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Abstract: This paper examines the effect of particle sizes in substrates on methane production yields of wheat and rice straw biomass without any other applied pretreatment. Anaerobic digestion of three different mean particle size (MPS) substrate of 1.5 mm, 0.75 mm, and 0.30 mm of wheat and rice straw biomass was carried out at 37oC mesophilic temperature. The observed result revealed that mean particle size of 0.30 mm, and 0.75 mm had increased methane production yield by 4.7%, and 38.7%, respectively, compared to 1.50 mm particle size of wheat straw. However, in case of rice straw substrates the methane production yield was found 7.9%, and 13.0% higher, respectively, for mean particle size of 0.30 mm, and 0.75 mm, compared to 1.50 mm particle size. Mean particle size of 0.75 mm had yielded highest biogas as well as methane yields in both cases of biomass, however, wheat straw resulted into considerably higher methane yield than rice straw.

Keywords: wheat and rice straw, biomass particle size, anaerobic digestion, methane yield

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1 Introduction

Among all bio-fuel production technologies from biomass, biogas production is one of the promising technique to alleviate the problems of global warming, energy security and waste management (Asam et al., 2011). Lignocellulosic agricultural and forestry based biomass has been considered as potential biomass resource for sustainable production of bio–energy (bioethanol, biohydrogen and biogas) and bio–chemicals in this 21st century of human civilization (Kaparaju et al., 2009; Naik et al., 2010; Chandra et al., 2012a; Baker and Keisler, 2011; Budzianowski, 2012; Budzianowski, 2011). The structure of lignocellulosic materials is mainly consists of cellulose, hemicelluloses and lignin, linked very strongly to each other through hydrogen bonds and van der Waals forces. The presence of lignin in biomass leads to a protective barrier to the biomass and provide resistance to any chemical and biological degradation that prevents plant cell destruction by fungi, bacteria and enzymes. For the conversion of biomass-to-fuel, the cellulose and hemicellulose must be broken down into their corresponding monomers sugars, so that micro-organisms can utilize them in the energy conversion process. The complex structure of lignocellulosic plant biomass material and role of pretreatment is presented in Figure 1. The complex structure of lignocellulosic biomass does not allow easy degradation of cellulosic and hemicellulosic contents of biomass during biological routes of energy conversion processes, therefore, prior pretreatment is an essential requirement to break the lignocellulosic structure to obtain higher hydrolyzate as well as product yield (Sambusiti et al., 2013; Gabriela et al., 2012; Kumar et al., 2009). The aim of pretreatment is to break the impermeable/resistant layer of lignin, so that the cellulose and hemicellulose present in the biomass get hydrolyzed by the micro–organisms and converted into simple sugars.

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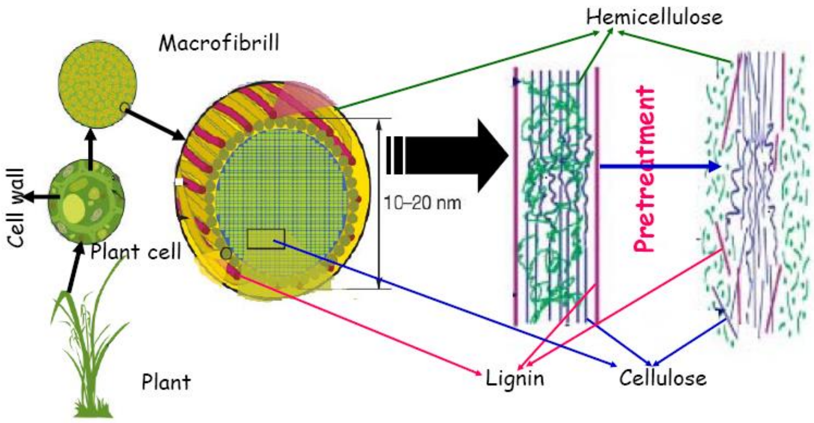

Figure 1 Complex structure of lignocellulosic plant biomass matter and role of pretreatment (adapted from Edward, 2008; Chandra et al., 2012(a))

Numerous articles on pretreatment of lignocellulosic biomass have been published in literature for production of bio–fuels/bio–chemicals. Pretreatment offer to increase in accessible surface area and porosity, decrease in crystallinity of cellulose and hemicellulose and degree of polymerization, resulting into removal of lignin from the biomass. These pretreatment methods are broadly classified under three categories; i) mechanical or physical, ii) chemical and physico–chemical, and iii) biological (Kumar et al., 2009; Sun and Cheng, 2008; Alvira et al., 2010; Bruni et al., 2010; Carrère et al., 2010; Taherzadeh and Karimi, 2009). Physical or mechanical pretreatment refer to reduction of particle size of biomass with the aim to increase specific surface area, so that involved micro–organisms can get more and more accessible area to work on biomass particles in the substrate during conversion process.

