Design of Small Scale Anaerobic Digester for Application in Indian Village: A Review

Abhinav Krishna Singh, Dr Rajendra Kumar Kaushal

Abstract— **Proper choosing of design of anaerobic digester and estimation of it size is an important point in the successful implementation of anaerobic digester. The end users of anaerobic digester in most cases are farmers whose technical knowledge of the systems is limited. And there is a lack of information available on design methods for these systems. The goals of this study were to develop literature that could be used by laymen to decide the design and size of anaerobic digester. To develop a design formula that could be used for anaerobic digester sizing based on livestock waste availability. The case studies were conducted on three scales: one household, six households, and a village of 67 and 28 households. The biogas produced in case study for one household was0.44 m^3, for six household was 2.60 m^3, for Kapurpur village of 67 household was 11.33 m^3.**

Index Terms— **biogas, anaerobic digester, bio energy, household digesters**

I. Introduction

Anaerobic digestion is a biological treatment process that recovers valuable products, energy and nutrients, from organic waste streams in useable forms. Energy is recovered in the form of biogas. Biogas consists of about 70 % methane (CH_4) and 29 % carbon dioxide (CO_2) and a small percentage of hydrogen sulfide (H2S) [1]. It also contains small proportions of other substances. Nitrogen and phosphorus, valuable nutrients that can be used as fertilizer, are recovered in the form of liquid effluent and bio solids from the digester [2].

A. Environmental and social benefits in using anaerobic digesters

Benefits of anaerobic digestion are improved indoor air quality [3], energy production in the form of biogas, which can be used as a cooking fuel, provides an alternative to unsustainable deforestation, provides treatment of human and/or animal waste [4], the amount of bio solids to be disposed is smaller than the amount resulting from aerobic treatment processes, nutrient- rich effluent may be used as a fertilizer for crops, mitigation of methane and carbon black emissions into the atmosphere.

B. Disadvantages of Anaerobic Digestion

Anaerobic digestion requires water for the operation [5]. This can be difficult in some places during the dry season. Anaerobic digestion takes more time to start the process because methanogens have slow growth kinetics. High effluent BOD_5 concentrations prevent direct discharge into water bodies. Anaerobic reaction rate is more sensitive to changes in temperature of the reactor [6]. And vulnerable to toxic compounds found in the waste stream [6].

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II. Literature Review

A. Microbiology of Anaerobic Digestion

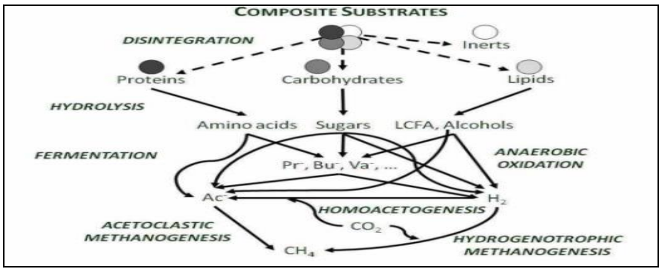

Figure 1: Major pathway in the anaerobic digestion of complex substrate, Source: R. A. Labatut and C. A. Gooch. Monitoring of anaerobic digestion process to optimize performance and prevent system failure

B. Simple Reactor Technologies

Microorganisms are used to remove organic matter, oxygen demand, and nutrient content from the influent waste streams in wastewater treatment. Two basic suspended growth reactor types that are used in India include: semi – batch reactors and plug flow reactors (PFRs).

a. Batch Reactor - Batch reactors are operated by filling the digester with slurry, letting the reactions that take place in the reactor proceed to completion, and then removing some or all of the contents of the reactor. In batch reactor, anaerobic digestion, sludge thickening, and the formation of a supernatant take place in the same batch reactor space simultaneously. As shown in Figure 2, at the bottom of a reactor, a layer of digested sludge, also known as bio solids, forms, above it a actively digesting sludge forms. And then a layer of supernatant liquid forms. At top a scum layer forms [2]. Finally, gas storage space constitutes the top portion of the digester.

