Co-digestion Technology to Reduce Biogas Deficit in Rural Poor Biogas Households: A Case Study in Nepal.

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ABSTRACT

Biogas technology has emerged as one of the effective alternative clean energy solutions for the scattered settlements in Nepal and has the potential to minimize the pressure on traditional biomass fuels. Almost all domestic biogas plants in Nepal are operated on cattle dung, which has a relatively low gas yield and even the quantity might not be enough to sustain biogas production throughout the year. The literature reveals that the use of agricultural residues or energy crops with dung for co-digestion can improve digester efficiency, and thus could be a viable option for improving biogas production capacity. However, the potential of using such organic wastes in co-digestion with animal dung in a domestic biogas plant has not been inadequately explored yet so this study aims to be focused on it. Both quantitative and qualitative research approaches were employed in this study. The field study for data collection was undertaken in two districts in Nepal, Chitwan and Lamjung. SPSS software and Volumetric Methane Productivity (VMP) model were used for data analysis.

Key words:
Biogas production efficiency, co-digestion, cattle dung, agriculture residue, VMP model

1. INTRODUCTION

A. Backkground of this study

Almost all domestic biogas plants in Nepal are operated on cattle dung, which has a relatively low gas yield (21), and even the quantity might not be enough to sustain biogas production throughout the year (13,18). Poor households, in particular, cannot afford the large numbers of livestock needed to supply the required manure for biogas production, resulting in an even lower gas output (9,15,18). The literature reveals that the use of agricultural residues or energy crops with dung for co-digestion can improve digester efficiency (32), and thus could be a viable option for improving biogas production capacity (23,24). However, the potential of using such organic wastes in co-digestion with animal dung in a domestic biogas plant has been inadequately explored (13). This study therefore aims to contribute to the knowledge gap in this area by exploring ways to optimize biogas production and utilization in rural poor households.

B. Biogas production process

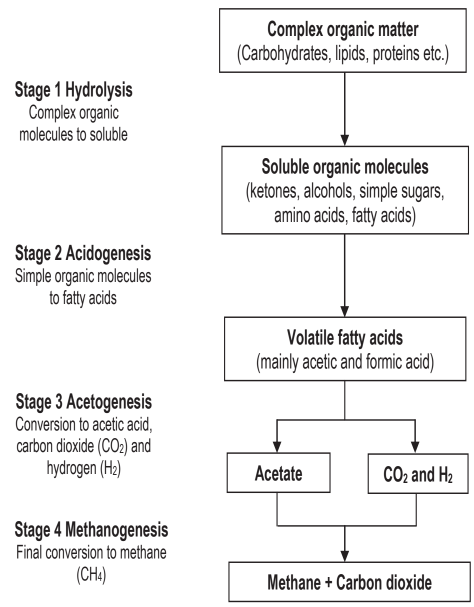

Figure 1: Scheme of single stage anaerobic digestion process
Source: 4, p. 8)

Biogas is a methane-rich gas that is produced from anaerobic fermentation of organic materials by the action of methanogenic bacteria in a digester (4, 14). Different groups of micro-organisms carry out conversion of complex organic compounds in a sequence of four stages: solubilization or hydrolysis, acidogenesis, acetogenesis and methanogenesis (4, 14) (Figure 1)

A substrate or feedstock contains moisture and solid content. Substrate's solid content, which is called total solid (TS), is measured in kg/m3. Volatile solid (VS, measured in kg/m3) is the only organic or biodegradable content of TS that is used for bio-methanation process (31). Anaerobic digestion converts the volatile solids into biogas. Volatile solids are constituted of protein, carbohydrate and lipid (organic fat), which are three major organic components considered for methane production (21).

Carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) are the major elemental compositions of any organic matter that greatly influence methane production. The largest percentage of carbon is assumed to be readily degradable, but only degradable nitrogen is used for an anaerobic digestion process (29). The amount of carbon and nitrogen present in a feedstock could be an important indicator to determine the methane yield and the ratio of co-substrates for co-digestion.

