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Research Article
Design and Performance Analysis of Floating Dome Type Portable Biogas Plant for Domestic Use in Pakistan-manufacturing Cost Optimization

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Abstract

Agriculture continues to play a vital role in Pakistan's economy, it contributes 21% toward the GDP and involves 45% of labor of Pakistan. Livestock is the largest depositor to the agriculture. Therefore, biomass can be used in Pakistan as one of the renewable energy source which can be utilized to create electrical power, provide heating and as a fuel for cooking. Fermentation process of biomass releases biogas which acts as a sustainable energy source. Generally two main types of plants are used worldwide to obtain biogas from biomass which are fixed dome type biogas plants and Floating Dome Biogas Plant (FDBP). Livestock owners in remote areas of Pakistan move themselves according to the climate conditions suitable for their livestock. The issue with these plants is that livestock owners cannot move the biogas plant at another spot easily. Hence, there is a need to develop a portable biogas plant which can be conveniently reinstalled at new place effortlessly. This study described the designing and development of portable biogas plant. The performance of the developed plant and biogas (methane gas) productivity is verified by experiment tests. The manufacturing cost of the FDBP is optimized to make it commercially viable. The developed portable FDBP is favorable for its long life, light in weight and it has ability to produce enough methane gas to suffice the domestic requirements in Pakistan.

Key words: FDBP, livestock, GDP, burner, gas consumption, renewable energy

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Energy is the major limiting factor and accountable for the setback in developing economies. As a consequence of energy deficit, renewable energy is gaining global attention for energy production. As energy demands are sharply rising along with rapid economic development, energy resources availability is one of the major tasks for every country in the world, whilst fossil fuel energy sources are depleting fast due to excessive exploitation and utilization. Hence, exploring new, reliable, renewable and sustainable energy sources has become one of the key quests to tackle the crises of energy shortage, worldwide[1].

In Pakistan energy demand is increasing day by day to fulfill the present and future need of the country[2]. To meet the increased demand of the energy resources, the aim of the engineers in Pakistan should be to develop better energy conversion techniques. Taking the economic aspect of the technology into consideration, the best one will be that which will use materials available locally and in plenty. To keep pace with the development of the world, the rural area must have access to basic energy-related utilities like lighting, cooking and heating. Expenses on these resources can be easily exchanged with a better and efficient source of renewable energy i.e., biomass.

Biomass is a sustainable renewable energy source and is widely available in Pakistan. Its production and applications has additional social and environmental benefits. If correctly managed, biomass is a sustainable source of renewable energy that can result in a significant reduction in net carbon emissions when compared with fossil fuels. The energy conversion efficiency of the conventional fossil fuel technologies can be high but they are quite inefficient in carbon conversion because of high CO_2 emissions[3].

Biogas is a renewable energy source derived from anaerobic digestion of biological wastes. The pre-treatment of waste slurries by producing biogas has become an eco-friendly and a sustainable environmental measure. Due to production of biogas several problems of energy crises and financial systems can be solved. The main benefit of biogas is its immediate storage and can be used easily as an alternative of the natural gas[4]. This study aims at establishing the modular floating dome type Portable Biogas Plant (PBP) for domestic purpose and utilizes this product to produce biogas for cooking and lighting purpose especially for the rural areas of Pakistan.

Related study: It is imperative that alternate and renewable resources for energy must be explored[5]. Among all renewable resources biomass energy, i.e., biogas is unique as its availability is de-centralized[6]. Almost all village households have animals and agro wastes to produce bio-energy. Biomass bonds almost 15% energy consumptions worldwide subsequently sharing 38% in developing countries[7]. In Pakistan, a household consuming biomass as sole energy source uses 2325 kg of firewood or 1480 kg of dung or 1160 kg of crop residues per annum approximately[8]. The livestock available in Pakistan which can be utilized for biogas production is shown in Fig. 1.