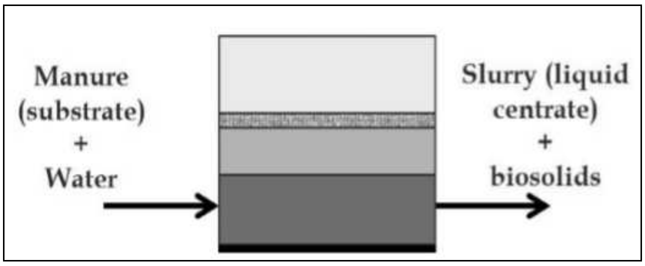

Figure2: Stratification in a Standard – Rate Anaerobic Digester, (Source: Lurel E Rowse, 2011)

b. Continuous Stirred Tank Reactor (CSTR) - Operation of CSTRs, includes continuous introduction of slurry into the reactor and continuous removal of the liquid effluent from the reactor.

c. Plug Flow Reactor (PFR) - A PFR is a tubular reactor. In PFR influent slurry entering continuously from one side and effluent slurry exiting continuously at the opposite side of reactor.

C. Operational Configurations of Reactors

Reactors may be combined and operated in different pattern in order to achieve more desirable treatment. Such as recycle (recycle flows return the effluent in some form to the entrance of the reactor), Reactors in Series, Two-Stage Anaerobic Digestion, Phased Anaerobic Digestion, Reactors in Parallel

In Semi-batch reactor substrate is added over a short period of time during the day. The period of time during which substrate is added, the digester has continuous flow in and continuous flow out, as shown in Figure 3, letter a.). The remainder of the day, the reactor operates as a batch reactor, with no flows in or out of the digester, as shown in Figure 3, letter b.) [2].

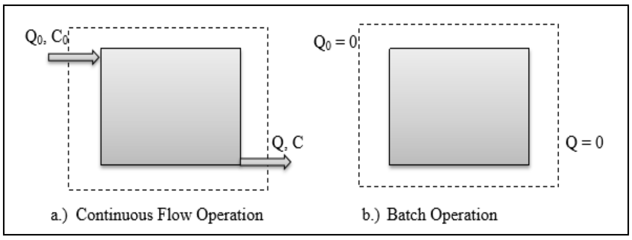

Figure 3: Semi-Batch Operation of a Reactor is a Combination Between Continuous Flow Operation and Batch Operation. (Source: Lurel E Rowse, 2011)

D. Reactor Designs Currently in Use for Small Scale Anaerobic Digestion in Indian Village

Small scale anaerobic digesters are generally operated as semi-batch processes. Three types of small scale anaerobic digesters are most often used in India. These are fixed-dome digesters, floating-drum digesters, and polyethylene tubular digesters.

a. Fixed-Dome Anaerobic Digester - The fixed dome digesters also called "Chinese" or "hydraulic" digesters. Fixed dome models developed in India include the janta and deenbandhu models. Action for Food Production (AFPRO) launched a modified janta model called the deenbandhu model. It consists of two spheres of different diameters. The lower sphere acts as a fermentation unit, while the upper one is the storage unit. Its advantages are Low construction cost, no moving parts, long life (20 years or more). And disadvantages are Plants often not gaslight, high technical skills are required for construction, gas pressure fluctuates substantially.

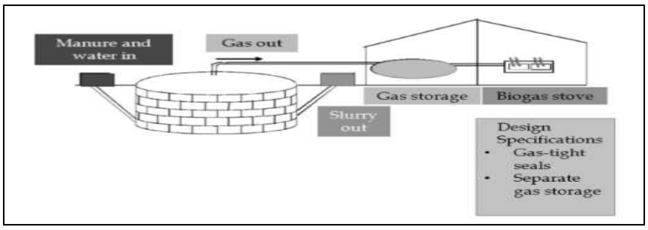

Figure 4: Fixed Dome Anaerobic Digester, (Source: Lurel E Rowse, 2011)

b. Floating-Drum Anaerobic Digester - Khadi and Village Industries Commission (KVIC) is the name of a floating drum digester model developed in 1962. Floating-drum plants consist of a digester and a moving gasholder. The gasholder floats either direct on the fermentation slurry or in a water jacket of its own. The gas collects in the gas drum. Its advantages are easily understood operation, constant gas pressure, volume of stored gas visible directly. And disadvantages are High construction cost, many steel parts liable to corrosion, short life (5 to 15 years).

