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Techno Economic Studies on the Effective Utilization of Non-Uniform Biowaste Generation for Biogas Production

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Abstract

Environmental effects from traditional energy sources and government regulations, necessitate the use of alternative energies like biogas for many uses including drying and refrigeration. Biowaste produced in educational institutions will not be uniform over the year. The non-uniform supply of biowastes, the absence of studies on bio digestion of likelihood biomass, the unreliability of energy from such conversion and the profitability of its usage in most applications are some of the factors to be considered while implementing this technology. In this regard, theoretical and experimental evaluations were carried out to accurately forecast biogas generation capabilities in educational campuses for obtaining biofuels with quantity and efficiency. It is observed that biogas generation with 52 to 58% methane content can be possible during an academic year. The quality of biogas shows that it is appropriate for almost any application. A broader analysis on different types of biogas digesters was conducted for their suitability in academic institutions. The economic benefits are analyzed for incorporating three biogas digesters namely KVIC, Fiber Reinforced Plastic (FRP) type and JANATA. There are some encouraging results to confirm the economic feasibility of biogas plants including positive net present value. Biogas generation with digesters of capacities varying between 25 and 450 cubic meter shows payback periods varies from 3.18 to 7.59 years, which confirms that it is profitable to use digesters in this range of capacities.

Keywords: biogas, biodigester types, economic analysis, payback period, non-uniform loading rates

1. Introduction

1.1 Renewable energy: current scenario

The environmental factors and depletion of conventional energy sources create a huge demand for technologies to substitute conventional fuels. Renewable Energy Sources (RES) such as solar, wind, tidal and biomass are available abundantly and they can be harvested without environmental degradation. The International Energy Outlook (IEO) states that the global primary energy demand will increase to

48% between 2012 and 2040 [1]. The share of non-renewable energy (liquid fuels, coal, natural gas and nuclear) will decrease from 91% in 1990 to 84% in 2040. However, renewable energy sources will continue to grow and catering from 9% of the world's energy demand to 16%. The share of primary energy sources in the world's energy generation also points a decrease in the non-renewable energy's share in electricity generation from 78–71% in 2040.

The growth of installed capacity of renewable energy sources in India shows that the country had gone up from 7.8% in 2008 to 15.9% in 2016 with the generation mix of wind power (57%), solar power (18%), biomass (15%), small hydro (9%) and waste to energy (1%). Waste to energy is one of the new classifications among the energy mixes in the country. Among the various renewable energy conversion technologies, biochemical conversion is one of the best techniques to convert biowaste to useful form of energy (biogas). This low-cost technology can convert any organic wastes to biogas which can be further used as a fuel for cooking, lighting, power generation, etc. Anaerobic Digestion (AD) is one of the RES conversion processes which is capable of handling 90% of moisture content [2]. The end product of the AD is biogas which is comprised mainly with CH_4 and CO_2 . CH_4 is the combustible gas with an energy content of $50 \pm 5 \text{ MJ/kg}$ which can be utilized for heating, power generation and other applications related with gaseous fuel [3].

The AD process involves four steps (hydrolysis, acidogenesis, acetogenesis and methanogenesis) which is effected by methanogens such as hydrogenotrophic and acidogenic [4]. The organic content consists of various particulate as well as water insoluble polymers, hence the polymers are not accessible for the microorganisms directly [5, 6]. During the first step i.e., hydrolysis the insoluble polymers break down to soluble oligomer and monomer. This is caused by the strains of hydrolytic bacteria which releases hydrolytic enzymes [7]. Carbohydrates, lipids, and proteins are converted to sugars, long-chain fatty acids, and amino acids. In the next step i.e., acidogenesis the soluble molecules are converted to CO_2 and H_2 along with acetic acid, propionic acid, ethanol, and alcohols. Other acids which are produced apart from acetic acid, propionic acid, ethanol are due to *Actinomyces*, *Peptostreptococcus anaerobius*, *Clostridium* and *Lactobacillus* respectively [8]. With the support of proton reducing agent the long volatile fatty acids as well as alcohols will oxidize to acetic acid and H_2 during acetogenesis (third step) [9]. During the last stage (methanogenesis) methanogens are generated namely *hydrogenotrophic* and *acetoclastic* [10, 11]. This is caused by the reduction of CO_2 to H_2 as well as scrubbing of sliced acetic acid which is formed in the third stage. The biochemical conversion process involved in the AD is shown in **Figure 1**.

1.2 Biogas production and utilization

The data obtained from the year-wise installed capacity in MW of bio-power energy sources for power generation in India reveals that the installed capacity of bio-power energy sources has been on the increase every year and the same can be utilized for about 70% of the rural basic energy needs in India [12]. Bio-power produced by thermochemical (biomass gasification) and biochemical (biogas) conversion techniques contributes significantly to India's rural energy supply. According to a 2012 World Bank report, waste is classified as organic, paper, plastic, bottles, metals, among others. For most solid waste preparation purposes, these six categories are normally appropriate. Studies in the field of biowaste utilization in Europe showed high initial cost for the implementation; however, such cost could be reduced by intensive research on process integration and intensification. The ministry of MNRE, India has set a target of 10 GW of bio-power capacity by 2022 [13]. A huge potential is observed for employing anaerobic digestion as waste

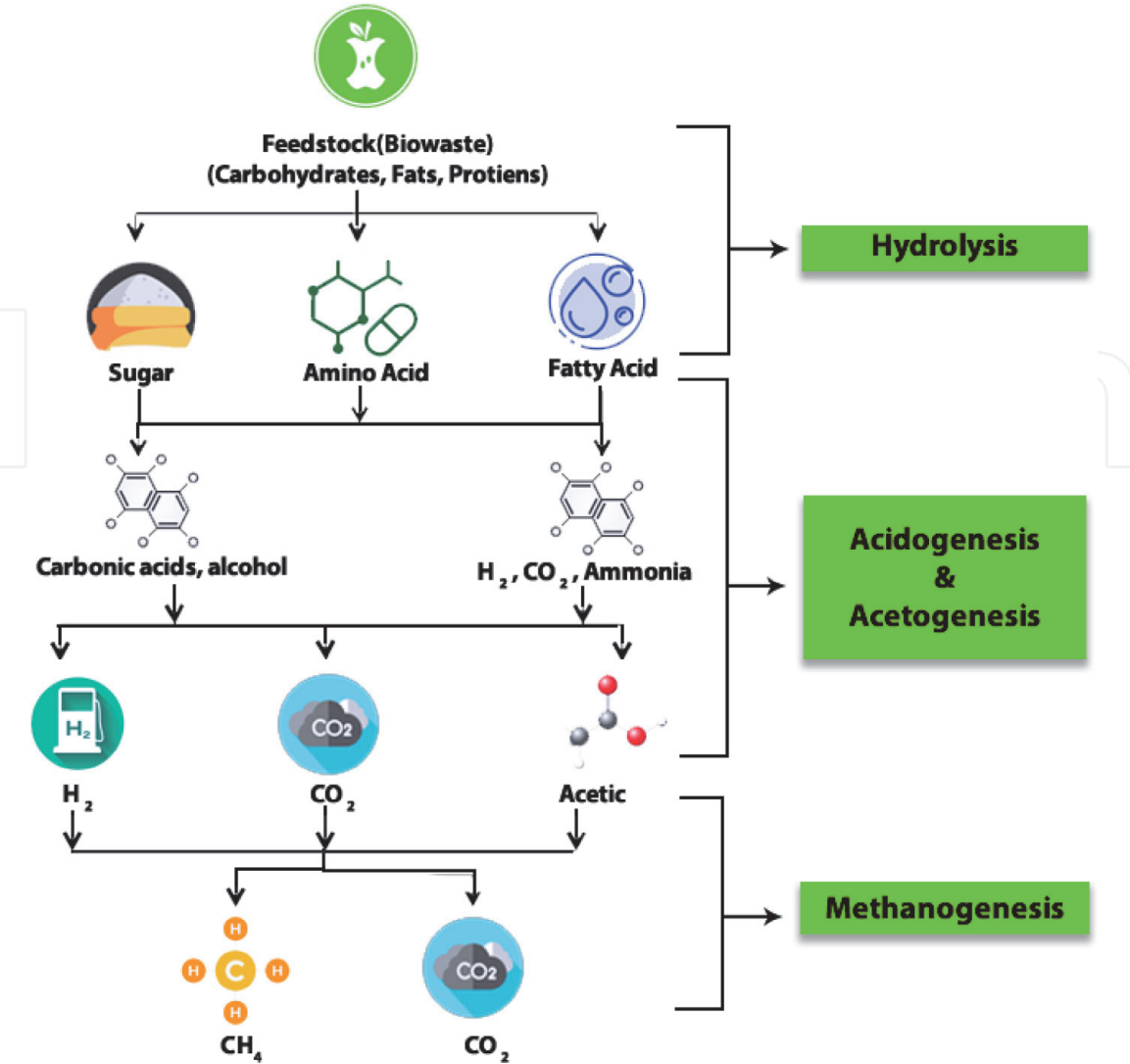


Figure 1.
Anaerobic digestion process.

management method and energy production technology in India and the rest of the world [14].

Realizing the potential of biogas as future energy source, many studies were conducted on biogas generation, utilization, and applications. The canteen and mess wastes which are rich in organic content could be used effectively for waste utilization and energy generation. The series of experiments conducted by varying HRT and OLR showed that with at Hydraulic Retention Time (HRT) of 20 days and $100 \text{ kg TS m}^3 \text{d}^{-1}$, the methane content of 50% with $0.981 \text{ m}^3 \text{ kg}^{-1} \text{ VS}$ could be achieved [15]. A test conducted with mesophilic tubular digester for generation of biogas showed that fruits and vegetable wastes were used as feedstock. Variations in HRT and feed concentration were used to assess the digester's efficiency. With a feed concentration of 6% TS and a 20-day HRT, the digester's efficiency was found to be the highest [16]. An experiment was conducted with pig manure in Anaerobic Batch Reactor (ABR) for hydrogen generation in two stages for pH values 5.0, 5.5 and 6.0. The OLR was taken as 96.4, 48.2 and $32.1 \text{ kg VS m}^{-3} \text{d}^{-1}$ whereas HRT was maintained as 12, 24 and 36 h. It was noted that at 12 h HRT and $96.2 \text{ kg VS m}^{-3} \text{d}^{-1}$ OLR, the hydrogen concentration was at the maximum [17].