Biogas industry is well developed in China and India. In China alone there were about 6.8 million household digesters and 1000 medium and big size digesters till 2007 with an estimated production of 2 million cubic meter, producing 5% of total gas energy in China[9]. In Tibet, Residential Biogas Model (RBM) was introduced to harvest the potential of cattle wastes and it has impacted positively on socio-economic conditions of the area[10]. Individual attempts were made to develop biogas units in Pakistan, first ever documented biogas plant running with farmyard manure was built in 1959 in Sindh[11]. Domestic biogas plants gained Pakistani government's attention as alternate energy source[7] in 1974. Pakistan Council for Appropriate Technology (PCAT) developed 21 biogas plants based on fixed dome Chinese type technology. These plants failed to perform due to gas leakage from hair line cracks in their structure. Later on Indian design was followed and 10 demo units were installed in Azad Jammu and Kashmir (AJK)[7]. These units worked well, hence; were adopted for mass propagation[12]. Meanwhile, Directorate General of New and Renewable Energy Resources (DGNRER) launched a project to establish 4000 biogas plants by 1986. This three tier program included 100 demonstration units sponsored by government, 2nd phase was on 50% subsidy and in 3rd phase subsidy ended with a continuing technical support to the willing people[13]. Biogas Support Program (BSP) was started in 2000 with the support of government of Pakistan to install 1200 household biogas units, the program has achieved its initial mandate and it is expected to install another 10,000 biogas plants in coming 5 years, it is expected to achieve 27% of total biogas potential of Pakistan[14]. Presently Pakistan Dairy Development Company (PDDC) has undertaken biogas units' installation in its horizon-3 initiative with an aim to provide alternate renewable energy at very low cost to rural groups[15]. Up to 13 May, 2009 almost 450 biogas plants were installed. However, due to overwhelming response this number jumped to 556 implementations soon after[16] July, 2009.