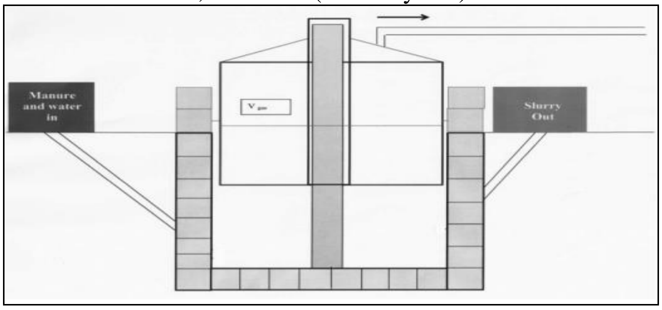

Figure 5: Floating Drum Anaerobic Digester, (Source: Lurel E Rowse, 2011)

c. Polyethylene Tubular Anaerobic Digester - Polyethylene tubular digesters are constructed of two layers of polyethylene plastic in a tubular form. A tubular digester is placed into a trench with a slope of 2-5% to facilitate gravity flow. It main advantages are Low cost, uncomplicated cleaning, emptying and maintenance. And disadvantages are Short life (about 2-5 years), easily damaged.

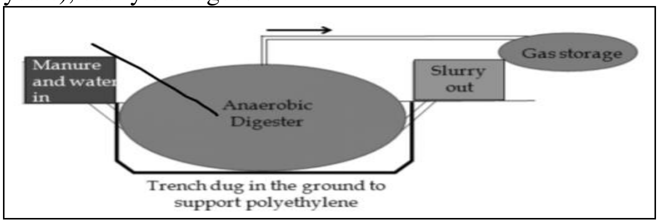

Figure 6: Polyethylene Tubular Anaerobic Digester, (Source: Lurel E Rowse, 2011)

E. Biogas

Biogas, the metabolic product of anaerobic digestion, is a mixture of 70 % methane (CH_4) and 29 % carbon dioxide (CO_2) with small quantities of other gases such as hydrogen sulphide [7].

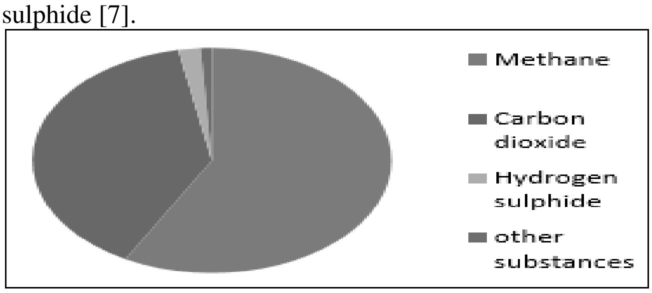

Figure7: Composition of biogas

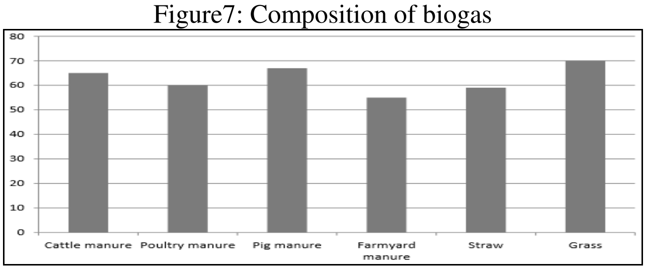

Figure 8: Methane content depends depend on feed material in percentage

F. *Factors Affecting Performance*

Some of the factors are as following. Recommended parameters are listed in Table 1.

Table 1: Suggested Operation Parameters for Rural Developing World Applications

Operation Parameters		**Source(s)**
SRT $^{min}_{lim}$ (d)	- 4	[6]
Safety Factor (SF)	- 0 - 30	[1]
SRT (d)	- 20 -70	[8]
pH	- 6.6 - 7.6	[6]
OLR (kg VS/(d*m^3))	- 1.0 - 3.5	[5]

a. Hydraulic Retention Time (HRT) **-** Hydraulic retention time, θ (days), is defined as the average amount of time one reactor volume of actively digesting sludge stays within the reactor. The numeric definition is

θ=V/Q

Where: θ = hydraulic retention time (d),V = volume of reactor (m3),Q = influent flow rate.