An analysis was carried out to check the stability and performance of anaerobic digestion with varying HRT and OLR. The analysis showed a decrease in methane yield with the increase in OLR as well as a decrease in HRT for low OLR

($0.1 \text{ g VS}^{-1} \text{ d}^{-1}$). At high HRT (25 days), the methane yield was maximum [18]. Co-digestion of food waste and fruit-vegetable waste was performed in single-phase and two-phase digesters. By varying the OLR, authors concluded that single-phase digester could produce more methane than two-phase for low OLR [19]. According to reports, co-digesting food waste with cattle manure will boost biogas production and methane yield [20]. The performance of biodigesters under overload conditions was evaluated based on two case studies. To study the interrelation between biomass population dynamics and digester stability, Anaerobic Digestion Model 1 (ADM1) was utilized. The study showed that the digester did not function in high OLR conditions [21]. The techno-economic study of a combined bioprocess, based on solid state fermentation for fermented hydrogen generation from food waste was conducted. The outcome shows that five years Pay Back Period (PBP), 26.75 percent Return on Investment (ROI) and 24.07 percent and Internal Rate of Return (IRR) respectively could be possible [22].

1.3 Scope and aims of the work

Many studies reported the production and utilization of biogas for various applications. In most of them, technical and economic viability of biogas plants for the utilization of biogas in various applications was studied for a stable organic loading in biodigesters. Despite the high potential for biogas use in educational facilities, only a few studies have been conducted to determine the techno-economic feasibility of using biogas technology in this field [23–25]. This is mainly due to the variation of student and staff population throughout a year, and the non-uniform generation of organic waste. Furthermore, in order to improve the accuracy of the forecast, the quality and quantity of biogas produced from various biowastes available in this area must be investigated. Hence, this current research focuses on predicting technological and economic influences, as well as their effect on the deployment of biogas plants in a few educational institutions in India's southern region. The following objectives have been established to scientifically research the feasibility of using biowastes available in educational institutions in the selected area, as well as to determine the effect of non-uniform loading on digester's efficiency and economic viability.

- Identify and characterize the biowaste available in educational institutions.
- Find the impacts of non-uniform loading of biowastes on the biogas generation in biodigesters using mathematical and experimental methods.
- Predict the economic factors for the implementation of biogas digesters in a few educational institutions.

2. Methodology

2.1 Grouping of biowastes and selection of biogas plants

Anaerobic digestion based waste management technology has an enormous significance in India because of the vital role of waste disposal methods as well as its role as a renewable energy source for cooking, lighting, electricity generation, and so on [26]. The anaerobic digestion process utilizes a variety of biowastes from various sources including municipal solid waste, households, institutions, and industry. The generation of biogas from anaerobic digestion of biowaste in

educational institutions is projected to play a significant role in ensuring rural and urban prosperity [27]. As a result, institutions in and around the southern part of India were chosen for this research, where biogas will substitute 35 percent to 40 percent of the traditional fuel used for cooking. The institutions in this region were categorized based on the student population, and the potential of biowastes and their availability throughout a year were studied. The strategy followed to select the biowaste and the digestion systems has been shown in **Figure 2**.

2.2 Categorization of institutions

More accurate research is possible in educational institutions because the large number of students living in the campus offers numerous opportunities for biogas production. Based on the population of students and staff, the institutes situated in southern part of India (the region selected for this study) were categorized as A, B, C, D and E as mentioned in **Table 1**. The population details were collected based on the published data of the respective institution.

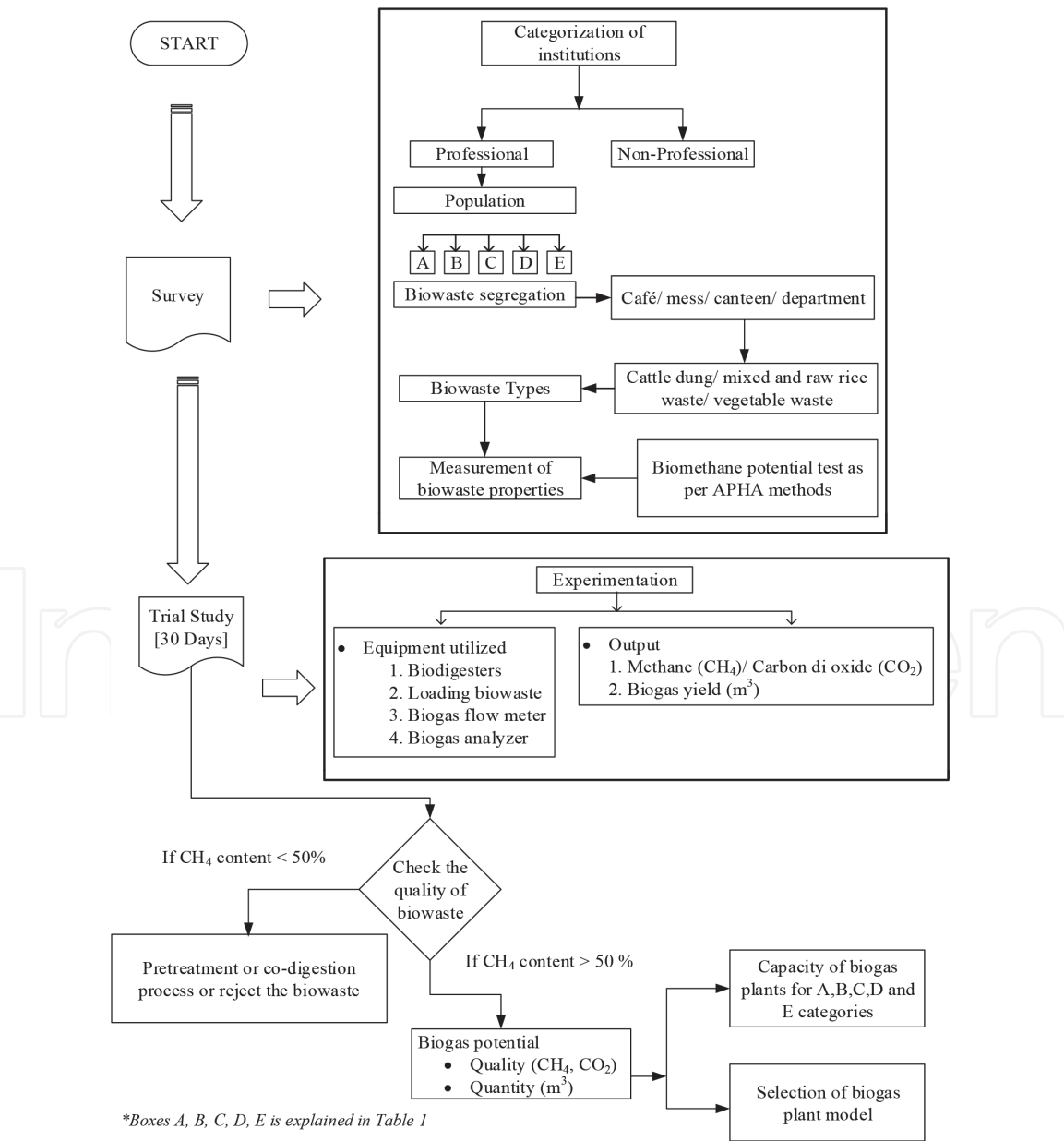


Figure 2.
Flow chart for the procedure involved in the grouping of biowastes and the selection of biogas plants.

Categories	Range of population	Institutions in numbers	Population mean
A	1000–2500	200	1728
B	2501–5000	180	3448
C	5001–9000	95	6399
D	9001–20,000	75	11,500
E	20,001–40,000	20	29,231

Table 1.
The various categories of institutions according to population range.

2.3 Selection of biowastes for this study

A survey was conducted with the required questionnaire to select the biowaste samples. Biowaste details such as amount, consistency, and varieties were discovered through the survey. The type of institution, academic schedule, population of students and staff living on and off campus, biowaste generation sources, conventional cooking fuel, and other relevant factors dominated questionnaire’s development. Personal information of people was also included. The data reliability was verified with relevant authorities.

2.3.1 Potential of biowaste sources

Sewage sludge (SS), food waste (FW), leaves, cotton waste, paper waste, and other biogas energy sources have been reported. **Table 2** shows the estimated data of a sample.

On a regular basis for different academic schedules, a survey on food waste supply in a group ‘A’ institution was performed. This research looked at the most traditional food menu trends used by different institutions. Food wastes produced before and after cooking were also taken into account. **Table 3** shows the specification of category ‘A’ institution.

Table 4 shows the common biowastes and the percentage of biowaste generated in a category ‘A’ institution. The samples were collected in the hostels before dumping. Separate buckets were kept for collecting the different food wastes. The students and staff members were instructed to dump the leftover food accordingly. It was observed that the availability of some wastes like fruit waste, meat waste and fish waste was low but their quantity in total waste had been checked at least twice a

Particulars	Category ‘A’ Institution
Geographical area of the institution (acres)	27–35
Total population	1000–2500
Literacy of population (%)	100
Density of livestock population	0–15
Waste disposal technology	Landfill, open heating
Biowaste suitable for anaerobic digestion (kg/day)	100–700
Quantity of dung production (kg/day)	0–70
Quantity of Convention fuel (LPG) used for cooking (kg/day)	12–15

Table 2.
The data grouped for a category ‘A’ institution.

Particulars	Sample Institution
Geographical area of the institution (acres)	34
Population range	200–2400
Literacy of population (%)	100
Density of livestock population	15
Waste disposal technology	Landfill
Biowaste suitable for anaerobic digestion (kg/day)	100–590
Quantity of dung production (kg/day)	45–70
Quantity of Convention fuel (LPG) used for cooking (kg/day)	12

Table 3.
The data grouped for a sample category ‘A’ institution.

Sl. no.	Biowastes	kg of biowastes
1.	Cooked rice	44
2.	Cooked vegetables	3.7
3.	Tea	2.8
4.	Coffee	2.2
5.	Salad	3.7
6.	Oil	11.2
7.	Fruit wastes	16.9
8.	Mixed rice wastes	490

Table 4.
Sample data for biowastes generated in a category ‘A’ institution on 100th day.

month to find any major deviation. The observation showed that the variation was not significant. Hence such wastes were added along with mixed rice waste.