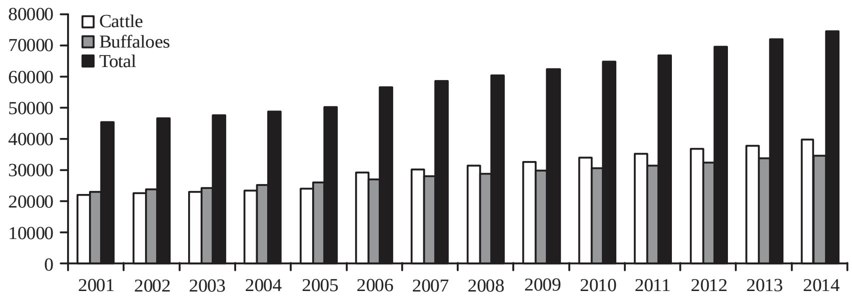

Fig. 1: Estimated live stock population, Pakistan statistical year book 2014

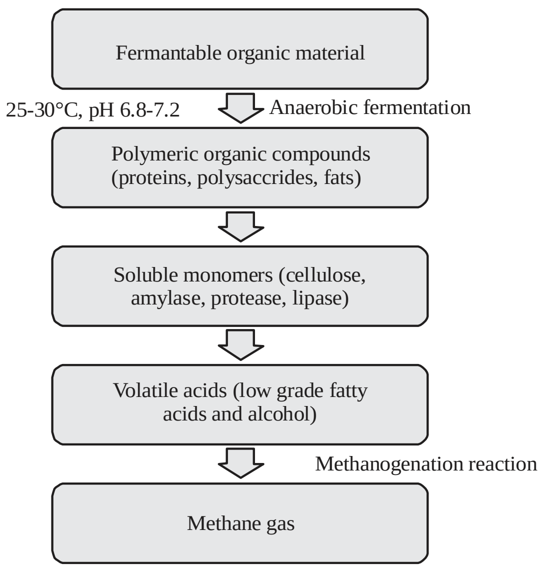

Fig. 2: Flowchart of bio-gasification process

Biogas plants can be classified based on the method of construction. Two main types of plants are used worldwide to obtain biogas from biomass which is fixed dome type biogas plant and floating dome biogas plant. It is a composite unit of a digester and a gas holder which floats on the top of the digester wherein gas is collected and delivered at a constant pressure to the gas appliances through the pipeline. Mostly, design of the brick/block masonry digest with a floating gas holder has been adopted for dissemination in the rural area. Livestock owners in remote areas of Pakistan relocate themselves as per the weather conditions suitable for their livestock. However, these biogas plans cannot easily relocate at a new place. Therefore, there is a need to develop a portable biogas plan which can be reinstalled at new place easily.

Theory: The bio-gasification method is used to produce the biogas and manure which is comprised of the steps as described in Fig. 2. First the fermentable organic material goes to anaerobic fermentation process where facultative microorganism activates at a temperature between 20-35°C and pH range 6.8-7.2. This is converted into polymeric organic compounds which comprises of proteins, polysaccharides and fats. These polymeric organic compounds are further converted into soluble monomers by extracellular enzymes of microorganism in thirds step. Then soluble monomers converted into micro molecular compounds that are volatile acids. Finally the methane gas start producing due to the reaction between volatile acids and bacteria.

MATERIALS AND METHODS

The floating dome type portable biogas plant is designed to have daily production capacity between 1.2-1.5 cubic meter of biogas. It is achieved through conversion of cattle dung obtained from two buffaloes/cows (fermentable organic matter) into combustible biogas and fully mature organic manure as byproduct.

Biogas plant design and development: The required product is designed in such a way that it fulfills the criteria of portability, durability and performance reliability. The light weight polypropylene tanks are chosen to fabricate biogas plant to keep it portable and durable. The floating dome type is chosen to keep the constant pressure for the burning of biogas at the stove. The complete assembled product has a cow dung holder (2400 L tank) fitted with an inlet pipe to fill slurry of cow dung and water from the base of the cow dung holder. The top surface of dung in the cow dung holder is enclosed by biogas holder. The biogas holder is placed in cow dung holder in such a way that it has spherical space to slide up and down. When biogas produced it store into the biogas holder. During production of biogas, the biogas holder rises vertically upward and its vertical limit is retained so as to avoid its toppling over once biogas is completely filled. A stopper has been placed outside the biogas holder, which is stopped by three pipes sliding in three slots fabricated at the outer side