b. Solids Retention Time (SRT) **-** Solids retention time, or mean cell residence time, is defined as the mass of organisms in the reactor divided by the mass of organisms removed from the system each day [1]. The numeric definition of solids retention time is

θc =(active biomass in system/production rate of active biomass)

= (V* X)/(Qw* Xw)

Where θc = Solids retention time (d),V = reactor volume (m^3),X = cell concentration in reactor, Qw = flow rate out of reactor, Xw = cell concentration in the flow out of the reactor

c.* Organic *Loading Rate **-** Organic loading rate is defined as the mass of volatile solids added each day per reactor volume or the amount of BOD or COD applied to the reactor volume per day.

Table 2: Characteristics of Agricultural Substrates (McCarty, 1976)

Animal	Total Solids (kg/(d*a))	Volatile Solids (kg/(d*a))	COD (kg/(d*a))	Nitrogen (kg/(d*a))	Total Manure (kg/(d*a))=(L/(d*a))	Moisture
Cattle- Beef finishing Cattle	2.353	1.895	1.961	0.163	29.412	92
Cattle- Dairy lactating cow	8.900	7.500	8.100	0.450	68.000	87
Poultry -layer	0.022	0.016	0.018	0.002	0.088	75
Poultry – broiler	0.027	0.020	0.022	0.001	0.102	74
Swine- Gestating-Sow	1.200	1.000	1.100	0.085	12.000	90
Swine-bore	0.380	0.340	0.270	0.028	3.800	90
Human feces	*	*	*	0.077	0.26	*

d. Safety Factor **-** The minimum SRT, or the SRT at which washout occurs is multiplied by a safety factor. Because the minimum SRT is the borderline of system failure, it is important to have a large safety factor.

e. Mixing **-** Mixing increases the rate kinetics of anaerobic digestion, accelerating the biological conversion process and allows uniform heating of the reactor [6].

f. Ph **-** The pH of the digester should be maintained between 6.6 and 7.6. One difficulty is maintaining pH above 6.6 [1].

g. Alkalinity **-** Bicarbonate alkalinity of at least 500 – 900 mg/L CaCO3 is required for a pH greater than 6.5. The addition of alkaline materials such lime, sodium hydroxide, and ammonia, when proper carbonate buffering is not present in the wastewater helps to maintain the pH in the recommended range [1].

h. Temperature **-** For mesophilic anaerobic digestion, the operational temperature range is 10 to 30°C. Above 40°C, enzyme denaturation is a concern. The operational temperature range for thermophilic anaerobic digestion is 55 to 65°C [1].

III. Scaling of Biogas Plant

To calculate the scale of a biogas plant, certain characteristic parameters are used. These are daily fermentation slurry arising (Sd), retention time (RT), specific gas production per day (Gd), which depends on retention time and the feed material [7].

Dry matter (DM) - The water content of natural feed materials varies. That's why, the solids or dry matter content of the feed material is used for exact scientific work.

Organic dry matter (ODM or VS) - Only the organic or volatile constituents of the feed material are important for the digestion process.

Digester loading (R) - The digester loading indicates how much organic material per day has to be supplied to the digester or has to be digested. It is calculated in kilograms of organic dry matter per cubic metre of digester volume per day (kg ODM/m³/day) [7].

Retention time (RT or t) indicates the period spent by the feed material in the digester.

A. Amount of manure collected **-** Livestock arrangements are important in the collection of manure [2]. If livestock were free-ranging during the day and penned at night, 50% of the manure was assumed to accumulate in the penned area.

The amount of biogas produced per day was calculated by first finding the mass of volatile solids (VS) loaded into the reactor on a daily basis.

mass VS = (mass VS)cow*(no. animal)cow + (mass VS)buffalo *(no. animal)buffalo + (mass VS)chicken*(no. animal)chicken + (mass VS)pig*(no. animal)pig + (mass VS)human*(no. animal)human + (mass VS)goat*(no. animal)goat

where mass VS = total mass VS loaded per day (kg VS/(m3*d)), no. animal = number of animals

***B. Volume of water fed per day* - ** Slurry with a solids content of 5-10% is desired. Water is added in manure to reduce the solids content in slurry.