*C. **Factors affecting biogas production***

Besides types and quantity of feedstocks, a number of factors affect the rate of digestion and biogas production, including temperature, carbon-nitrogen (C/N) ratio, hydraulic retention time (HRT), organic loading rate (OLR), dilution and consistency of inputs, pH value of the input mixture, toxicity, altitude and precipitation(4; 8; 14; 22).

a) C/N Ratio

A C/N ratio is the relationship between the amount of carbon and nitrogen present in organic materials. A C/N ratio of 20-30 is considered favorable for biogas production (7, 14). Co-digestion of substrates with a desired C/N ratio increases methane production potential by stabilizing the fermentation process (7).

b) Temperature

Temperature is the most important factor in biogas production because it determines the rate of hydrolysis and methane formation. During the anaerobic digestion process methanogen bacteria are inactive in extreme high and low temperatures (6, 25, 26, 27). Anaerobic fermentation is, in principle, possible between 3°C to about 70°C, which can be differentiated in three temperature ranges: anaerobic fermentation or digestion at a temperature range below 20°C is referred to as psychrophilic digestion; at a temperature range between 20°C and 40°C is referred to as mesophilic digestion; and at a temperature range above 40°C is referred to as thermophilic digestion (12,25). Satisfactory gas production occurs in the mesophilic range, the optimum temperature being 35°C (4,26).

c) Hydraulic retention time (HRT):

Hydraulic retention time is the average duration of time a feedstock remains in the digester. It is calculated by dividing the total volume of the digester by the volume of slurry added daily (25,26). On average, a retention time of 40 to 60 days is required.

d) Feedstocks/ Substrates for biogas production

Cattle dung (Dung)

The methane production potential of dung is also determined by carbohydrate, protein and lipid contents. Carbohydrate content in dung is lower than the selected crop residues (Table 1), but is still suitable for methane production. Although dung has a much lower TS content than crop residues, it is still greater than the minimum range of 5-15% necessary for anaerobic digestion (31)

Human excreta (HE)

Despite lower TS content, it has a significant amount of carbon content making it a suitable feedstock. It has a much higher protein content than other feedstocks (20), giving high methane production potential but affected by a low C/N ratio (Table 1). It is therefore best used in co-digestion with crop residues in order to balance the C/N ratio.

Agriculture residues

Crop residues have good potential as a biogas feedstock due to their carbon characteristics (32. The VS content, which characterizes the amount of digestible organic matter that can be converted into biogas, is also higher in the crop residues than in dung or human excreta. But C/N ratios of crop residues are much higher than the optimum of 20-30 for anaerobic digestion (7), so a nitrogen supplement is needed to enhance biogas production from crop residues, which can be achieved by co-digestion with animal dung to give a lower average C/N ratio. Crop residues have higher carbohydrate content, but comparatively lower protein and lipid content than animal dung (Table 6.1). Although lower protein and lipid contents may result in lower biogas production, higher carbohydrates and lignin contents increase the biogas production potential of crop residues (19). Rice Straw (RS); Wheat Straw (WS), and Corn Stover (CS) were the major agriculture residues used for co-digestion with dung and human excreta in this study (Table 1).

D. *Feedstock characteristics*

Table 1: Typical characteristics of livestock dung and crop residues as feedstock

Feedstock	Buffalo dung	Cattle dung	Rice straw	Wheat straw	Corn stover	Human excreta
Total solid TS (%)	19	16.7	84	88.9	84.9	20
Volatile solid (VS) (% TS)	71.8	80	79.5	83.5	76.9	75
Carbon (C) (% TS)	37.8	37.6	41	42.7	46.2	38.8
Hydrogen (H) (% TS)	4.3	5.1	5.4	5.7	5.9	5.4
Oxygen (O) (%TS)	40.1	42.9	38.2	39.6	43.3	40
Nitrogen (N) (% TS)	1.6	1.8	0.7	0.5	0.8	5
C/N ratio	23.6	20.9	53.7	85.4	54	7.8
Carbohydrate (% VS)	45.6	43.5	79.0	72.3	78.0	52.0
Protein (% VS)	16.4	17.0	5.6	3.8	5.0	17.6
Lipid (% VS)	6.2	6.9	5.9	2.3	5.1	5.6
Volatile fatty acid (VFA)(% VS)	2.7	3.6	0	0	0	2.9
Lignin (% VS)	8.9	7.9	10.8	11.8	10.3	6.4