The effect of biomass particle size on production yields of biogas and methane have been investigated by the various researchers and are reported in literature for wide variety of biomass materials, some of them are, i.e., sisal fiber waste (Mshandete et al., 2006), ley crop leaves (Lindmark et al., 2012), wheat straw, rice straw (Sharma et al., 1988; Menardo et al., 2012), barley straw (Menardo et al., 2012), maize stalk and leaves (Menardo et al., 2012; Bruni et al., 2010), ensiled sorghum forage (Sambusiti et al., 2013), *Mirabilis* (herbaceous plant) leaves, cauliflower leaves, *Ipomoea fistulosa* (ornamental shrub) leaves, dhub grass, banana peelings (Sharma et al., 1988), water hyacinth (Moorhead and Nordstedt, 1993), castor oil cake (Gollakota and Meher, 1988), sunflower oil cake (De la Rubia et al., 2011), food waste (Izumi et al., 2010) and municipal solid waste (Zhang and Banks, 2013). Moreover, extensive analysis of available literature reveals inconsistent reports on effect of lignocellulosic biomass particle size to enhance the sugar yield in hydrolyzate. Some say that smaller size particles produces higher sugar yield, while some say that larger size particles produces higher sugar yield, and some say that particle size does not have effect on sugar yield in hydrolyzate (Zhang et al., 2013). Furthermore, the particle sizes are characterized as coarse, fine, and ultra–fine on the basis of mean particle size. Particles having mean particle diameter ≥800 μm are generally considered as coarse size, and particles <100 μm as fine, and particles <25 μm as ultra–fine. The levels of particle size of biomass determine the level of increase in available surface area as well as mechanical disruption to the lignocellulosic structure of individual biomass, and on other hand the amount of energy required in the grinding process (Gabriela et al., 2012).

This experimental study was conducted with the aim to evaluate and understand the effect of biomass particle size (in coarse range, mean particle size in range of 0.30–1.50 mm) in the substrate on methane production yield in anaerobic digestion process of lignocellulosic biomass (untreated wheat and rice straw).

2 Material and methods

2.1 Characterization of wheat and rice straw biomass

The characterization of wheat and rice straw biomass was carried out by using the standard methods of proximate, ultimate, and compositional analyses. Proximate analysis included determination of moisture content, total solids, volatile solids and non–volatile solids (ash) contents of the wheat and rice straw. Ultimate analysis covered determination of carbon, hydrogen, and nitrogen contents, and compositional analysis included determination of cellulose, hemicellulose, and lignin contents in wheat and rice straw. The proximate analysis of rice straw biomass was carried out using standard procedures as described by APHA, 1999. Ultimate analysis in terms of carbon, hydrogen and nitrogen contents of biomass was carried out using standard procedure of CHN analysis by using a fully automatic analyzer. The compositional contents of wheat and rice straw were analyzed by the Japan Food Research Laboratories using standard method of P. J. Van Soest [Proc. Nutr. Soc., 32, 123 (1973)]. Table 1 shows the observed properties of used wheat and rice straw.

Table 1 Proximate, ultimate, and compositional properties of used wheat and rice straw

Sl. no.	Properties parameter (on dry weight basis of biomass)	Wheat straw	Rice straw
Proximate properties			
1	Volatile solids, %	88.90	84.00
2	Non–volatile solids (ash), %	11.10	16.00
Ultimate properties			
3	Carbon, %	45.80	41.00
4	Hydrogen, %	6.00	5.40
5	Nitrogen, %	0.42	0.74
Compositional properties			
6	Cellulose, %	35.10	38.90
7	Hemicellulose, %	25.60	24.00
8	Lignin, %	7.50	5.60
9	Others (minerals, crude fats and proteins), %	31.80	31.50

2.2 Mechanical size reduction of wheat and rice straw biomass

Dried wheat and rice straw biomass samples were ground using a force mill (centrifugal grinding). The ground samples were sieved using analytical sieve shaker (make Retsch GmbH, Germany, model AS200). The sieve shaker was equipped with 5.0 mm, 2.0 mm, 1.0 mm, 0.50 mm, and 0.10 mm opening size sieves, having sieve diameter and height of 200 mm and 50 mm, respectively. Sieving of ground samples were performed for a period of 5 min. Three range of particle size 0.10–0.50 mm, 0.50–1.00 mm, and 1.00–2.00 mm, having mean particle size of 0.30 mm, 0.75 mm, and 1.50 mm, respectively, were separated for further study.