C. Scaling of the digester

The size or volume (VD) of the digester is determined by the length of the retention time (RT) and by the amount of fermentation slurry supplied daily (Sd). The amount of fermentation slurry consists of the feed material and the mixing water. Fermentation slurry = Feed material + Mixed water

The digester volume is calculated by the formula

VD(l) = Sd(L/day) x RT (days)

D. Scaling of gasholder

The gasholder volume depends on gas production and the volume of gas drawn off. Gas production depends on the amount and nature of the fermentation slurry, digester, temperature and retention time (Figures 9,10,11,12,13,14,15). The curves represent averages of laboratory and empirical values. The values vary a wide range owing to differences in the solids content of the dung, animal feeds and types of biogas plant. The 26-28 °C line is a secure basis for scaling in the majority of cases.

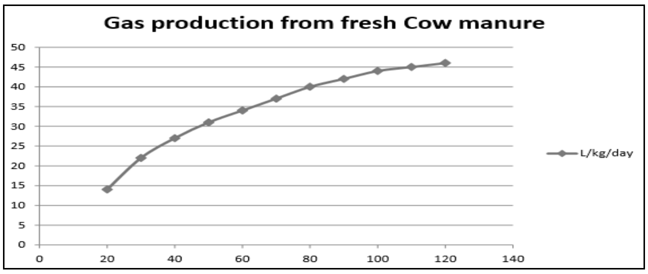

Figure 9: Gas production from fresh Cow manure depending on retention time

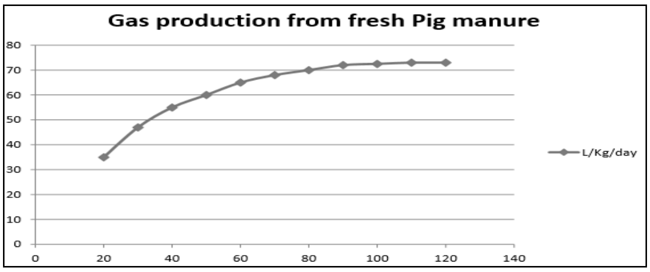

Figure 10: Gas production from fresh Pig manure depending on retention time

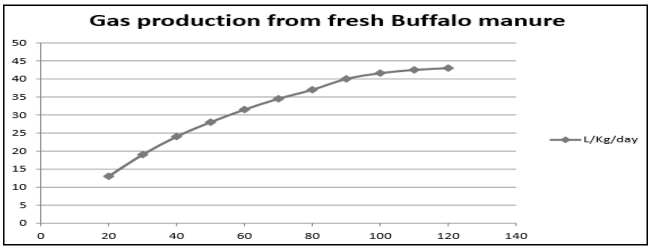

Figure 11: Gas production from fresh Buffalo manure depending on retention time

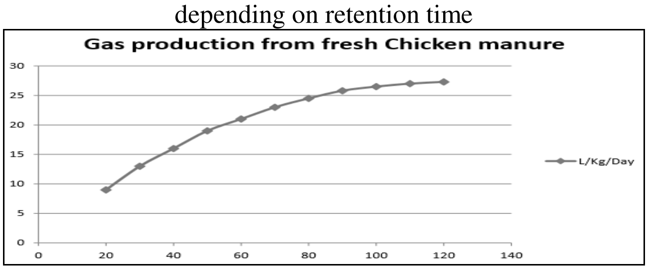

Figure 12: Gas production from fresh Chicken manure depending on retention time

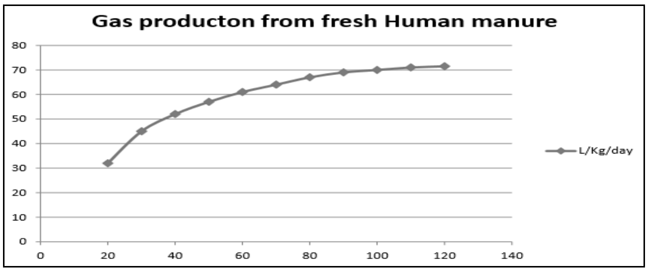

Figure 13: Gas production from fresh Human manure depending on retention time

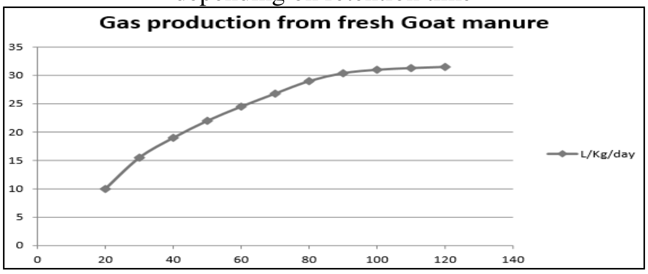

Figure 14: Gas production from fresh goat manure depending on retention time

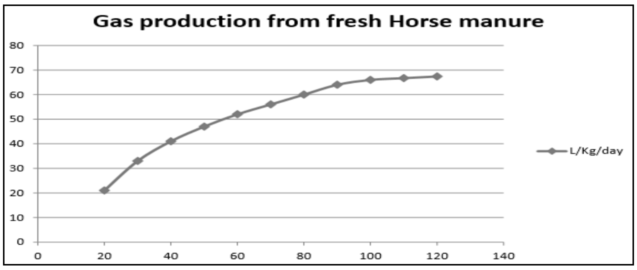

Figure 15: Gas production from fresh Horse manure depending on retention time

If the gasholder capacity is insufficient' part of the gas produced will be lost. If the gasholder is made too large, construction costs will be unnecessarily high. The gasholder must therefore be made large enough to be able to accept the entire volume of gas consumed at a time. It must also be able to accept all the gas produced between consumption times. The gasholder must be able to compensate for daily fluctuations range from 75% to 125% in gas production [7].

Examples for the Calculation:

Feed material: cow dung, amount (Dd): 20 kg/day

Mixing ratio: dung: water = 1:1