Among the numerous biowastes generated in the study area, Rice Waste (RW), Mixed Rice Waste (MRW), and Vegetable Waste (VW) were some of the potential biowastes available. Therefore, they were selected for the anaerobic digestion. Meat, fish, potato, and rice wastes, left out after consuming were used in MRW. **Table 5** shows the grouped-biowastes used as feedstock for biogas generation. Other biowastes, apart from VW and RW, were mixed with MRW due to insufficient availability.

2.4 Measurement of biowaste properties

The important parameters which control biogas generation are pH, VS and TS, therefore these properties were experimentally measured as per the standard procedure discussed below [28].

Sl. No.	Biowastes	kg
1.	Rice waste	5–50
2.	Mixed rice wastes	70–490
3.	Vegetable waste	5–50

Table 5.
Biowastes grouping for category ‘a’ institution.

2.4.1 Total solids

The following technique was used to assess the feed’s TS according to APHA guidelines [28]. 50 g of each biomass was placed in pre-weighed porcelain vessels and heated at 60°C for 24 hours and then at 103°C for 3 hours in a hot air oven. The weight of the dry samples, as well as the container, was determined in a weighing balance with a precision of 0.001 g. A sample’s TS percentage was determined as follows:

$$TS = \left(\frac{W_d}{W_w} \right) \cdot 100 \tag{1}$$

The dry and wet sample weights are W_d and W_w , respectively.

2.4.2 Volatile solids

The standard formula for determining the VS of feed materials was used. The oven-dried samples were dried at 550°C ± 50°C and ignited fully inside the muffle furnace. The desiccator’s cooled samples were measured, and VS was determined using the Eq. (2).

$$VS = \left[\frac{(W_d - W_a)}{W_a} \right] \cdot 100 \tag{2}$$

where W_d is the dry sample weight, and W_a is the dry ash weight.

2.4.3 pH

The pH of biowastes Cow Dung (CD), RW, MRW, and VW was measured at least once in a day using a pH electrode with 0.05 percent accuracy. The samples were taken from the slurry until where it was fed to the digesters. A pH electrode dipped in the inoculum was used to test pH of digesters on daily basis. **Table 6** shows chemical properties of the four types of biowastes used in this study. Eqs. (1) and (2) were used to measure the values of TS and VS. The validity of experiments was verified after the findings were compared to literature.

2.5 Biogas plants commonly used in India

In India, more than seven models of biogas plants are available and they are being used in various parts of the country according to the requirement of a particular area [35]. This study examines the feasibility of applying appropriate model in educational institutions from Khadi and Village Industries Commission (KVIC),

Sl. No.	FEED	pH %		TS %		VS %	
		Current study	Reference values	Current study	Reference values	Current study	Reference values
1	CD	6.50	6.30 [29]	15.98	17 [29]	64.99	89 [29]
2	MRW	4.91	4–7 [30]	20.25	14.4 [31]	90.15	89.5 [31]
3	RW	6.61	4–7 [30]	30.28	14.4 [31]	90.11	89.5 [31]
4	VW	6.35	7.1 [32]	10.55	9.3 [33]	90.45	78–93 [34]

Table 6.
Characterization of feedstock.

JANATA, and Fiber-Glass Reinforced Polyester (FRP) [36]. These three models were selected based on the ease in construction as well as operation compared with other models. The selection of biogas plant model varies for all institutions based on the nature and activities of the students. For selected category of institutions these three models were considered.

2.5.1 Biogas Plant: Khadi and Village Industries Commission

This type of biogas plants consists of a floating drum made of steel, fiber glass reinforced polyester or high-density polyethylene. Its underground digester tank is made of bricks and cement as shown in **Figure 3**. The floating drum which moves up and down according to the biogas generation serves as the gas holder. The major disadvantage of these models is high maintenance due to corrosion of drum which leads to regular coatings. The rainwater should be prevented from entering the tank as it corrodes the steel. The advantage is seen when the same model floating drum is made of fiber glass reinforced polyester or high-density polyethylene, it can work efficiently without affecting the digestion process but it makes the biogas plant more expensive. The life of the plant is found to be 15 years [37].

2.5.2 Biogas plant: JANATA

The fixed dome instead of the floating drum, as seen in **Figure 4**, distinguishes this from KVIC model. Initial cost of dome is lower than that of KVIC model since it is constructed by bricks, blocks, and cement. The major disadvantage of this model is making a gas tight dome because in such models, leaks are observed in the cracks formed in the dome due to poor construction. Thus, this type of biogas plants required skilled supervisors and labourers for construction. This kind of small-scale biogas plant has a lower cost, making it a good choice for institutions in categories A, B, and C. A long life of 20 years or more can be expected due to non-corrosive parts used in construction [37]. Compared with other two models, this model has the largest life span.

2.5.3 Biogas plant: fiber-glass reinforced polyester

The FRP model biogas plants as shown in **Figure 5** are most used in household applications in both rural and semi-urban parts of India. FRP is used in the

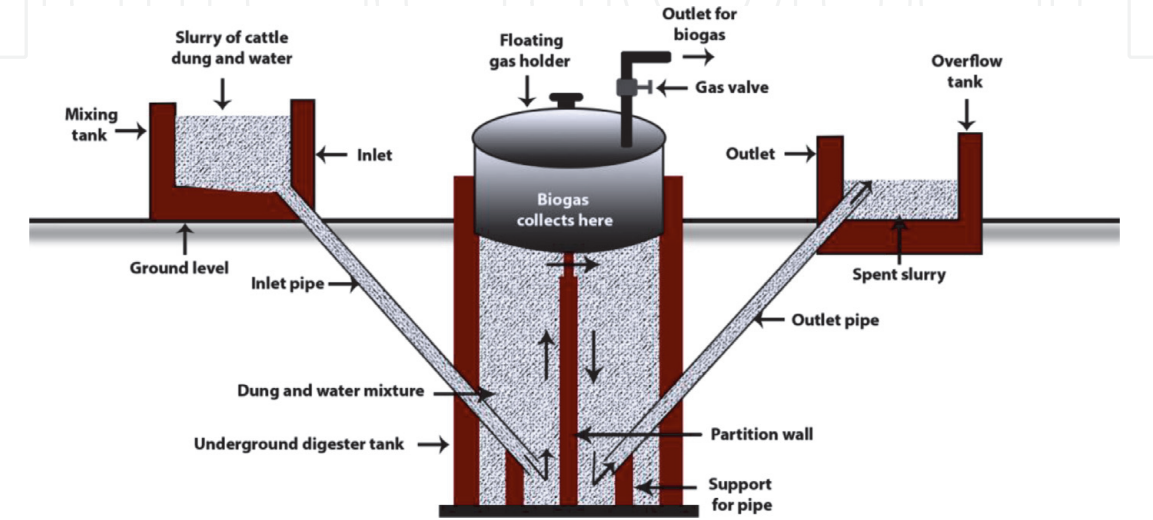


Figure 3.
Biogas plant with floating-drum and cylindrical digester (KVIC model).

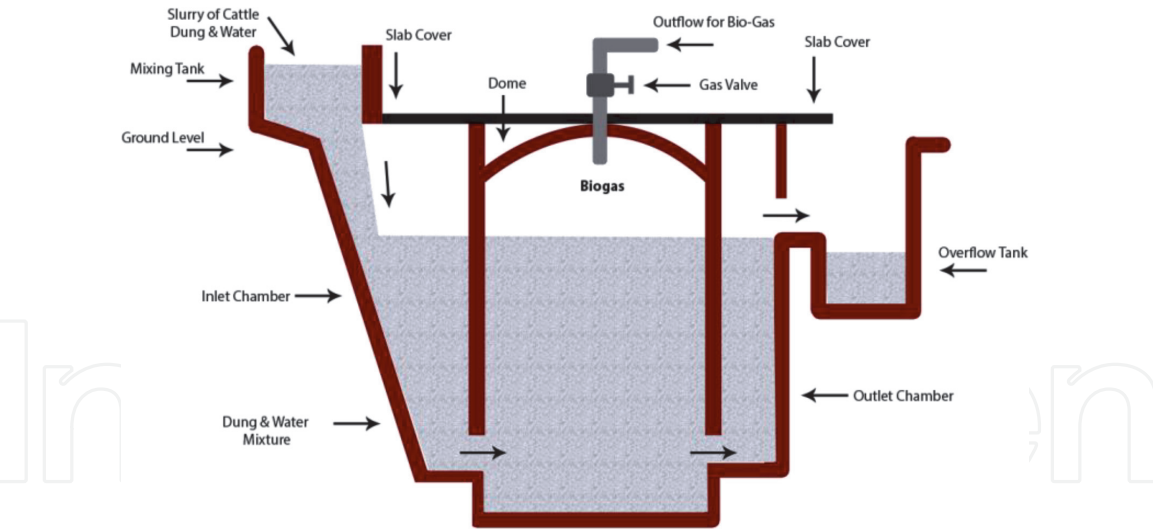


Figure 4.
Brick-reinforced fixed-dome biogas plant (JANATA model).