Source: (7, 20 , 21, 30, 31)

Note: These values are taken as average value of data given in literatures

E. *Biogas production yield*

The theoretical maximum biogas yield can be determined through the basic composition of the feedstocks and their energy potential (Table 2). Organic fats yield higher biogas and have higher energy potential compared with other organic compounds. The methane production potential of feedstock material is determined by carbohydrate, protein and lipid contents

Table 2.: Energy potential of organic compounds

Material	Biogas (litre/kg)	CH_4 Volume fraction (%)	CO_2 Volume fraction (%)	Energy content (Watt-hour/gram)
Protein	704	71	29	4.96
Carbohydrate	790	50	50	3.78
Organic fat	1270	68	32	8.58

Source : (31)

The elemental composition formula of a substrate was derived based on the elemental composition data, i.e., content (%) of each element (C, H, O, N) in a molecule of the compound (Table 1), using the method explained in 28, 16). In order to compare these elements to each other stoichiometrically, they were expressed in terms of moles (16; 28). Assuming that the total mass of the elements is 100 gm and the mass of each element is the percent given, the number of moles of each element was calculated by dividing the number of grams of each element by the atomic weight of the element from the periodic table. The empirical formula is then determined by a stoichiometric comparison between the elements, by dividing each of the mole values by the smallest number of moles calculated (16; 28) (Table 1).

It estimates methane production from the anaerobic breakdown of an organic material with its generalised elemental composition formula, $C_nH_aO_bN_c$ (2), assuming that all the biodegradable organic materials present in the substrate are converted to methane, CO_2 and ammonia (2).

$$C_nH_aO_bN_c + (n - a/4 - b/2 + 3c/4)\,H_2O = (n/2 + a/8 - b/4 - 3c/8)\,CH_4 + (n/2 - a/8 + b/4 + 3c/8)\,CO_2 + c\,NH_3 \quad \text{(Equation)}$$

The BMPth can then be calculated using Equation 2 (2):

$$BMP_{th} \text{ or } B_0\ (m^3\ CH_4/kg\ VS) = 22.4 * (n/2 + a/8 - b/4 - 3c/8) / (12n + a + 16b + 14c) \quad \text{…………………………….. (Equation2)}$$

F. *Volumetric methane production*

Volumetric methane production (VMP) yield was calculated to predict how much methane could be produced in a day. VMP is defined as the rate of methane production per day per unit size of biogas digester and can be predicted by using the kinetic equation (Equation 3) (10, p. 27).

$$\gamma V = \frac{B_oS_o\,[1 - K / (\mu m * HRT - 1 + K)]}{HRT} \quad \text{…………(Equation 3)}$$

where, γV = volumetric methane production rate, $m^3/day/m^3$ biogas digester

B_o = ultimate methane yield, m^3/kg VS

S_o = VS concentration, kg VS/m^3

HRT = hydraulic retention time, day

K = kinetic parameter (dimensionless)

μm = maximum specific growth rate of micro-organism/day

= 0.013 T - 0.129, where T is temperature in °C (10)

II. RESEARCH METHODOLOGY

Both quantitative and qualitative research approaches were employed in this study. The field study was undertaken in two districts in Nepal, Chitwan and Lamjung. Total 157 households were randomly selected in each district for sampled biogas households. Quantitative data was required for empirical data analysis and qualitative data was important to identify the status of biogas development and feedstock availability. Socio-economic factors are also important for biogas development and replication in the context of Nepal. A wide range of data was therefore collected from household to district and national levels including household survey, key informant interviews, observation and discussion.

A survey was undertaken in the sampled biogas households in each district. Different strategies were employed to ensure the quality of the research, including triangulation, and reflective analysis moving between the data and emergent results. The raw data was systematically coded, entered into the spreadsheet, and was assessed using descriptive analysis in SPSS version 20.0 software (11). Biogas production efficiency was analyzed using the Volumetric Methane Productivity (VMP) model (Equation3). The potential biogas yield of cattle dung and agricultural residues were calculated both for individual and co-digestion conditions.