Fermentation slurry amount (Sd): 20 kg/day x 2 = 40 L/day

Retention time (RT): 80 days

Digester volume (VD): 40 L/day x 80 days = 3200 L

Digester temperature (t): 26 - 28 °C

Specific -gas production (Gd) from Fig. 9: 40 L/kg

Daily gas production (G): 40 L/kg x 20 kg/day = 800 L/day

Gasholder capacity (C): 60 %

Gasholder volume (VG): 800 L x 0.60= 480 L

E. Digester Dimensions

Based on the user input of the digester design type, following equations were utilized to calculate dimensions of the specified digester. For the polyethylene tubular digester, the diameter was fixed at 1.11 meters based on polyethylene tube availability. The length of the polyethylene tubular digester was calculated as follows:

$$L_{polyethylene} = V_{vessel} / (3.14*(D_{polyethylene}/2)^2$$

where $L_{polyethylene}$ = length of polyethylene reactor (m)

V_{vessel} = volume of reactor vessel, including the headspace (m^3)
$D_{polyethylene}$ = diameter of polyethylene tube (m)

The dimensions of the fixed dome digester were calculated as follows. The H/D ratio was defined as 2.0 [10].

$$\mathbf{D_{fixed\ tank} = V_{vessel}*4 / (3.14*(H/D))^{1/3}}$$

where $D_{fixed\ tank}$= diameter of fixed dome anaerobic digester (m)
V_{vessel}= volume of reactor vessel, including the headspace (m3)
H/D = height-to-diameter ratio (2.0 for fixed dome reactor) (dimensionless)
The height of the fixed dome reactor was calculated as follows:

$$\mathbf{H_{fixed\ tank} = (H/D)*D_{fixed\ tank}}$$

where $H_{fixed\ tank}$ = height of the fixed dome digester (m).

The dimensions of the floating drum digester were calculated similarly as fixed tank plant, except that the H/D ratio was defined as 3.5 [10].

IV. Results and Discussion

The value for the following case studies were taken from data collected by the author by conducting house to house survey in Kapurpur village which is located in Mainpuri district, in Uttar Pradesh, India
In the Kapurpur village there are total 67 households of which 29 families or 43% of the families in the village owns cows and buffalos, 15 families or 23% of the families own goats, 4 families or 6% of the families own chicken, 2 families or 3% of the families own pigs and 1 families or 1.5% of the families owns horses.
In the following case study retention time of 30 days, digester temperature of 26-28 °C and 100% of manure collected has been taken.