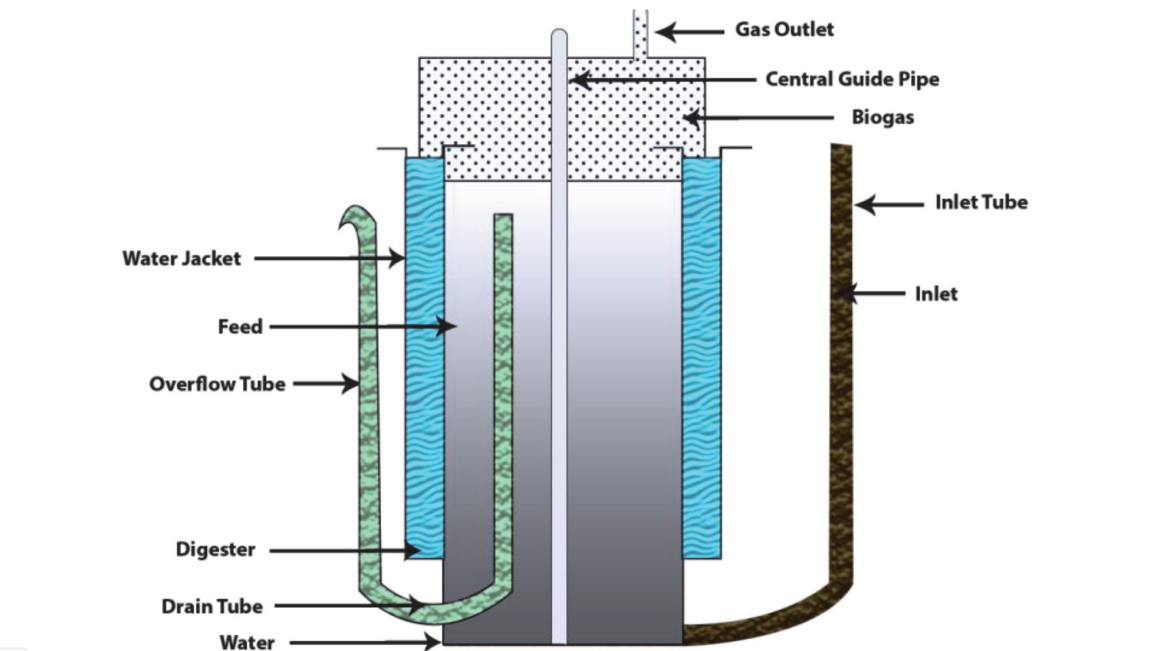


Figure 5.
Biogas plant with floating drum made by fiberglass reinforced polyester.

construction of digester tank, floating drum, and water jacket. PVC pipes are used for inlet and outlet pipes, and the central guide pipe is made of GS. Unlike other models, these biogas plants are placed above earth due to smaller in size. The maximum size of this type of biogas plants is limited to 1 to 12 m³. The FRP model biogas plants are portable and can be easily maintained. The investment cost is less, and such models are more attractive for small scale applications. The space occupied by this model is one of the disadvantages compared with other two models. An average of 10 year life span has been reported for this model [23].

2.6 Mathematical modeling

Educational institution is a place where the generation of biowaste is high during academic schedule whereas low in non-academic schedules. This non-uniformity in biowaste availability affects the loading rate which results in reduced methanogens activity. Hence, by understanding the performance of digesters with available

biowastes throughout a year, the minimum and maximum production of biogas in various academic schedules can be predicted. Further, it can be used to design the capacity of a biogas plant toward efficiently manage the variations in daily yield. As part of a theoretical simulation, a study was conducted to predict biodigesters' efficiency and their effect on non-uniform loading. The equations that state the mathematical representation of biochemical reactions are used for the analysis in Anaerobic Digestion Model 1 (ADM1). Therefore, ADM1 toolbox was adopted to represent the complete metabolic network of an anaerobic digestion [11]. This toolbox aids in determining the system's operational conditions as well as its behaviour. Moreover, it could help in the design of biogas plants of large scale.

The various steps used for the simulation are depicted in **Figure 6**. The simulation process starts with the selection of biowastes for anaerobic digestion. The properties such as pH, TS, VS, and moisture content (MC) of biowaste were studied through APHA procedures and taken as input parameters [38, 39]. The temperature levels, digester tank scale, and simulation phase were chosen from the respective inbuilt parameter control menus. Then the simulation was carried out in steps of a day, and the quality and quantity of the biowaste were measured. If the measured quality of methane was less than 50% the biowaste was rejected and a new one was selected for the simulation.

2.7 Experimental setup

Figure 7 shows a schematic diagram of the experimental system included in the analysis. It holds a digester tank which is surrounded by a water jacket. The floating drum, known as gas holder, is fixed in such a way that it can move up and down based on the generation of biogas. The water jacket holds the floating drum and prevents the

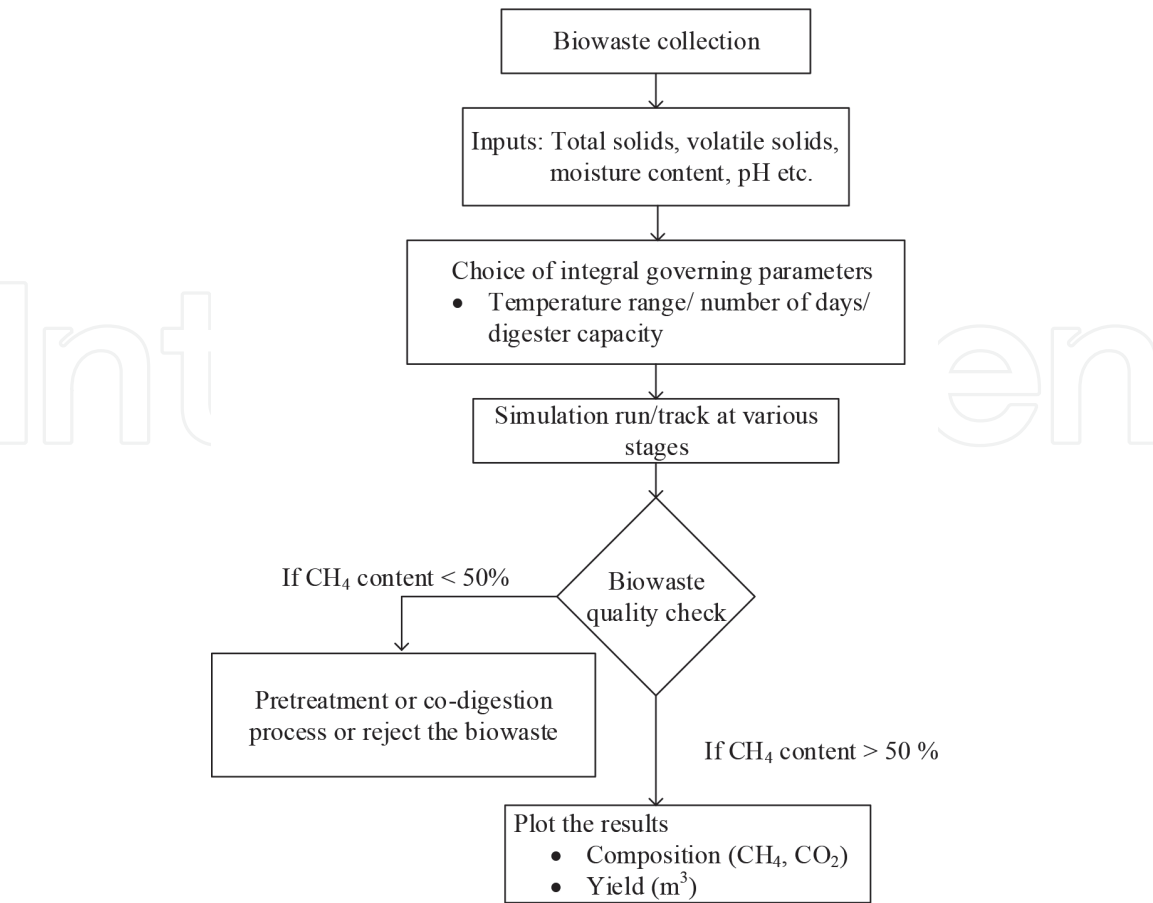


Figure 6.
Flow chart of the simulation procedure.

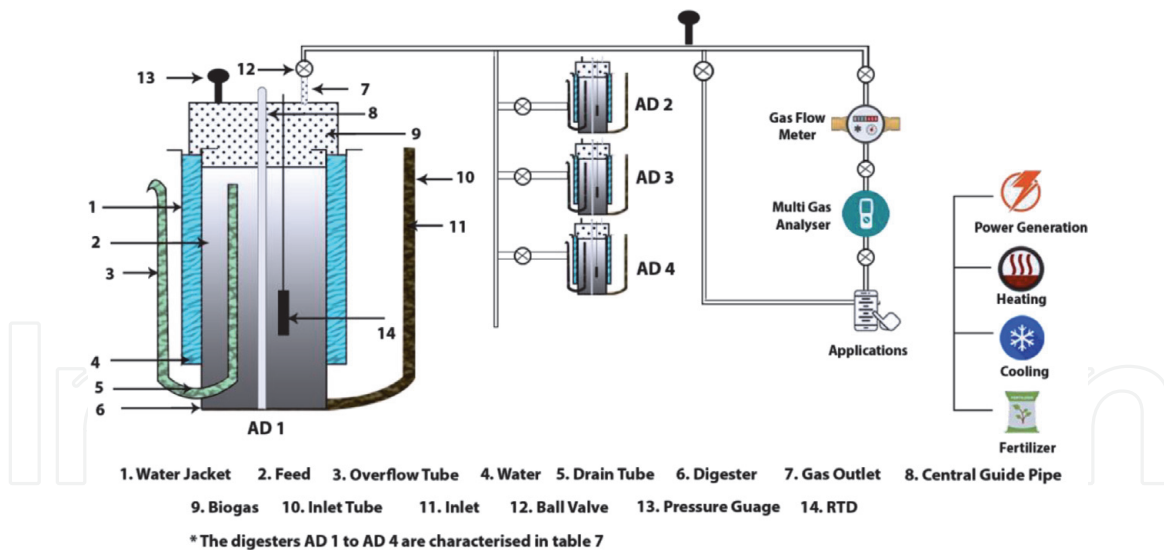


Figure 7.
Schematic diagram of the experimental setup.

leakage of biogas and odor of inoculum. A stainless-steel central guide is mounted in the centre of the digester tank to ensure smooth flow of the floating drum. To load biowaste and drain digestate, inlet and outlet pipes are provided appropriately. Drainpipes are also provided to clean the digester tank and water jacket. Suitable arrangement is made in the floating drum to transfer the biogas for any application.

To calculate the quantity and consistency of the biogas, a thermal gas flow metre (mass flow measurements of liquids) with a 0.5 percent Full Scale (F.S) accuracy and a multi gas analyzer (NUCON) with 0.3 percent accuracy are attached in the gas line. A pH electrode and temperature sensors are dipped inside the inoculum. The manifold connects all the digesters with the instrumentation panel.