III. RESULT AND DISCUSSION

A. *Biogas demand and consumption*

In order to identify the daily biogas deficit, information was collected on daily biogas demand and availability. The information was collected in terms of daily actual and required cooking time from each respondent household, which was later converted into equivalent energy. The respondents were asked about the number of biogas stoves in use, specific gas consumption rate of the stoves, daily required cooking (or stove operating) time, and actual stove operating time.

Table 3: Required and actual biogas stove burning time

District	Summer (hour/day)		Winter (hour/day)	
	Required burning time	Actual burning time	Required burning time	Actual burning time
Chitwan	2.83	2.48	3.06	1.84
Lamjung	2.61	2.07	2.76	1.35

Source: (30).

The average required and actual stove burning time per household in Chitwan during summer was 2.83 hours/day and 2.48 hours/day while that during winter was 3.06 hours/day and 1.84 hours/day respectively (Table 3). This research showed that 87% and 79% of the biogas demand for cooking during summer was fulfilled in Chitwan and Lamjung, respectively, whereas only 60% and 49% of the demand during winter was fulfilled in the two districts, respectively.

B. *Reasons for lower biogas production*

The respondents were asked about the reasons for low gas production. A household mentioned/chose more than one reason for lower gas production. Lower temperature was felt as a main reason for less gas production during winter in 76% and 87% of households in Chitwan and Lamjung, respectively (Table 2). Similarly, insufficient feedstock, lower than the prescribed amount, fed into the digester was considered as another major reason in 49% of households in Chitwan and 46% of households in Lamjung. Besides, 13% of households in Chitwan and 20% in Lamjung did not feed the digester daily, and this irregular feeding practice could be another reason for lower gas production.

Table 4: Reasons for lower gas production

Reasons	Chitwan	Lamjung
Insufficient feedstock	77	72
Cold in winter	119	137
No daily digester feeding	21	31
Technical problems	72	26
Older plant	37	68
Use of chemical to clean toilet	2	1
Small plant size	1	6
Don’t know the reason	21	1

Source: (30)

C. *Insufficient Feedstocks*

The data showed that the main reason behind lower biogas production is underfeed of biogas plants. There are 4, 6, 8, and 10 m3 sizes plants are used in domestic level. The daily feedstock requirement per m3 plant is 6 kg dung hence the households with bigger plants produced higher amounts of daily feedstock. The average daily feedstock produced in the households with 4 m3 size plants was 27.4 kg, whereas that in the households with 10 m3 size plants was 43.8 kg. This, when compared with the daily prescribed feedstock input requirement, shows that only biogas plants of 4m3 size had sufficient feedstock produced to meet the daily requirement. However, the average quantity of feedstock fed was lower than the daily prescribed quantity, even in the 4 m3 size plants. This clearly indicates that all sizes of biogas plants are underfed (30).

D. *Availability of co-feedstock for co-digestion*

The respondents in both districts had mixed responses when asked whether there would be any implication on previous or other potential uses of agricultural residues if they were used as feedstock. Respondents expressed that livestock feed was directly correlated with the amount of dung produced; hence changes in the feed would have direct implications on biogas production (Table 4).

More households in Lamjung produced rice straw and corn stover, while more households in Chitwan produced wheat straw and other agricultural residues.

Table 5 Characteristics of mixed feedstocks

Co-digestion	TS %	VS %	C %	H %	O %	N %	C/N
Cod-1	18.1	75.8	37.8	4.8	41.4	2.0	20.8
Cod-2	24.7	76.2	38.1	4.8	41.0	1.9	23.9
Cod-3	34.6	4.9	38.6	4.9	40.5	1.8	28.7
Cod-4	25.2	76.6	38.3	4.9	41.2	1.9	27.1
Cod-5	35.8	77.7	39.1	5.0	40.9	1.7	36.6
Cod-6	24.8	5.9	8.7	9	1.5	.9	24.0
Cod-7	34.8	76.1	39.9	5.1	41.8	1.8	28.7
Cod-8	32.4	76.3	39.0	5.0	41.2	1.8	27.1
Cod-9	31.8	76.9	38.6	4.9	40.8	1.8	30.3
Cod-10	1.9	6.7	9.2	.0	1.3	1.8	30.3