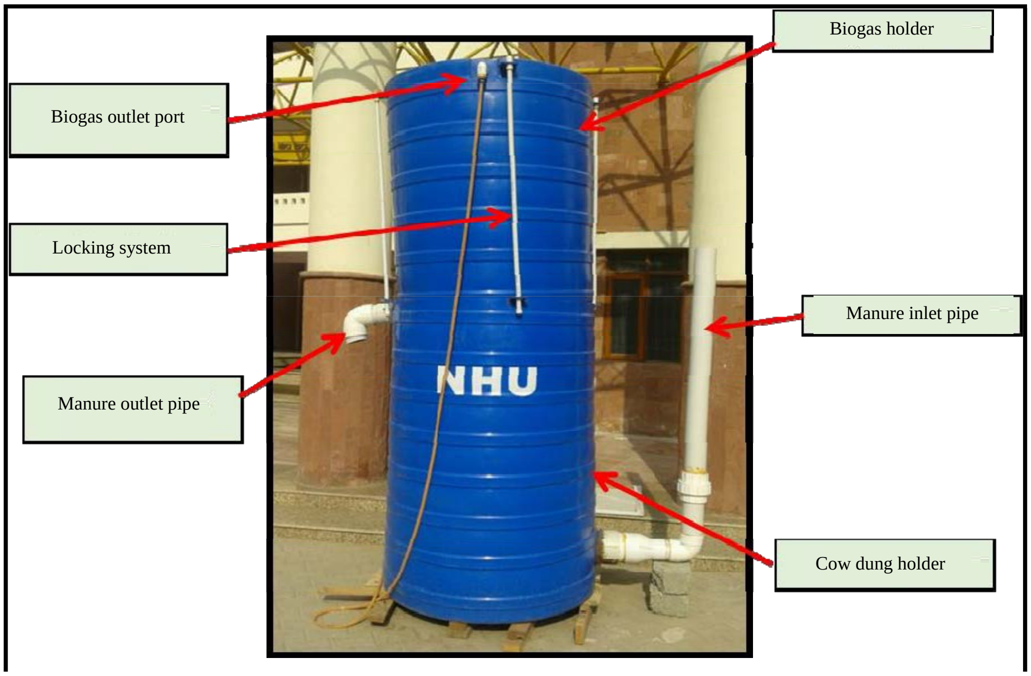

Fig. 3: Assembled portable biogas plant located at national university of science and technology, Karachi, Pakistan

Table 1: Weight of developed portable biogas plant

Components	Material	Weight (kg)
Digester tank	Polypropylene	40
Biogas holder tank	Polypropylene	35
Fittings and other accessories	PVC	10
Total weight (without cow-dung)		85

Table 2: Decision Variables (DV)

DV	Description	Units
x_1	Amount of biogas daily production	m^3 day^{-1}
x_2	Amount spend on cow-dung holder tank	US\$ L^{-1}
x_3	Amount spend on gas-holder tank	US\$ L^{-1}
x_4	Amount spend on pipe fitting	US\$ set^{-1}
x_5	Amount spend on product fabrication	US\$ product^{-1}
x_6	Amount spend on daily feed of cow dung	US\$ kg^{-1}
x_7	Daily maintenance and labor cost	US\$ day^{-1}

of cow dung holder. The weight of developed portable biogas plant is described in Table 1. The final developed product of portable biogas plant is shown in Fig. 3.

Design parameters: One buffalo excrete about 20-22 kg manure day^{-1}. On average two buffalos will excrete about 40 kg manure day^{-1} that is equivalent to 1.48 m^3 (37 m^3 biogas produced from 1000 kg biomass i.e., 0.037 m^3 kg^{-1}). Cow dung holder of 2.4 m^3 (84.75 ft^3) capacity is required and it is fabricated to the final size of 1.143 m (45 inch) diameter and height of 1.68 m (66 inch). Biogas holder of 2 m^3 (70.63 ft^3) capacity is required and it is fabricated to the final size of 1.067 m (42 inches) diameter and height of 1.524 m (60 inches). The cow dung holder was filled with 1000 kg of cow dung and 1000 kg L^{-1} of water. The ratio of dung and water used for this product is 1:1 i.e., 40 kg of each dung and water. Total input per day become 80 kg. Then, total input for 30 days will become 2400 kg (30 days$\times$80 kg = 2400 kg approx per month).

The produced biogas sample is collected and tested at PERAC Research and Development Foundation (PRD) Laboratory. The mole percentage composition of biogas obtained through this experimental setup is as shown in Fig. 4.

Manufacturing cost optimization: The resources available for this project are optimized considering the annual saving by consumer, production cost of the product and annual maintenance cost. Linear programming is considered to simplify the approach toward optimization. This budget optimization is done to know that how much amount of the finance may be consumed on components so that annual profit from the product will be maximized. The decision variables are given in Table 2.