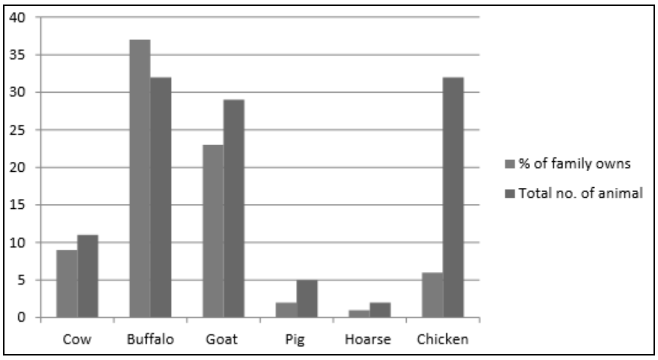

Figure 16: Total number of different animals in Kapurpur village and % of family owning them

A. *Case study 1-* Family sized anaerobic digester

Case study one was one family-sized digester and included the waste from 2 cows. Outputs from the model for case study 1 are shown in table 4.

Table 3: Output for Case Study 1: Family size Anaerobic Digester

Scaling of small scale anaerobic digester for application in indian village

		Discharge per day approx. (Kg)	T.S. value of fresh discharge (% by wt)	Feed material	Slurry	L Biogas/Kg manure
No of Cow	2	10	16	20	40	22
No of Buffalo	0	12	14	0	0	19
No of Goat	0	1	30	0	0	15.5
No of Horse	0	10	25	0	0	33
No of Pig	0	2	17	0	0	47
No of Chicken	0	0.1	25	0	0	13

Total feed material generated per day	-	20	Kg/day
Fermentation slurry amount(Sd)	-	40	L/day
Retention time (RT)	-	30	Days
Digester volume (Vd)	-	1200	L
Specific gas production (G)	-	440	L/DAY
Gas holder capacity ©	-	100	%
Gas holder volume (Vg)	-	440	L
Vvessel (=Vr * 1.2)	-	1440	L

Digester dimensions

Polyethylene tubular digester		Fixed dome digester		Floating drum digester	
DPolyethylene tubular	1.11 m	DFixed dome	0.648861 m	DFloating drum	0.413193 m
LPolyethylene tubular	1.39248 m	HFixed dome	1.297721 m	HFloating drum	1.446177 m
Gas Storage Vessel	0.44 m^3	Gas Storage Vessel	No external gas storage required	Gas Storage Vessel	0.44 m^3

Outputs

According to Nijaguna (2002), one family in India used 850 L of biogas per day or 0.85 m^3 biogas/d. 0.44 m^3 biogas/d is the calculated biogas production rate. Based on the model calculations, a family would need more manure than 100 % of manure from 2 cows to meet there daily needs.
Polyethylene tubular digester diameter is 1.11m, length is 1.39m and gas storage vessel size is 0.44m^3. Fixed dome digester diameter is 0.64m, height is 1.29m and no external gas holder is required. Floating drum digester diameter is 0.41m, height is 1.44m and gas holder vessel size is 0.44m^3.

B. Case Study 2: Anaerobic Digester for Six Households

In order to save on materials and to share in operation and maintenance considerations, it is an option to build a slightly larger anaerobic digester for the animal wastes from six households. It was estimated that there was an approximate average of 2 cow at the households that owned cow, 6 chickens at the households that owned chickens, and 3 goat at the households that owned cattle.
Case Study 2 included the waste from 3 cow, 8 buffalo, 7 Goat and 6chicken. Table 5 shows the inputs and outputs of Case Study 2.

Table 4: Output for Case Study 2: Anaerobic Digester for six Households

Scaling of small scale anaerobic digester for application in indian village

		Discharge per day approx. (Kg)	T.S. value of fresh discharge (% by wt)	Feed material	Slurry	L Biogas/Kg manure
No of Cow	3	10	16	30	60	22
No of Buffalo	8	12	14	96	192	19
No of Goat	7	1	30	7	21	15.5
No of Horse	0	10	25	0	0	33
No of Pig	0	2	17	0	0	47
No of Chicken	6	0.1	25	0.6	1.8	13