2.3 Experimental details of anaerobic digestion setup and parameters

Anaerobic digestion was performed in 1.0 L glass bottles (Schott Duran). The total effective volume capacity of individual bottle was 1130.0 ml. The reactors containing the desired substrates were placed into a programme incubator (YAMATO model IN602W) maintained at 37^oC temperature. The volume of biogas produced on any given day was measured by using a water displacement system, and corrected to the standard temperature and pressure condition (0^oC and 1 atm).

Pressure generated inside the reactors due to biogas production was measured daily using a handy digital manometer.

C/N ratio of all substrate was adjusted to 25.0 by adding appropriate amount of urea to the substrates. Total solids concentration in the substrates of wheat and rice straw were maintained as 5.00% (50.00 g/L). The concentration of volatile solids in the substrates were 4.45% (44.50 g/L) and 4.20% (42.00 g/L), respectively, for wheat straw and rice straw. Substrate–to–inoculum ratio was kept as unity in all the reactors. The inoculum used in the study was prepared from anaerobic digestion of rice straw and had 95.70% moisture with a 4.30% of total solids content on weight basis of wet biomass. The volatile and non–volatile solids contents were 71.80% and 28.20%, respectively on dry weight basis of biomass. The inoculum was pre–incubated for seven days and fully degassed at the same temperature (37^{o}C) as selected for methane fermentation of wheat straw substrates. The methane fermentation reactors were checked for any leakage and flushed with 99.0% pure nitrogen in order to ensure anaerobic condition.

2.4 Analytical measurements

Anaerobic digestion of each substrate was carried out in duplicate reactors and basic observational data were recorded for biogas, methane and carbon dioxide production volumes. The measurement of volumetric composition of methane, carbon dioxide and others (N_2, O_2 and CO) contained in biogas was determined using Porapak Q column (length 2.0 m, outer diameter 4.0 mm, inner diameter 3.0 mm, mesh range 80/100) and thermal conductivity detector equipped on a gas chromatograph (YANACO, model G1880). The injection volume of the individual gas sample to the column was 0.20 ml.

2.5 Errors in measurements

Proximate, ultimate and compositional analysis for characterization of wheat and rice straw biomass was analyzed for three replications for each parameter. Furthermore, the gas composition for methane, carbon dioxide and other gases was also analyzed for three replications. Anaerobic digestion of each substrate was carried out in duplicate reactors and basic observational data were recorded for biogas, methane and carbon dioxide production volumes. Statistical analysis using one way analysis of variance (ANOVA) for the observed data for proximate, ultimate, compositional and gas compositions showed that there is no significant variation among the recorded data at 95% confidence level (a value of 0.05). However, a highly significant variation in the recorded data among the duplicate methane fermentation reactors was observed. The variation in biogas production yield between the duplicate reactors was found in the range of 10%–15% from the average. The observed variation in biogas production yields was might be due to non–homogeneity of the substrates and bacterial population in inoculum used.

3 Results

3.1 pH of substrates

The values of pH for wheat straw substrates mixed with inoculum at the time of start-up was recorded as 7.60, 7.67, and 7.68, respectively, for WS:0.30 mm, WS:0.75 mm, and WS:1.50 mm. The pH value for rice straw substrates were as 7.40, 7.47, and 7.58, respectively, for RS:0.30 mm, RS:0.75 mm, and RS:1.50 mm. Initial pH data showed that all the substrates were well within the suitable pH range required for starting anaerobic digestion process. The digestate pH value after 60 d of incubation time were observed as 7.88, 7.98, and 7.92, respectively, for WS:1.50 mm, WS:0.75 mm, and WS:0.30 mm. The pH value of digestate for rice straw, RS:1.50 mm, RS:0.75 mm, and RS:0.30 mm were found as 7.44, 7.10, and 7.05, respectively.

3.2 Cumulative biogas and methane production yield

Figure 2 shows the observed cumulative biogas production yield of all the substrates having 10 g of total solids in each. The maximum biogas production for wheat straw was found as 1774.5 ml for WS:0.75 mm substrate, followed by WS:0.30 mm as 1372.0 ml, and

WS:1.50 mm as 1206.5 ml. Similarly, the maximum biogas production for rice straw was found as 1316.6 ml for RS:0.75 mm substrate, followed by RS:0.30 mm as 1268.1 ml, and RS:1.50 mm as 1184.5 ml. In both the cases of biomass, the highest biogas yield was recorded for particle size of 0.75 mm, with lowest yield for 1.50 mm particle size. A similar trend on methane production yield was also observed for various wheat and rice straw substrates. Figure 3 presents the cumulative methane production for various substrates with respect to the hydraulic retention time. It was observed that the biogas production completely seized after 20th day of retention time for all substrates of wheat as well as rice straw, as the reactor pressure did not increase afterwards, which was monitored up to 60 d of hydraulic retention time. This showed complete failure of anaerobic digestion process resulted due to stoppage of activities of anaerobic micro–organisms.