The objective function is formulated to minimize the manufacturing cost of the product to be paid by the consumer. The objective function is given below minimize:

$$Z = Ax_1\text{-}Bx_2\text{-}Cx_3\text{-}x_4\text{-}x_5\text{-}x_6\text{-}x_7 \quad (1)$$

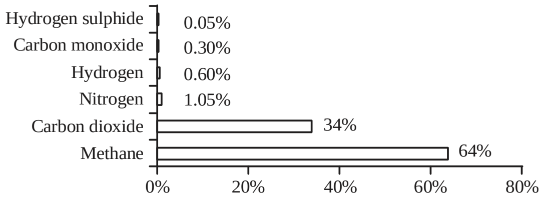

Fig. 4: Mole percentage composition of biogas obtained through given experimental setup

Where:

$$A = \frac{365\text{ day}}{\text{Year}} \times 0.7\frac{\text{kg}}{\text{m}^3} \times 54000\frac{\text{kJ}}{\text{kg}} \times \frac{4\text{ sec}}{1054800\text{ kJ}} = 52$$

B = 2400 L of digestion tank

C = 2000 L of biogas holder tank

Subjected to following constraints:

- The manufacturing cost of product should be less to make it affordable and commercially viable:

$$Bx_2+Cx_3+x_4+x_5 \leq 1000 \quad (2)$$

- The minimum amount saved yearly by the consumer through biogas production:

$$Ax_1 \geq D\ (\$\ \text{year}^{-1}) \quad (3)$$

Where:

$$D = 1.2\frac{\text{m}^2}{\text{Day}}\frac{365\text{ day}}{\text{Year}} \times 0.7\frac{\text{kg}}{\text{m}^3} \times 54000\frac{\text{kJ}}{\text{kg}} \times \frac{4\text{ sec}}{1054800\text{ kJ}} = 63$$

- The constraint related to daily feed of the cow-dung:

$$Ex_1 \leq F\ (\text{kg day}^{-1}) \quad (4)$$

Where:

$$E = \frac{1\text{ kg}}{0.037\text{ m}^3} = 27\text{ kg m}^{-3}$$

F = 40 kg day^{-1} is the daily feed of the cowdung into the product

- Capacity constraint for purchasing of digester tank:

$$6x_2+7x_3 \leq B+C\ (\text{L}) \quad (5)$$

- Financial constraint for purchasing of pipe fitting:

$$x_4 \leq 50\ (\$\ \text{set}^{-1}) \quad (6)$$

Table 3: Results of optimization

DV	Optimized values for product budget	Values
x_1	Amount of biogas daily production	1.21 m^3 day^{-1}
x_2	Amount spend on cow-dung holder tank	0.1690 US$ L^{-1}
x_3	Amount spend on gas-holder tank	0.2740 US$ L^{-1}
x_4	Amount spend on pipe fitting	25.72 US$ set^{-1}
x_5	Amount spend on product fabrication	20.81 US$ $product^{-1}$
x_6	Amount spend on daily feed of cow dung	0 US$ kg^{-1}
x_7	Daily maintenance and labor cost	2 US$ day^{-1}
	Optimized value of objective function	939 US$

- Financial constraint for product fabrication:

$$x_5 \leq 40\ (\$\ \text{product}^{-1}) \quad (7)$$

- Expenses on the daily feed, maintenance and labour should be limited:

$$365 \times (Fx_6+x_7) \leq 370\ (\$\ \text{year}^{-1}) \quad (8)$$

These equations are interpreted in terms of MATLAB program and MATLAB coding is given.

The manufacturing cost of the portable biogas plant will be optimized using the budget given in the Table 3. The plant will be installed at place having atleast dung of two cows. The daily maintenance and operational requirement of plant may be catered by hiring a person with monthly salary of 60$ which is good amount in Pakistan for part-time job of just 2 h.

RESULTS AND DISCUSSION

The developed portable biogas system is tested for compression, stability and punctures. The developed product qualified all these tests as no leakage was found. During test 100 kg load were placed on top of the biogas holder for 2 days and there is no leakage of gas occurred from the biogas holder tank. The system was further tested for stability by putting 180 kg weight over the top of biogas holder and found to be very stable.