2.7.1 Experimental procedure

Initially Cow Dung (CD) was filled in all the four digesters for the generation of methanogens with an HRT of 55 days. After confirming the complete digestion of CD, the required quantity of biowastes collected from the educational institution of category A was loaded for 30 days with the same quantity per day. The quality and quantity of methane generated per day was measured using the multi gas analyzer and thermal gas flow meter. The pH and temperature of the feedstock during digestion process were also measured at regular intervals and their averages were calculated. During this trial study, the temperature was observed between 29–34°C. **Figure 8** depicts a photographic image of the digesters used in the experimental setup as mentioned in **Table 7**.

After the trial study the same digesters were used for the pilot study for 365 days. However, the loading was varied according to the non-uniformity in the availability of biowastes. Since the total quantity of biowastes generated inside the campuses cannot be digested completely with the small digesters, only 10% of each type of waste was taken every day and the same was used for loading the digester. Thus, the impact of non-uniform generation of biogas was incorporated in the pilot study. The results were used in the prediction of quality and quantity of biogas generated for the proposed systems.

2.8 Economic study

The economic feasibility of a biogas plant for non-uniform loading is also important to confirm the selection of any type. As a result, the economic study was

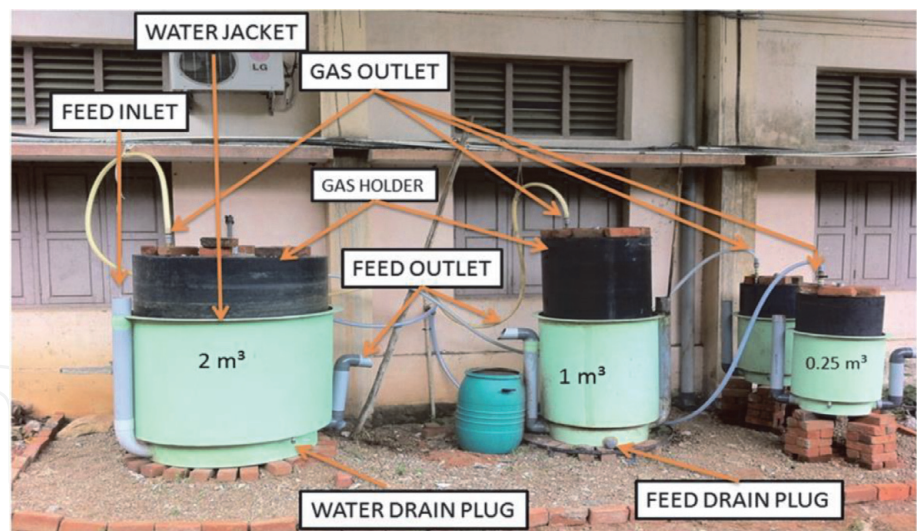


Figure 8.
Experimental setup of different capacity biogas digesters.

Digester	Capacity (m ³)	Feed	Slurry ratio (Feed: water)	Temperature/State	Period (days)
AD1	2	MRW	1:1	32 ± 5 °C/Mesophilic	365
AD2	1	CD	1:1	32 ± 5 °C/Mesophilic	365
AD3	0.25	RW	1:1	32 ± 5 °C/Mesophilic	365
AD4	0.25	VW	1:1	32 ± 5 °C/Mesophilic	365

Table 7.
Summary of the experimental design.

done using Capital Cost (CC), Annual Operating Cost (AOC), Payback Period (PBP), Net Present Value (NPV), and Life Cycle Cost (LCC). For this study, standard equations from previous studies have been chosen [37, 40]. Based on the pilot study performed in category ‘A’ institution, the biogas produced per person per day was determined and found vary from 0.014 to 0.019 m³. A mean value of 0.015 m³ per person was taken into consideration. Methane content was found as 53%. The capacity of the biogas plant for each category was calculated using the mean value. The quality and quantity of biogas generated over the course of a year were also determined using primary data.

The biogas plant’s volume (size) for an institution is determined by the availability of biowaste and the biogas yield from it. Using data from a pilot study conducted in category “A” institution, the supply of biowaste in the other categories of institutions over the span of a year was calculated and plotted in **Figure 9**. It is observed that the capacity of the biogas plant for each category varies between 25 m³ and 450 m³. The calculations were carryout based on the average values taken from the population range as mentioned in **Table 1**. Hence, different types of biogas plants are required for each institution based on certain parameters such as geo-graphical location, climatic condition, transportation and so on. Hence, the specifics of the different biogas plants available in India were investigated.

2.8.1 Selection of biogas plants in an economic analysis

The three types of biogas plants namely KVIC, JANATA and FRP were considered in this economic analysis. These models were selected based on the geographic

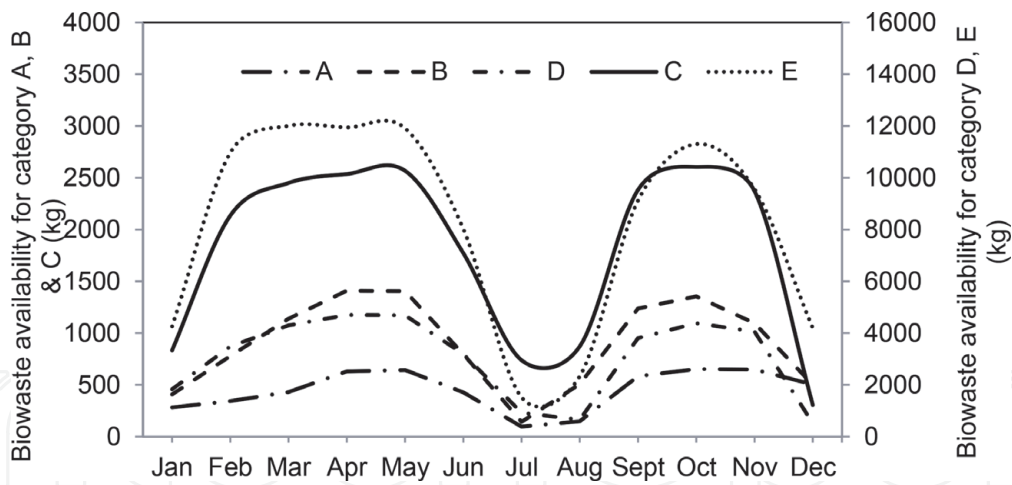


Figure 9.
Estimation of the biowaste availability for all categories.

location and the capacity of waste in an institution. Because of the simplicity of design and construction, KVIC models are the best choice for higher capacity biogas plants. The KVIC model plants suffer from a disadvantage in hilly areas because of the rusting in floating drum according to various climatic changes. JANATA model biogas plants, on the other hand, which are entirely made of bricks, resist rusting and are thus strongly recommended. Due to portability feature, FRP models are highly suggested for less capacity requirement. The initial investment is one of the major concerns for these types of biogas plants. Due to such concerns, the various economic factors are studied and discussed below.

2.8.1.1 Capital cost

The cost of the digester, construction costs, and government subsidies are all included in the CC of the Biogas Plant (BGP). Eq. (3) is used to calculate the capital expenditure.

$$\text{Capital Cost} = \text{Cost of the biogas plant} + \text{Installation cost of biogas plant} \quad (3)$$

2.8.1.2 Running cost

The operating and repair costs as well as the annual depreciation value, contributes to the plant's running expense. The cost of maintenance is estimated to be 2% of the plant's capital cost. (Jatinder & Sarbjit, 2004). For KVIC, JANATA, and FRP models, the life span was assumed as 15, 20, and 10 years, respectively. The measurements are dependent on a handling fee of Rs 0.40 per kg for biowaste, which covers shipping and labour costs.

$$\begin{aligned} \text{Running Cost} = & \text{Cost of the biowaste used} \\ & + \text{cost of maintenance and operation of biogas plant} \\ & + \text{cost of manpower/labour} + \text{transportation charge} \\ & + \text{depreciation value} \end{aligned} \quad (4)$$

2.8.1.3 Payback period

The economics of a biogas plant includes the calculation of the payback period to substitute the LPG cooking stoves with biogas-based cooking stoves. It has been calculated as

$$Payback\ period = \frac{Cost\ of\ Installation}{Annual\ Profit} \tag{5}$$

Where, Annual profit is the difference between the annual income and the annual operational cost of the BGP.

2.8.1.4 Net present value

The present value of a system’s spending and operating costs over its lifespan is known as the net present value (NPV). NPV is one of the main economic factors for comparing the energy conversion systems. The difference between the present value of the benefits and the costs resulting from an investment is the net present value of the investment. It is calculated by,

$$NPV = \left[S. \left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) \right] - CC \tag{6}$$

Where, ‘S’ - benefits at the end of the period, CC - initial capital investment, i - annual interest rate (12%).

The below are the approval conditions for an investment project as determined by the NPV method:

- a. accept the system if NPV > 0
- b. reject the system if NPV < 0

2.8.1.5 Life cycle cost

Another significant economic metric is the system’s LCC, which accounts for all expenses involved with the system over its lifetime by considering the worth of money. The Life Cycle Cost Analysis (LCCA), which considers the initial costs, operation costs, repair costs, replacement costs, and salvage prices, is a valuable method for determining whether the selected biogas plants could be installed in educational institutions. A life cycle of 15, 20 and 10 years were assumed in calculating the Present Worth Cost (PWC) of KVIC, JANATA and FRP biogas plants [41].

$$LCC = Initial\ costs + POC + PMC + PRE + PSV \tag{7}$$

where, POC – present worth cost of the operating cost. PMC– present worth cost of the maintenance cost. PRE– present worth cost of the replacement cost. PSV– present worth cost of the salvage value.

Parameter (INR)	Relation
Annual operation cost (AOC)	Energy source cost + running (operation as well as maintenance) cost + depreciation value
Income From Gas (IFG)	Cost of LPG per kg * Equivalent of 1 LPG
Income From Slurry (IFS)	0.3 * Annual dung requirement
Total Income (TI)	IFG + IFS
Annual profit	TI - AOC

Table 8.
 The relations used to calculate selected economic parameters.

Parameters	Value	Reference
Annual O&M cost (INR/year)	2% of CC	[37]
Annual interest rate (%)	12	[42]
NPV (evaluation period in years)	KVIC (15) JANATA (20) FRP (10)	[42–44]
LCC (life span in years)	KVIC (15) JANATA (20) FRP (10)	[42–44]

Table 9.
Economic parameters for the analysis.

Tables 8 and 9 lists the several parameters that are incorporated in the economic analysis.