Total feed material generated per day	-	133.6	Kg/day
Fermentation slurry amount(Sd)	-	274.8	L/day
Retention time (RT)	-	30	Days
Digester volume (Vd)	-	8244	L
Specific gas production (G)	-	2600.3	L/DAY
Gas holder capacity ©	-	100	%
Gas holder volume (Vg)	-	2600.3	L
Vvessel (=Vr * 1.2)	-	9892.8	L

Digester dimensions

Polyethylene tubular digester		Fixed dome digester		Floating drum digester	
DPolyethylene tubular	1.11 m	DFixed dome	4.311851 m	DFloating drum	2.838639 m
LPolyethylene tubular	9.566338 m	HFixed dome	8.623702 m	HFloating drum	9.935237 m
Gas Storage Vessel	2.6003 m^3	Gas Storage Vessel	No external gas storage required	Gas Storage Vessel	2.6003 m^3

Output

The calculated flow rate of biogas produced was approximately 2.6 m^3 biogas/d. If one family uses 0.85 m^3 biogas/d (Nijaguna, 2002), that would be an equivalent flow rate of 0.433 m^3/(d*family). This flow rate would be enough biogas for three households, not six.

Polyethylene tubular digester diameter is 1.11m, length is 9.5m and gas storage vessel size is 2.6m^3. Fixed dome digester diameter is 4.1m, height is 8.6m and no external gas holder is required. Floating drum digester diameter is 2.8m, height is 9.93m and gas holder vessel size is 2.6m^3.

C. Case Study 3: Village-Sized Anaerobic Digester for Kapurpur Village

In Kapurpur village, there are 67 househols and the total numbers of animals where 11 Cows, 32 Buffalos, 29 Goats, 5 Pig, 2 Horses and 32 Chicken. These numbers are used in Case Study 5.3.

Table 5 : Out for Case Study 3: Village-Size Anaerobic Digester for Kapurpur Village

Scaling of small scale anaerobic digester for application in indian village

		Discharge per day approx. (Kg)	T.S. value of fresh discharge (% by wt)	Feed material	Slurry	L Biogas/Kg manure
No of Cow	11	10	16	110	220	22
No of Buffalo	32	12	14	384	768	19
No of Goat	29	1	30	29	87	15.5
No of Horse	2	10	25	20	60	33
No of Pig	5	2	17	10	20	47
No of Chicken	32	0.1	25	3.2	9.6	13

Total feed material generated per day	-	556.2 Kg/day
Fermentation slurry amount(Sd)	-	1164.6 L/day
Retention time (RT)	-	30 Days
Digester volume (Vd)	-	34938 L
Specific gas production (G)	-	11337.1 L/DAY
Gas holder capacity ©	-	100 %
Gas holder volume (Vg)	-	11337.1 L
V_{vessel} (=Vr * 1.2)	-	41925.6 L

Digester dimensions

Polyethylene tubular digester		Fixed dome digester		Floating drum digester	
$D_{Polyethylene\ tubular}$	1.11 m	$D_{Fixed\ dome}$	18.38301 m	$D_{Floating\ drum}$	12.03013 m
$L_{Polyethylene\ tubular}$	40.54206 m	$H_{Fixed\ dome}$	36.76603 m	$H_{Floating\ drum}$	42.10545 m
Gas Storage Vessel	11.3371 m^3	Gas Storage Vessel	No external gas storage required	Gas Storage Vessel	11.3371 m^3

Output

The calculated flow rate of biogas produced was approximately 40.5 m^3 biogas/d. If 0.85 m^3 biogas/d are needed for one household's cooking each day, there would be enough biogas in the community to supply 48 households with biogas.

Polyethylene tubular digester diameter is 1.11m, length is 40.54m and gas storage vessel size is 11.33m^3. Fixed dome digester diameter is 18.38m, height is 36.7m and no external gas holder is required. Floating drum digester diameter is 12.03 m, height is 42.1m and gas holder vessel size is 11.33$m^{3.}$

To achieve sustainable development in rural India, it is imperative that access to clean and affordable (renewable) energy is made available. Biogas has the potential of providing clean and reliable energy, while presenting the local and global environment. However the use of anaerobic digester is low in India, despite the potential of a wide variety of benefits. There are several potential problems, limiting the uptake of small scale anaerobic digester including high capital cost, design, maintenance, operational problem and availability of materials for maintenance. Modernization is needed in design and uses to overcome the drawback in long run.

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