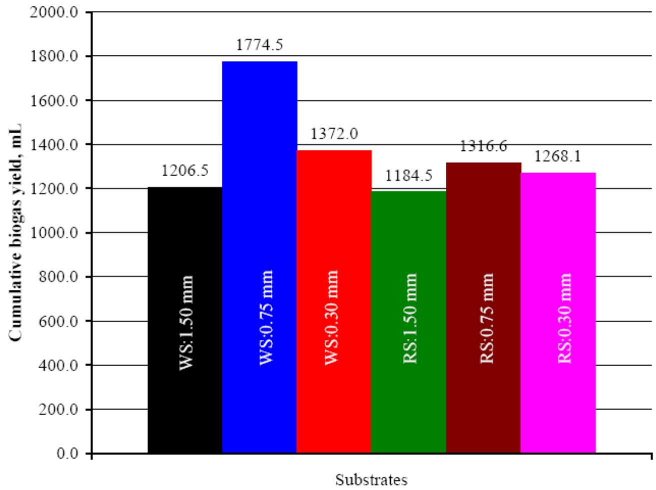

Figure 2 Cumulative yield of biogas observed from different substrates

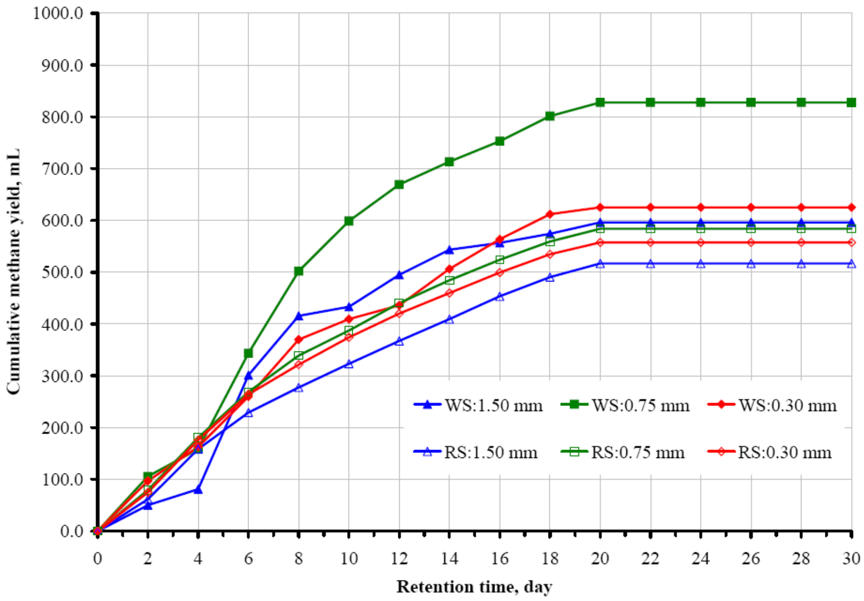

Figure 3 Variation of cumulative methane yield observed from different substrates

3.3 Specific biogas and methane productions

Specific biogas production yield of wheat straw substrates of WS:0.30 mm, WS:0.75 mm, and WS:1.50 mm were found as 154.3, 199.6, and 135.7 L/kg VS_a, respectively. However, the specific biogas production yield of rice straw substrates of RS:0.30 mm, RS:0.75 mm, and RS:1.50 mm were found as 142.6, 148.1, and 133.2 L/kg VS_a, respectively. Figure 4 shows the variation of specific methane production yield with respect to hydraulic retention time. Specific methane production yield of wheat straw substrates of WS:0.30 mm, WS:0.75 mm, and WS:1.50 mm were found as 70.3, 93.1, and 67.1 L/kg VS_a, respectively. However, the specific methane production yield of rice straw substrates of RS:0.30 mm, RS:0.75 mm, and RS:1.50 mm were found as 62.7, 65.7, and 58.1 L/kg VS_a, respectively. The amount of methane production yield from substrates of rice straw having mean particle size range 0.30–1.50

mm, was ranged from 58.1 to 65.7 L/kg VS_a, with an increase of 13.0% only, and from 67.1 to 93.1 L/kg VS_a, with an increase of 38.7% for wheat straw substrates.