3. Results and discussion

3.1 Pilot study: influence of non-uniform loading rate

The non-uniform generation of biowaste in an educational institution for 365 days was studied to check the performance in terms of methane content and biogas yield. To understand the different academic schedules the study period has been divided into four phases as mentioned in **Table 10**.

According to academic schedules, the biowaste generation per day during maximum population was found as 70 kg, 280 kg, 120 kg and 80 kg for CD, MRW, RW and VW, and during minimum population it was 70 kg, 120 kg, 60 kg and 20 kg respectively. 10% of each biowaste was taken for the loading throughout a year as shown in **Figure 10**.

The biogas yield was observed for all the biowastes during different phases according to the loading pattern. To study the deviation of this biogas yield from uniform loading, a constant loading was assumed as shown in **Table 11** and the yield was predicted. The methane content obtained for both the uniform and non-uniform loadings of RW, MRW and VW is shown in **Figure 11(a)-(c)**. The figures show that the average methane content for simulation and experimental studies is 52% and 53% for RW, 55.69% and 54.85% for MRW and 52.28% and 53.26% for VW respectively.

3.2 Biogas yield prediction for various categories

The pilot study shows that the theoretical and experimental results are similar as shown in **Figure 12(a)**. Therefore, the current approach could be followed for

Phases	Description	Student population	Days
Phase I	Spring working days	1000–2400	1–150
Phase II	Summer break	200–800	151–225
Phase III	Autumn working days	1000–2400	226–315
Phase IV	Winter break	200–800	316–365

Table 10.
Definition of phases according to academic schedule.

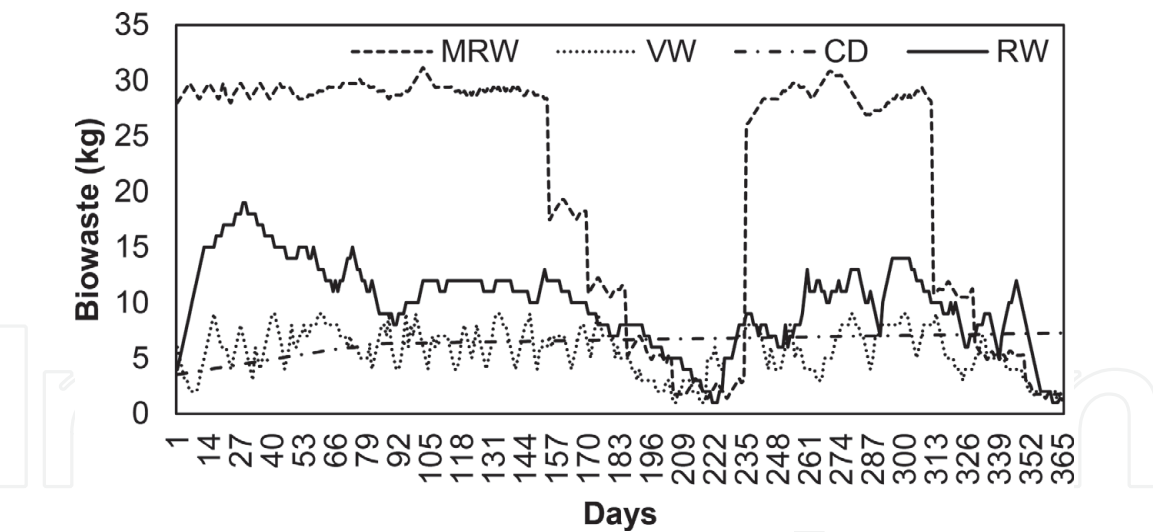


Figure 10.
Loading pattern of biowastes for 365 days.

Biowaste	Biogas yield (m ³)				
	Non-uniform loading				Uniform loading
	Phase I	Phase II	Phase III	Phase IV	Phase (I – IV)
RW	0.16–0.18	0.01–0.05	0.03–0.15	0.01–0.08	0.09
MRW	1.8	0.1	0.8–1.3	0.1–0.3	1.07
VW	0.01–0.18	0.01–0.03	0.04–0.14	0.01–0.09	0.09

Table 11.
Biogas yield during various phases according to academic schedules.

forecasting the biogas yield for different loading rates as shown in **Figure 12(b)**. The yield for each category was determined by academic schedules and biowaste availability.

3.3 Installation and annual operational costs for different biogas plant models

The installation cost and AOC of KVIC, JANATA, and FRP model biogas plants are reviewed for different categories (A to E) as shown in **Figure 13**. The costs of construction, installation, annual service, and other costs are estimated based on the current market price prevailing in the southern part of India.

The Indian government offers subsidies for household digesters regardless of their use. Commercial digesters, on the other hand, are only eligible for subsidies if they are used for power generation. As a result, the subsidy is not considered in this research. The emphasis of the investigation is on the selection of an appropriate biogas plant for non-uniform loading, and its contribution to the reduction of LPG consumption. FRP model has the highest average cost per cubic metre, followed by KVIC and JANATA. The pattern is due to constraints in plant size (12 m³) and the need for more units. The cost of the KVIC model is higher than JANATA model which may be due to the cost of gas holder. The cost of a gas holder in the KVIC model is high since the steel body needs frequent maintenance; besides, its susceptibility to corrosion. The investment cost is high even though the same gas holder is replaced with FRP. However, the cost of installation for KVIC model decreases steadily from category A to category E, whereas the cost of installation for JANATA

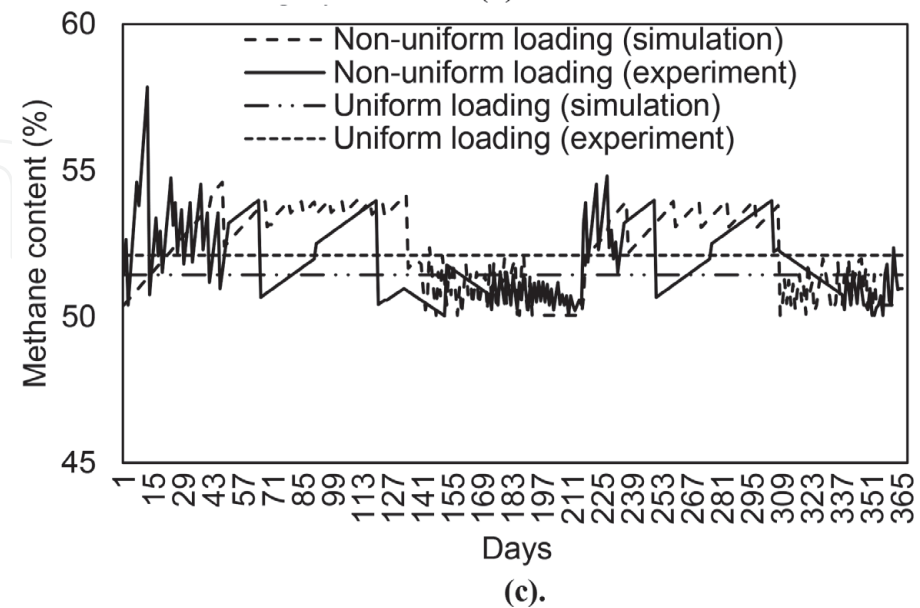
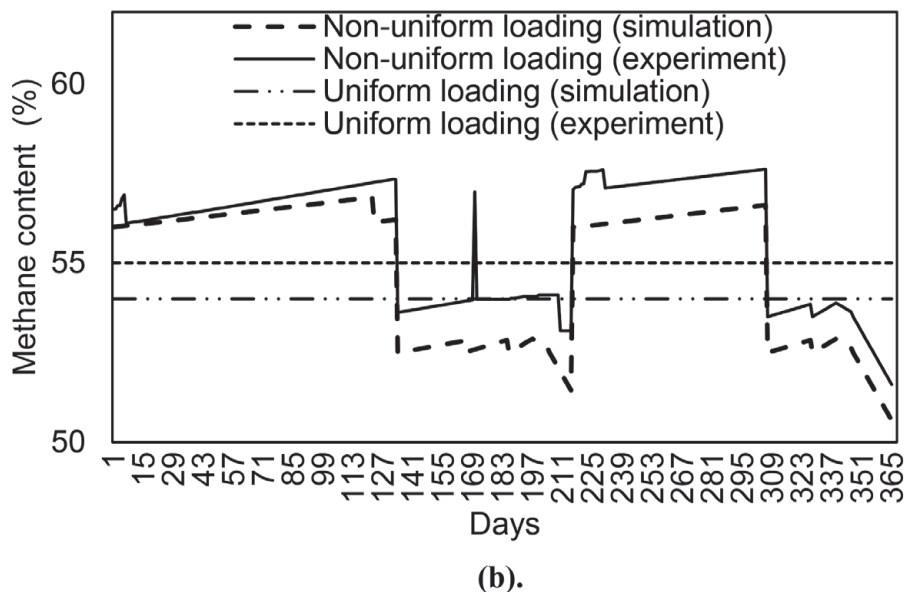
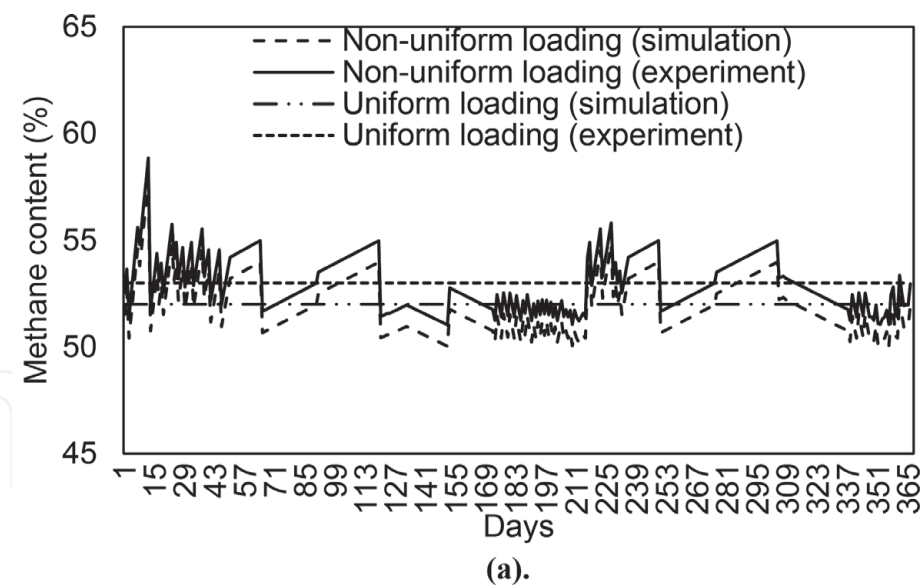


Figure 11.
(a) Methane content in biogas for rice waste. (b) Methane content in biogas for mixed rice waste. (c) Methane content in biogas for vegetable waste.