Besides that, biogas productivity is also tested through biogas productivity tests. For experimental testing purpose, cole-parmer digital pressure gauge (P-1PSIG-D) is installed at outlet pipe of the developed portable biogas system and readings are taken for 10 weeks. The measuring range of the installed pressure gauge is 0-30 inch of water column. The GMT series flow-meter (Range: 0.5-5.0 m^3 h^{-1}) is also installed to measure biogas production flow-rate and its consumption at the stove and lamp. The experimental test setup is shown in Fig. 3. These results are accumulated for 10 weeks and these are checked through pressure gauges, flow meter, conventional gas stoves and gas lamps, which are shown in Fig. 5-7.

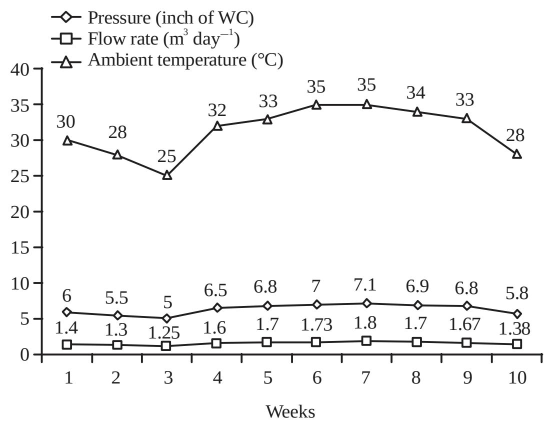

Fig. 5: Biogas pressure and flow rate measured for 10 weeks

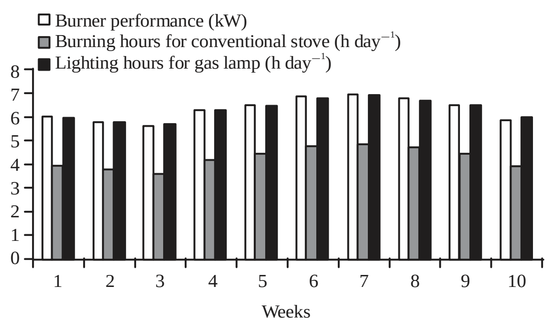

Fig. 6: Gas consumption for gas lamp and biogas consumption for stove measured for 10 weeks

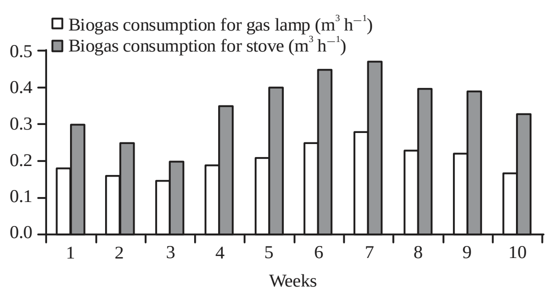

Fig. 7: Burner performance, burning hours for stove and lighting hours for gas lamps are measured for 10 weeks

It is evident through the result mentioned in Fig. 6, one of the factors effecting biogas production is the ambient temperature condition. It is observed that during third week ambient temperature drop to 25°C and therefore biogas production reduces. The bio-gasification reaction is dependent on the ambient condition, in order to maintain its daily production, slurry water intake should be heated up to 40°C. This practice will be helpful to get uniform biogas production during winter season. The burner performance is directly proportional to the production of biogas. It is reduced in 3rd week and 10th week as shown in Fig. 7.

The biogas consumption is directly proportional to biogas production and it is evident through results summarized in Fig. 7.

CONCLUSION

Biogas technology offer unique set of benefits, it is sustainable source of energy, benefiting the environment and provides a way to treat and reuse various landfill wastes. The portable biogas plant design presented in this paper is tested and experimental results proved that this portable floating doom type biogas plant is beneficial for its long life, light in weight. It has capacity to sufficiently produce biogas to suffice the requirements of public living in rural areas which do not have access to electricity and natural gas resources but they have livestock. The result of optimization studies encourage us to go for manufacturing of this product at mass scale level as commercial product.

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