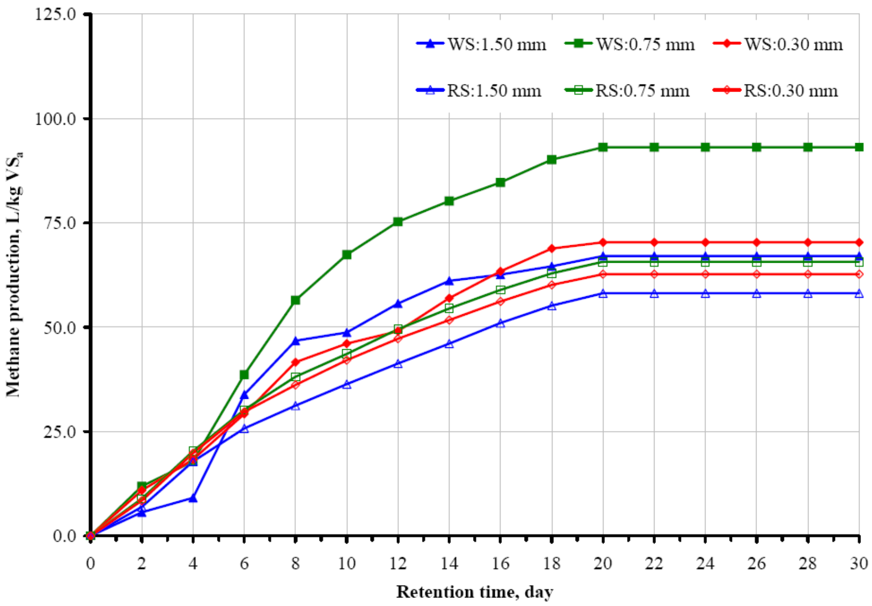

Figure 4 Variation of methane production from different substrates

3.4 Volatile solids mass removal efficiencies

The conversion efficiency of volatile solids into biogas is presented in Figure 5. The volatile solids mass removal efficiencies for wheat straw substrates were 24.9, 31.5, and 21.4%, respectively, for WS:0.30 mm, WS:0.75 mm, and WS:1.50 mm. This efficiency for rice straw substrates were found as 23.3%, 24.4%, and 22.0%, respectively, for RS:0.30 mm, RS:0.75 mm, and RS:1.50 mm. The analysis of observed data showed that about 5.7–8.0% of mass of total available volatile matter was converted into methane production, and about 15.7–23.6% into carbon dioxide production, in case of wheat straw substrates. However, in case of rice straw substrates about 5.0%–5.6% of mass of total available volatile

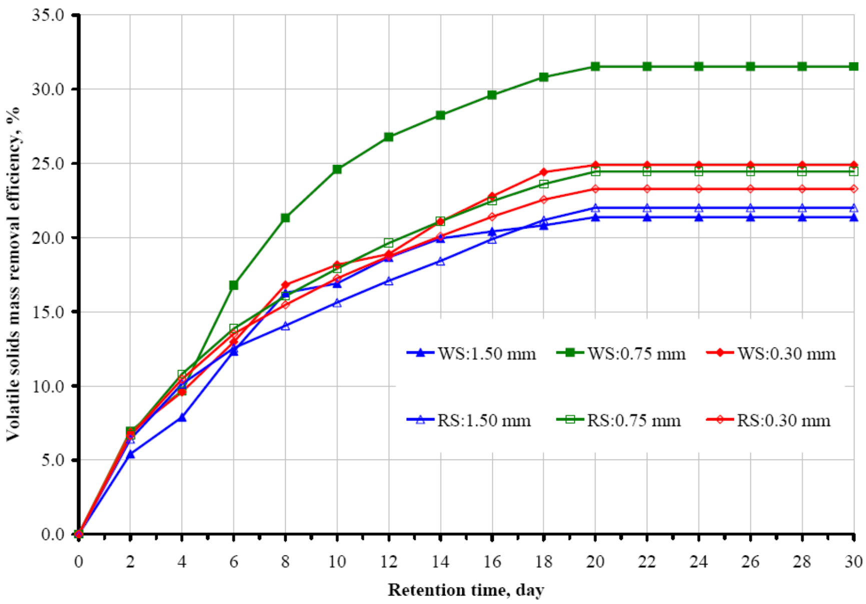

Figure 5 Variation of total volatile solids mass removal efficiencies

matter was converted into methane production, and about 17.0–18.8% into carbon dioxide production.

Moreover, the observed yields of methane production from untreated wheat and rice straw substrates are quite very low than the theoretical biochemical methane potential yield as reported in available literature. This low production yield of methane had been resulted due to early failure of biomethanation process, i.e., lower retention time (only 20 d), lower substrate/inoculum ratio (only one), and might be presence of unfavourable environment in the digesting substrate, resulted into loss in anaerobic microbial activities.