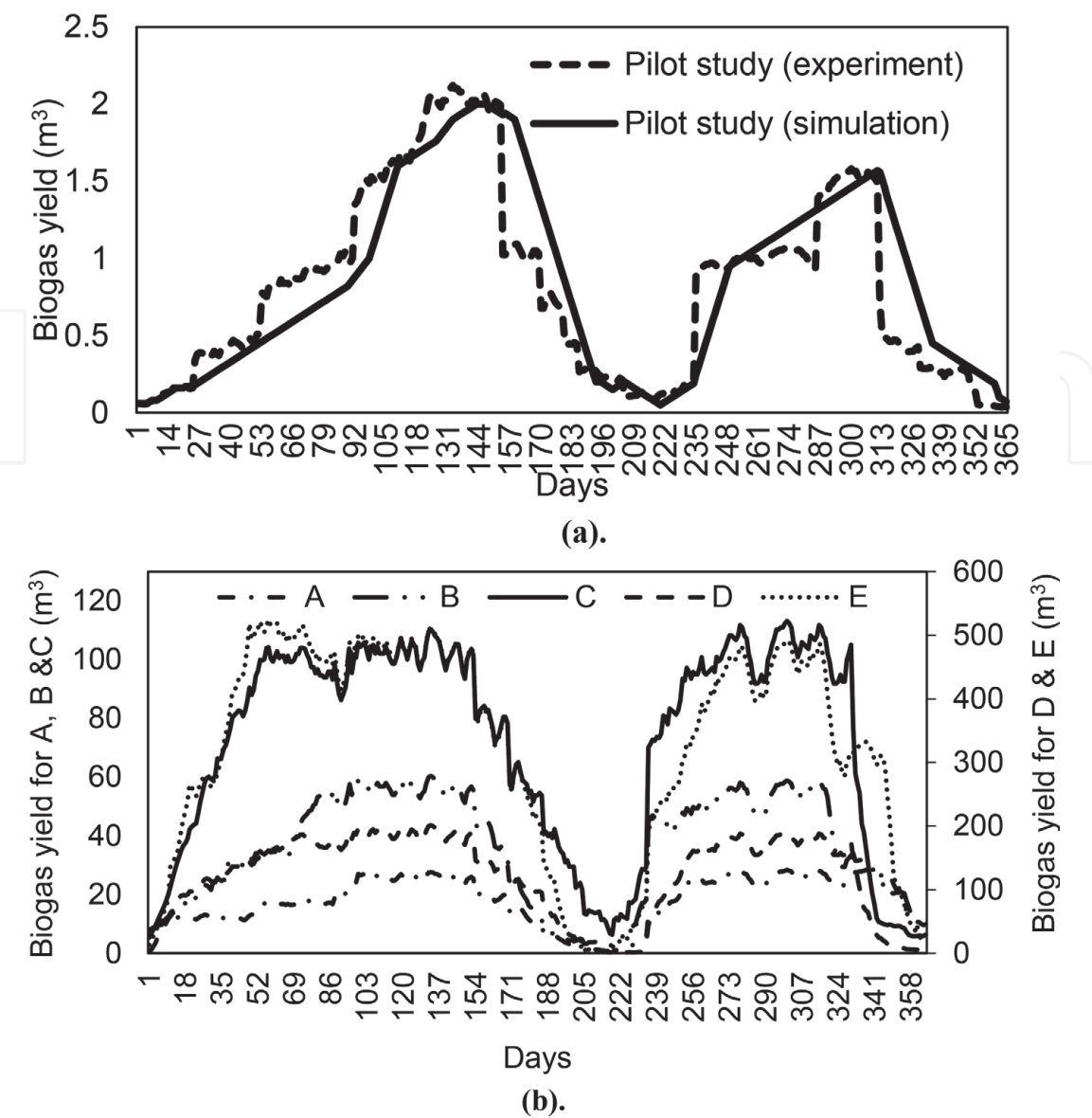


Figure 12.
 (a) Biogas yield of pilot plant for 365 days. (b) 365-day biogas yield for categories A, B, C, D, and E.

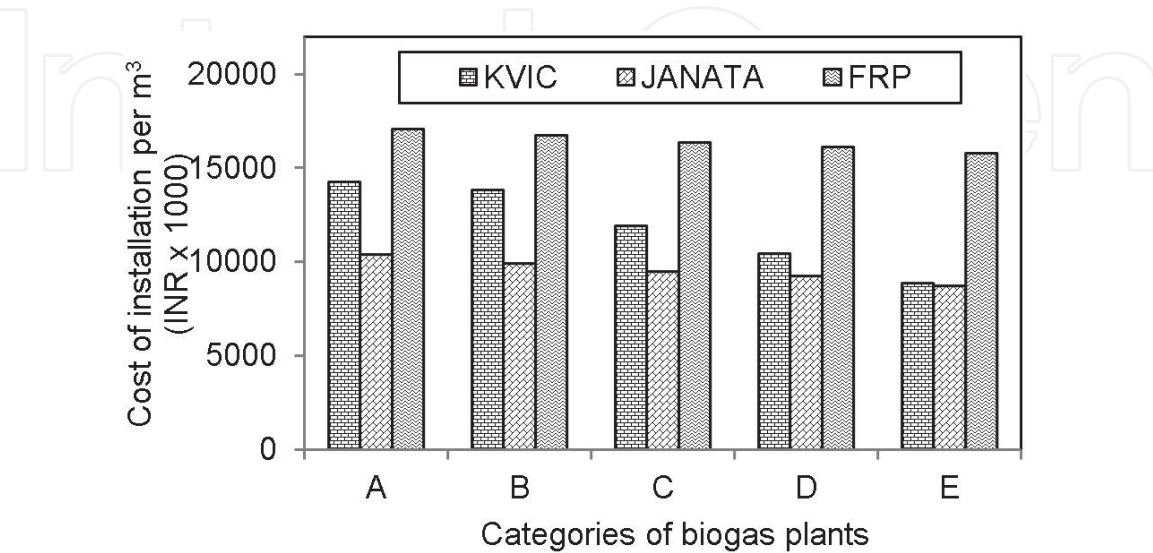


Figure 13.
 Installation cost per cubic metre of various biogas plant models.

model is almost same for both categories. **Figure 14** depicts the annual operating cost per cubic metre capacity of all biogas plants in each segment. The FRP model seems to have the highest operating costs, followed by KVIC and JANATA models. The running cost per cubic metre volume for both groups is almost the same for corresponding types and capacities.

3.4 Payback period

The payback period (PBP) of all digesters in various categories has been investigated and is depicted in **Figure 15**. The study reveals that as the volume of the biogas plant increases, PBP decreases, which is consistent with many research findings [45]. The FRP model demands the largest PBP for all categories ranging from 25 to 450 m³ due to its high construction and operating costs. The KVIC models are well-known for being the most optimal for the production of biogas plants of any size. Though the JANATA style biogas plants are more difficult to build than the other two types, they are very feasible in educational institutions. The payback period for a system with non-uniform loading is 44 to 57 percent

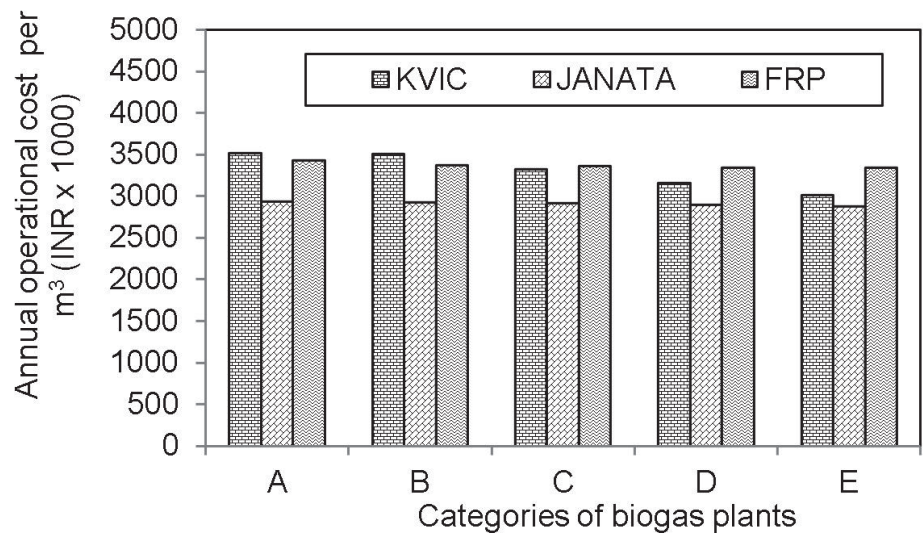


Figure 14.
Annual operational cost per cubic metre of various biogas plant models.

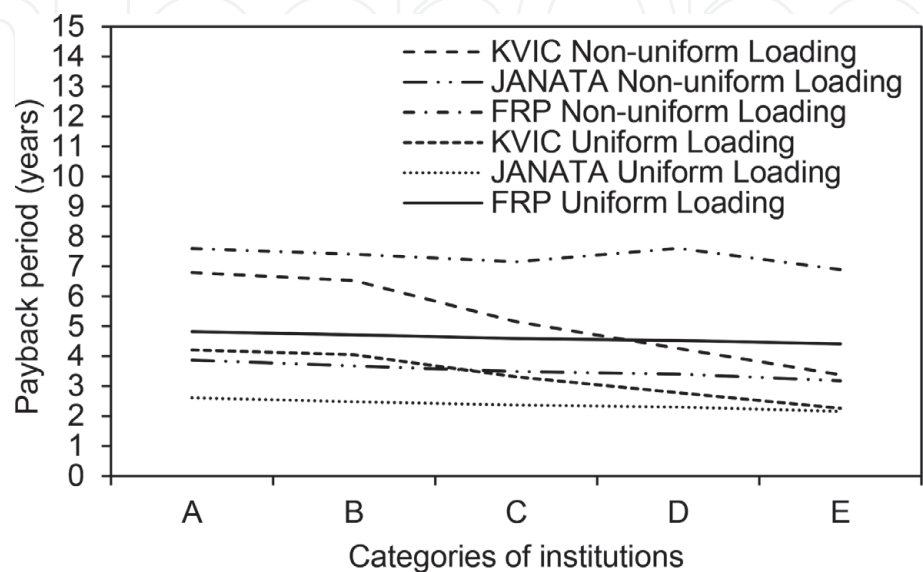


Figure 15.
Payback period for biogas plants for all categories.

longer than for a system that is fully loaded during the year. As a result, if the design and development process is carried out by an expert, the installation of JANATA biogas digester in educational institutions is highly feasible.