Source: (30)

Around 23%. households in Chitwan and 19% in Lamjung with surplus dung production did not see any need for changing the existing use practices of agricultural residue, but would consider using it as biogas feedstock if its use increased biogas production significantly. About 61% of households in Chitwan and 59% in Lamjung, which produced a relatively less amount of livestock feed with respect to the number of livestock raised, responded that use of agricultural residues for purposes other than animal feed would have implication on livestock productivity, including dung production. They were required to provide alternatives to agricultural residues to meet their demand for animal feed if they were to use the residues as feedstock. However, 10% of households in Chitwan and 21% in Lamjung, who had sufficient alternative livestock feed and used agricultural residues as an energy source or for making compost, would not have any implication from using it as biogas feedstock on their present or future use (30).

1) *Elemental composition analysis method*

Theoretical methane production potential feedstock using elemental composition formula

The characteristics of the substrate mixtures were obtained from the theoretical mixture of the individual substrates using Equation 2 (30)

Table 6: theoretical methane yield of individual feedstocks

Feedstock	Elemental composition formula	BMPth (m3/kg VS)
Buffalo dung	$C_{27.56}H_{37.63}O_{21.93}N$	0.386
Cattle dung	$C_{24.37}H_{39.67}O_{20.85}N$	0.381
Rice straw	$C_{68.33}H_{108}O_{47.75}N$	0.464
Wheat straw	$C_{99.63}H_{159.60}O_{69.30}N$	0.471
Corn stover	$C_{77.0}H_{118.0}O_{54.13}N$	0.459
Human excreta	$C_{9.05}H_{15.12}O_{7.0}N$	0.385

Note: The values are calculated by using the values of Table 5 in equation 2.

2) *Characteristics of co-digestion mixtures*

Co-digestion of mixture and weighted methane yield as in equation 4. Ten sets of mixtures were used for co-digestion yield analysis (Table 5). For that proportion of 90 % dung and 10 % HE for Cod-1, 80% dung, 10% RS and 10% HE for Cod-2. Similarly, 65% dung, 25% RS and 10% HE for Cod-4, and 65% dung, 25% WS and 10% HE was for Cod-5. Likewise, the proportions were 80% dung, 10% CS and 10% HE for Cod-6. For cod-7 the proportion was 65% dung, 25% CS and 10% HE. For the rest of mixing proportion of Cod- 8, 9 and 10, 70% dung and 10% HE was mixed in every case with 10% RS and 10% CS; 10% RS and 10% WS; and 10% WS and 10% CS respectively

Table 7: Average weighted VMPs at co-digestion of crop residues with dung in different proportions during summer and winter in Chitwan and Lamjung.

$$\text{Characteristics of mixture} = \frac{(S1 * W1) + (S2 * W2) + .. + (Sn * Wn)}{(W1 + W2 + ... + Wn)} \quad \text{……(Equation 4)}$$

where, and W1, W2, ... Wn are the weight or proportion of individual substrates S1, S2, ...Sn are the specific characteristics of individual substrates (e.g.TS,V, H,O,N,C,C/N ratio, and W1, W2, …Wn are the weight or proportion of individual substrates.

Note: Taken HRT = 70 days (3, 14), K = 0.6 (10).

The literatures (2, 31, 30) suggests that the theoretical biogas yield is always higher than the measured yield because the theoretical methods consider both biodegradable and non-biodegradable components of the organic matter and assume 100% anaerobic degradability of the substrate (2, 32,). But a precise prediction of methane yield depends on the accuracy of the anaerobic degradability of the substrates. Co-digestion of crop residues with dung in different proportions promotes synergistic effects and also supplements the feedstock deficit, thus increasing the volumetric methane production.

3) Research validity

In order to evaluate the accuracy of the predicted methane yields and ability of the theoretical models to accurately estimate the yields, this study compared and validated the theoretical yields with the measured yields reported in the literature (2) .