4 Discussion

4.1 Effect of particle size on methane production

Figure 6 shows an overall conclusive result on methane production yields from the different particle sized substrates of untreated wheat and rice straw biomass. It was found that untreated substrate of wheat straw having mean particle size of 0.75 mm, and 0.30 mm had increased methane production yield by 4.7%, and 38.7%, respectively, compared to untreated substrate having mean particle size of 1.50 mm. Furthermore, the untreated substrate of rice straw having mean particle size of 0.75 mm, and 0.30 mm had increased methane production yield by 7.9%, and 13.0%, respectively, compared to untreated rice straw substrate. Further again, it had been noticed that the increase in methane production yield was higher in case of substrate having mean particle size of 0.75 mm, instead of substrate having mean particle size of 0.30 mm. Although, the substrate having mean particle size of 0.30 mm had provided maximum available surface area to each biomass particles compared to larger sized biomass particles. Furthermore, considerably higher difference in increase in methane yield was observed for wheat straw substrate of 0.75 mm, compared to same size of rice straw substrate. It had been reported that a reduction of particle size below 40 mesh (0.40 mm) to the most of the biomass has very little effect on the hydrolysis yield as well as hydrolysis rate of the biomass (Hendriks and Zeeman, 2009).

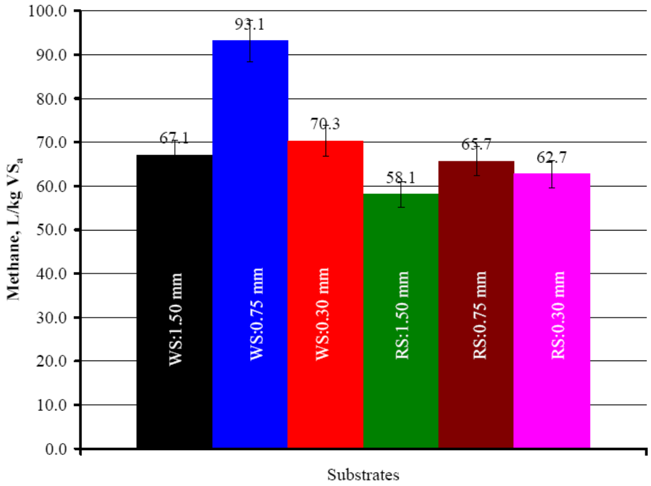

Figure 6 Comparative representation of methane production yield of different substrates

Table 2 presents methane production yields of some of the common biomass materials in respect to different sizes of biomass particles. Sharma et al. (1988) revealed that the methane yield of wheat straw had increased by 6.2%–9.7%, when the particle size was reduced from 6 mm to 0.088 mm. In an another experiment it had been found that methane yield of wheat straw had increased by 17.2%, when the particle size was reduced to 0.2 mm as compared to 5 mm size. Menardo et al. (2012) also revealed that the mechanical comminution of barley straw to 0.5 mm size found to increase methane production by 29.4% compared to 5 mm size of straw in the substrate. Further again, et al. (1988) also revealed that the methane yield of rice straw biomass had increased by 3.2%–5.8%, when the particle size was reduced to 1 mm and 0.4 mm compared to 6 mm particle size. Further reduction is particle size of rice straw to 0.088 mm compared to particle size of 0.4 mm had no effect on methane production yield. Sambusiti et al. (2013) conducted experiment on the effects of particle size on methane production, revealed that ensiled sorghum forage milled into 2, 1, 0.5 and 0.25 mm particle sizes, have not showed any significant differences in methane yields, and also confirmed that the chemical and structural composition did not be affected by particle size reduction. They also observed that after addition of NaOH only (10 gNaOH/100gTS), a solubilization of lignin, cellulose, and hemicelluloses was observed. However, even in this case (NaOH pretreatment), results were unaffected by particle size reduction of 1.0 mm and 0.25 mm. Zhang et al. (2012) compared the cellulose content of poplar wood particles milled using different sieve sizes. They revealed that the particles of larger sieve size (4 mm) had higher sugar yield than the particles of smaller sieve size (2 mm and 1 mm) for two milling methods, i.e., knife, and hammer milling.