3.5 Net present value

The net present value of installing biogas digesters in different types of institutions has been estimated and shown in **Figure 16**.

The NPV of an investment is the difference between the present value of the gains and the present value of the costs arising from the investment. The NPV increases as the scale of the biogas plants increases. The biogas plant project could be preferable for implementation in academic institutions based on NPV selection criteria. The results show that the uniformity in loading produces more useful data than non-uniform loading. However, non-uniform loading rate values indicate that those digesters could be effectively applied in institutions with differing academic schedules.

3.6 Life cycle cost

The most cost-effective solution among competing alternatives that are equally suitable for deployment on technical grounds is determined by a LCC study. As a result, the LCC for uniform and non-uniform loading rates was measured and plotted in **Figure 17**, demonstrating that the LCC of JANATA is the most preferred alternative when compared to the other two versions. However, according to the literature [46], KVIC is recommended because the design and development of larger JANATA model biogas plants is difficult.

3.7 Cost per unit of electricity

The various cost involved in the electricity generation from biowaste available in an educational institution and its equivalent quantity LPG were calculated per year and show in **Figure 18**. The cost of unit electricity was obtained from the following Eq. (8).

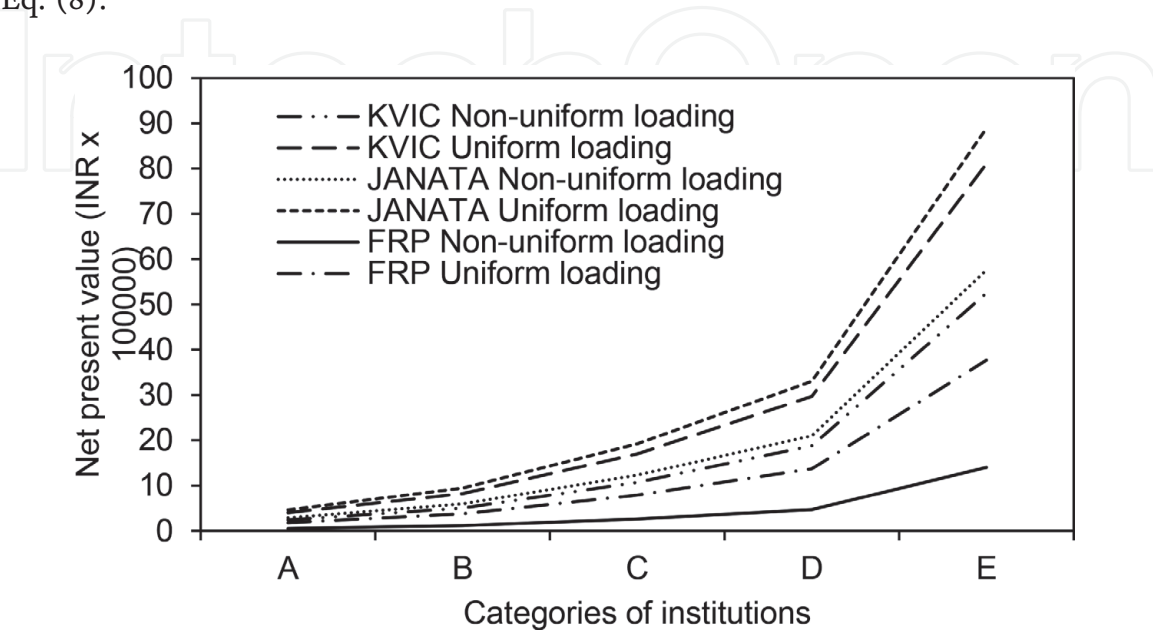


Figure 16.
Net present value of biogas plants for all categories.

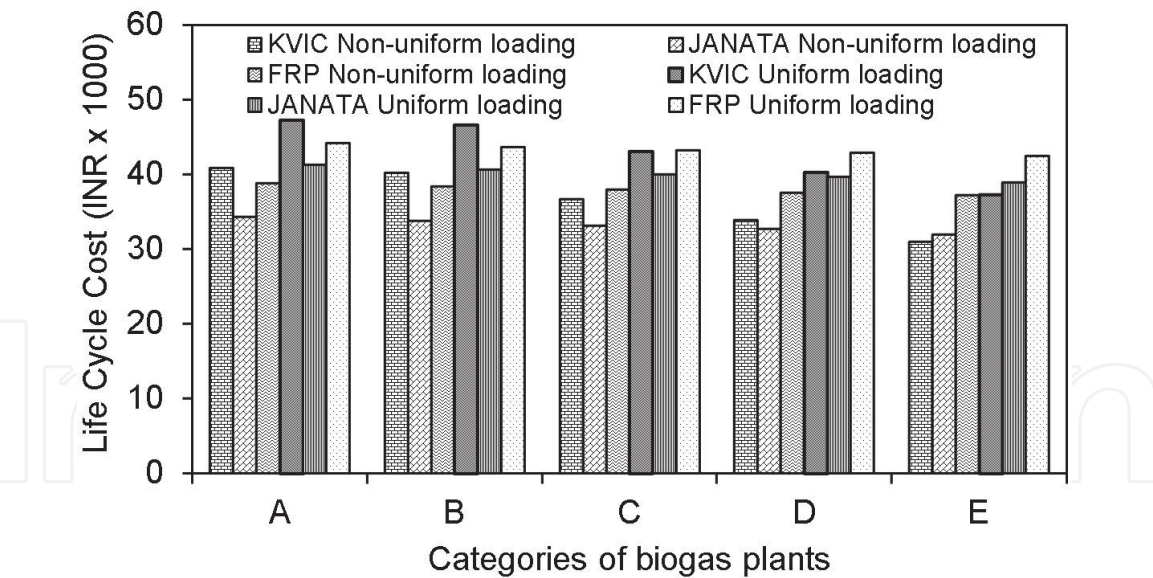


Figure 17. Lifecycle cost for per cubic meter with uniform and non-uniform loading rates.

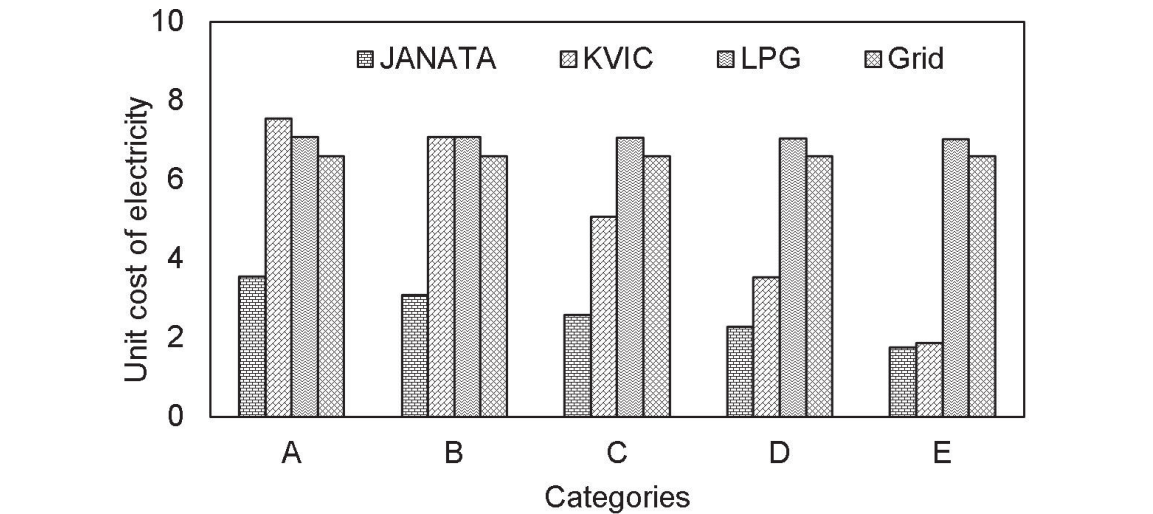


Figure 18. Comparison of unit cost of electricity from biogas, LPG and grid.

$$\text{Unit cost of electricity generated} = \frac{(\text{Investment cost} + \text{maintenance cost}) \text{ per annum}}{\text{Total units generated per annum}} \quad (8)$$

4. Conclusions

The yield of biogas and the efficiency of its production from biowaste of educational institutions, such as rice waste, mixed rice waste, and vegetable waste, were investigated to determine the effect of nonuniform feeding of digesters on the technical and economic viability. As less than 5% of the experimental values were different from the expected content of CH₄ in biogas, the proposed simulation method was found appropriate. Although the biowaste's pH before loading was less than 5, the inoculum's pH was 6.5 to 7.5; thus, the sufficient pH for optimum gas production could be preserved in this method. For all biowastes, the calculated parameters such as total solids, volatile solids and humidity were found within the

best suited range of anaerobic digestion. The biogas produced from all biowastes contained 52 to 58% methane which shows that biowastes generated in educational institution included in this study can be used for all types of applications such as electricity generation, lighting and cooling. The amount of biogas generation was affected by population; however, the content of methane in biogas was not affected. In an educational institution, the amount of biogas generated by person per day was 0.014 m³ to 0.019 m³ all year. The PBP was 50% higher for both models than that of uniform loading. For the installation in category A, B, C and D institutions based on the PBP, JANATA biogas plants is attractive. JANATA and KVIC are suggested for E group of institutions. The optimistic NPV for the three models and the five separate biogas plant capacities indicates the economic viability of all the designs.

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