*4) **Biogas plant design***

Design of a biogas plant could affect the use of crop residues as feedstock for biogas production. As discussed earlier, use of lignocellulosic biomass as feedstock may result in separation of solids from the liquid phase developing into a floating scum layer that negatively influences the operation of the biogas plant. Many researchers argued that most household-level digesters are not designed to handle more than 15% solids. The Chinese-dome type design lacks a slurry mixing feature that prevents mass transfer of substrate to anaerobic digestion (31). The GGC-2047 model biogas plant, the design mostly installed in Nepal, is also not considered very suitable for digestion of crop residues due to the absence of a mechanism to remove digested inert materials accumulated at the bottom of the plant, which reduces the biologically active digester volume over time, resulting in a lower biogas production (15, 17).

Modifying the design to remove the materials accumulated at the bottom of the digester and provide agitation to minimise scum layer formation will lead to more biological activity in the digester, and could enhance biogas production efficiency of the plants (17).

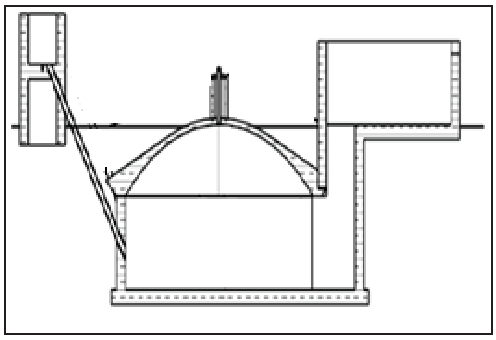

Figure 2(a) and 2(b)

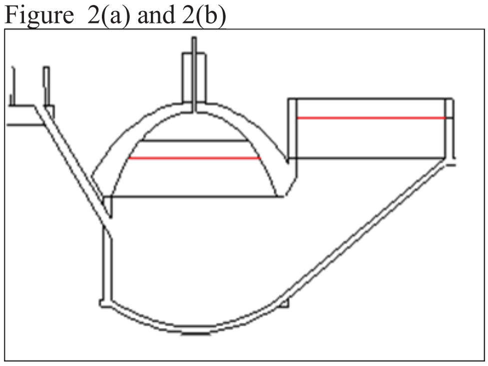

Figure 2: General design sketch of (a) existing GGC-2047 biogas plant (5) and b) proposed modified GGC-2047 biogas plant design (17)

Note: These sketches are shown here only for basic design concept, hence dimensions are not mentioned.

Co-digestion mixture	VMPth (m3/day/m3 size of digester)				VMPth (m3/day/4 m3 size of digester)				Increase in VMP (%)
	Chitwan		Lamjung		Chitwan		Lamjung		
	29° C	17 °C	23° C	11° C	29 °C	17 °C	23° C	11° C	
Cod-1	0.273	0.255	0.268	0.239	0.191	0.178	0.188	0.167	1
Cod-2	0.406	0.379	0.399	0.355	0.284	0.265	0.279	0.249	50
Cod-3	0.605	0.565	0.594	0.530	0.423	0.395	0.416	0.371	124
Cod-4	0.427	0.399	0.420	0.374	0.299	0.279	0.294	0.262	58
Cod-5	0.659	0.616	0.648	0.578	0.462	0.431	0.454	0.404	144
Cod-6	0.401	0.374	0.394	0.351	0.281	0.262	0.276	0.246	48
Cod-7	0.593	0.554	0.583	0.519	0.415	0.388	0.408	0.364	120

Hence it is recommended to revise biogas plant design that suits co-digestion technology.

IV. CONCLUSION

Co-digestion of crop-residues with dung and human excreta could increase volumetric methane production up to 150%. Co-digestion of crop residues with dung for domestic biogas production has not been practiced in Nepal yet, and users lack knowledge in regards to co-digestion. Extending awareness and training on co-digestion to potential users is important for the adoption and smooth operation of co-digested plants. Moreover, it is necessary to test the suitability of the existing GGC-2047 biogas plant for co-digestion. Modification of the plant design also needs to be investigated and promoted for wider replication of biogas technology as a reliable and cost-effective source of energy in rural households. Co-digestion compatible plants could also be suitable for low temperature areas to increase biogas yield and thus could be an effective solution for reducing biogas deficit.

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