Table 2 Reported methane production yield and its variability in relation to particle size of some of biomass materials

Biomass	Particle size, mm	Experimental details; incubation period; and operating temperature	Gas yield	Change than in value, %	Reference
Wheat straw	6.0, 1.0, 0.40, 0.088	Batch; 5 L glass bottle; 55 d; 37 ^{o}C	227.0, 241.0, 248.0, 249.0 ml/g VS_a, respectively, methane.	Reference, +6.2, +9.3, +9.7	Sharma et al., 1988.
	5.0, 0.2	Batch; 2 L glass bottle; 60 d; 40 ^{o}C	285.0, 334.0 ml/g VS_a, respectively methane.	Reference, +17.2	Menardo et al., 2012.
	<1.0	Batch; 1 L glass bottle; 25 d; 37 ^{o}C	78.4 ml/g VS_a methane.	-	Chandra et al., 2012(b).
Barley straw	5.0, 2.0, 0.5	Batch; 2 L glass bottle; 60 d; 40 ^{o}C	286.0, 339.0, 370.0 ml/g VS_a, respectively methane.	Reference, +18.5, +29.4	Menardo et al., 2012.
Rice straw	6.0, 1.0, 0.40, 0.088	Batch; 5 L glass bottle; 55 d; 37 ^{o}C	347.0, 358.0, 367.0, 365.0 ml/g VS_a, respectively methane.	Reference, +3.2, +5.8, +5.2	Sharma et al., 1988.
	5.0	Batch; 2 L glass bottle; 60 d; 40 ^{o}C	203.0 ml/g VS_a methane.	-	Menardo et al., 2012.
	<1.0	Batch; 1 L glass bottle; 25 d; 37 ^{o}C	59.8 ml/g VS_a methane.	-	Chandra et al., 2012(c).
Ensiled sorghum forage	2.0, 1.0, 0.5, 0.25	Batch; 0.5 L plasma flask; 35 d; 35 ^{o}C	298.0, 290.0, 291.0, 288.0 ml/g VS_a methane.	Reference, -2.7, -2.3, -3.4	Sambusiti et al., 2013.
Sisal fiber	100, 70, 50, 30, 10, 5, 2	Batch; 1 L glass bottle; 65 d; 33 ^{o}C	178.0, 190.0, 192.0, 202.0, 203.0, 205.0, 216.0 ml/g VS_a, respectively methane.	Reference, +6.7, +7.9, +13.5, +14.0, +15.2, +21.3	Mshandete et al., 2006.
Water hyacinth	12.7, 6.4, 1.6	Batch; 55 L digester; 60 d; 35 ^{o}C	140.0, 180.0, 160.0 ml/g VS_a, respectively methane.	Reference, +28.6, +14.3	Moorhead and Nordsted, 1993.
Sunflower oil cake	1.4–2.0, 0.710–1.0, 0.355–0.55	Batch; 08 d; 35 ^{o}C	213.0, 186.0, 186.0 ml/g VS_a, respectively methane.	Reference, -12.7, -12.7	De la Rubia et al., 2011.
Castor oil cake	1.4–2.1, 1.0–1.4, 0.5–1.0, <0.5	Batch; 5 L glass bottle; 15 d; 37 ^{o}C	275.0, 215.0, 200.0, 260.0 ml/g TS_a, respectively biogas.	Reference, -21.8, -27.3, -5.5	Gollakota and Meher, 1988.

In cases of similar study conducted on some oil seed cakes (sunflower and castor), it had been revealed that the effect of particle size reduction has negative effect on enhancement of biogas as well as methane production yields. De la Rubia et al. (2011) found that the methane production yield of sunflower oil cake did not show any difference when the particle size were in the ranges of 0.710–1.0 mm, and 0.355–0.55 mm. Furthermore, they observed that methane yield was decreased by 12.7% when the particle sizes were reduced from 1.4–2.0 mm to 0.710–1.0 mm, and 0.355–0.55 mm. Almost similar kind of result was reported for castor oil cake for particle sizes of 1.4–2.1 mm, 1.0–1.4 mm, 0.5–1.0 mm, <0.5 mm (Gollakota and Meher, 1988). Further, in a case of highly degradable biomass material (food waste); Izumi et al. (2010) reported that the methane production rate increased by 28% when the mean particle size of food waste was decreased from 0.888 mm to 0.718 mm by bead mill pretreatment. However, further reduction of the particle size of the substrate resulted in accumulation of volatile fatty acids, decreased methane production, and decreased solubilization and biodegradability the substrate in the anaerobic digestion process.

Moreover, the coarse and fine range for most of the cellulosic biomass had been reported to have very little effect on increasing methane production yield in anaerobic digestion process, as well as ethanol recovery yield in alcoholic fermentation process. Based on observations collected from extensively available literature, it had been hypothesized that milled particles of different sizes might have different compositions. Particles of a larger size might have higher cellulose content or lower lignin content or both than those of a smaller particle size (Zhang et al., 2013; Zhang et al., 2012).

Gabriela et al. (2012) reported that the effect of particle size reduction can be decoupled from the effect of internal changes in the lignocellulosic structure during the milling process. The degradability of wheat straw was found to increase by the decrease of particle size until a limit, which only overcomes when the internal structure of wheat straw particles was altered. They observed that the reduction of particle size to ultra–fine range, i.e., below ~ 25 μm using ball mill, disrupted partially the crystalline structure of cellulose, and appeared to be an effective mechanical pretreatment for wheat straw, as it had increased its degradability with similar glucose yield and superior total carbohydrate yield comparable to the steam explosion (hydrothermal) pretreatment. Khullar et al. (2013) reported that the enzymatic hydrolysis of unpretreated miscanthus biomass samples had resulted in increased total conversions efficiency as the particle size was decreased from 6 mm to 2 mm, and 0.08 mm, although mean conversions efficiency were much lower (10–20% only) than that of pretreated biomass samples having mean conversions efficiency in the range of 53%–94%, thus, revealed the need for chemical pretreatments in biomass conversion process, instead of mechanical size reductions.

4.2 Particle size reduction and grinding energy requirement

The most important disadvantage of mechanical comminution is that the process requires high energy input. The energy required in the particle size reduction process is largely depends on the final particle size required, and partially on the type of biomass used. Hardwood requires more energy than softwoods and more energy is needed to achieve smaller particle size. Even though studies showed that milling increases biofuel yields produced from lignocellulosic biomass, this method is not likely to be very economically profitable due to the high energy requirement in the grinding process (Hendriks and Zeeman, 2009; Agbor et al., 2011). It had been reported in vast available literature that the ratio of particle size of initial biomass to size of product particles, is more or less directly proportional to the energy consumption in the mechanical comminution process. Zhang et al. (2012) found that the energy consumption required in knife milling of poplar wood chips (contained moisture of 1.2%) varied from 0.58 MJ/kg for particle size of 4 mm, to 4.97 MJ/kg for particle size of 1 mm. Further, to produce finer particles for efficient conversion, sometimes the specific comminution energy consumption may be higher than the energy available in feedstock, i.e., heating value; for an example, to reduce particle size of miscanthus biomass to 80 μm size (near to ultra–fine range), the energy consumption required for the knife milling would be about 16.5 MJ/kg of dry matter, which is more than the heating value of 16.2 MJ/kg of dry matter for the feedstock (Miao et al., 2011).

5 Conclusions

The investigation revealed that the reduction of particle size (mechanical pretreatment) in the coarser range had little effect on methane production yields from anaerobic digestion of wheat and rice straw lignocellulosic biomass, compared to other pretreatments, if used. The effect of particle size revealed that the maximum methane production yield corresponded to a mean particle size of 0.75 mm for wheat as well as rice straw substrates, although, the total methane production yields for all the untreated substrates of wheat and rice straw was found quite low. The methane yield for different particle sized substrates, i.e., 0.30 mm, 0.75 mm, and 1.5 mm were found as 70.3, 93.1, and 67.1 L/kg VS_a, respectively, for wheat straw, and 62.7, 65.7, and 58.1 L/kg VS_a, respectively, for rice straw. Further, the overall analysis of the study and literature results revealed that excessive reduction of particle size of biomass (in coarse to fine range) does not have significant and favourable effect on recovery of volatile matters in the hydrolyzate, until the internal destruction of the lignocellulosic structure occurs, which can only be achieved when the particle size is to be reduced to a ultra–fine level. Moreover, the reduction of biomass particle size to ultra–fine level requires very high amount of energy input in the comminution process, and, therefore, is not an economical method to process biomass in the energy conversion processes. Conclusively, it is a better and highly economical way to go for other biomass pretreatment methods rather than excessive reduction of biomass particle size.

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Nomenclature

MPS	mean particle size
RS:0.30 mm	rice straw substrate having particle size in between 0.10–0.50 mm with a mean particle size of 0.30 mm
RS:0.75 mm	rice straw substrate having particle size in between 0.50–1.00 mm with a mean particle size of 0.75 mm
RS:1.50 mm	rice straw substrate having particle size in between 1.00–2.00 mm with a mean particle size of 1.50 mm
TS_a	total solids added
VS_a	volatile solids added
WS:0.30 mm	wheat straw substrate having particle size in between 0.10–0.50 mm with a mean particle size of 0.30 mm
WS:0.75 mm	wheat straw substrate having particle size in between 0.50–1.00 mm with a mean particle

size of 0.75 mm

WS:1.50 mm — wheat straw substrate having particle size in between 1.00–2.00 mm with a mean particle size of 1.50 mm