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Review

Household Biogas Digesters—A Review

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Abstract: This review is a summary of different aspects of the design and operation of small-scale, household, biogas digesters. It covers different digester designs and materials used for construction, important operating parameters such as pH, temperature, substrate, and loading rate, applications of the biogas, the government policies concerning the use of household digesters, and the social and environmental effects of the digesters. Biogas is a value-added product of anaerobic digestion of organic compounds. Biogas production depends on different factors including: pH, temperature, substrate, loading rate, hydraulic retention time (HRT), C/N ratio, and mixing. Household digesters are cheap, easy to handle, and reduce the amount of organic household waste. The size of these digesters varies between 1 and 150 m^3. The common designs include fixed dome, floating drum, and plug flow type. Biogas and fertilizer obtained at the end of anaerobic digestion could be used for cooking, lighting, and electricity.

Keywords: biogas; household digesters; bioenergy; waste management; fixed dome digesters; floating drum digesters; plug flow digesters

1. Introduction

Due to the increasing prices of fossil fuels and taxes on energy sources, finding alternative, clean and economical sources of energy has nowadays become a major concern for households' and nations' economies. In addition, economic prosperity and quality of life, which are linked in most countries to *per-capita* energy consumption, is a great determinant and indicator of economical development [1–4].

Energy demand is a critical reason for extensive climate change, resource exploitation, and also restricts the living standards of humans [5,6].

By the time fuel and fertilizer reaches rural areas, the end price is relatively expensive due to high transport costs, leaving people to find alternative resources other than oil [7]. Starke [8] reported wood as the traditional source of fuel to produce energy for domestic purposes for 2.5 billion people in Asia. Many of the rural communities in developing countries are forced to rely on the traditional energy sources such as firewood, dung, crop residues, and paraffin. These traditional methods are often expensive and/or time-consuming [9–11]. Cooking accounts for 90% of energy consumption in the households of developing countries [12]. Furthermore, access to electricity in rural areas is relatively scarce [13].

Biogas is a substitute for firewood and cattle dung that can meet the energy needs of the rural population [14,15]. Biogas is a renewable source of energy that can be used as a substitute for natural gas or liquefied petroleum gas [16]. There are different models to assess the energy content of different energy sources, which includes water boiling test, controlled cooking test and kitchen performance test [17]. The energy content of 1.0 m^3 of purified biogas is equal to 1.1 L of gasoline, 1.7 L of bioethanol, or 0.97 m^3 of natural gas [16]. The application for rural and urban waste biogas production is widely spread. It is a challenge for engineers and scientists to build an efficient domestic digesters with the materials available, at the same time taking the local and economical considerations into the account. Although many digesters have been built, additional research and awareness are needed to meet the changing needs and conditions [18].

Biogas production can be carried out in very small reactors ranging from 100-mL serum bottles in the lab up to 10,000 m^3 large digesters as normally used, for example, in Europe. This review deals with a summary of different household biogas digesters, their operating parameters, cost and materials used to build them, startup, and maintenance, the variety of applications employed, and associated social and environmental effects.

1.1. Biogas

Biogas, the metabolic product of anaerobic digestion, is a mixture of methane and carbon dioxide with small quantities of other gases such as hydrogen sulfide [19,20]. Methane, the desired component of biogas, is a colorless, blue burning gas used for cooking, heating, and lighting [21]. Biogas is a clean, efficient, and renewable source of energy, which can be used as a substitute for other fuels in order to save energy in rural areas [22]. In anaerobic digestion, organic materials are degraded by bacteria, in the absence of oxygen, converting it into a methane and carbon dioxide mixture. The digestate or slurry from the digester is rich in ammonium and other nutrients used as an organic fertilizer [11,23–27].

Methane formation in anaerobic digestion involves four different steps, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Different bacterial/archaea communities work in a syntrophic relationship with each other to form methane. In hydrolysis, complex carbohydrates, fats, and proteins are first hydrolyzed to their monomeric forms by exoenzymes and bacterial cellulosome. In the second phase (acidogenesis), monomers are further degraded into short-chain acids such as: acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, caprionic acid, alcohols, hydrogen, and carbon dioxide. During acetogenesis, these short-chain acids are converted into acetate, hydrogen, and carbon dioxide. In the last phase, methanogens convert the intermediates produced into methane and carbon dioxide. Almost one-third of methane formation is due to reduction of carbon dioxide by hydrogen [28].

1.2. Digestion Factors

Anaerobic digestion depends on several different parameters for an optimum performance. Different groups of microorganisms are involved in the methane production, and suitable conditions have to be established to keep all the microorganisms in balance. Some of these parameters are: pH, temperature, mixing, substrate, C/N ratio, and hydraulic retention time (HRT). Digestion is a slow process and it takes at a minimum of three weeks for the microorganisms to adapt to a new condition when there is a change in substrate or temperature [28].

A symbiotic relationship is necessary between the hydrogen-producing acetogenic microorganisms and the hydrogen-consuming methanogens. Furthermore, a neutral pH is favorable for biogas production, since most of the methanogens grow at the pH range of 6.7–7.5. Temperature is also an important factor in the biogas production. Most of the acid forming microorganisms grows under mesophilic conditions; however, for methanogens, a higher temperature is favorable [28]. Mixing is also an essential parameter for biogas production. Too much mixing stresses the microorganisms and without mixing foaming occurs. Methane-forming microorganisms grow slowly, with a doubling time of around 5–16 days. Therefore, the hydraulic retention time should be at least 10–15 days, unless these bacteria are retained by, for example, entrapment. Substrate and the balance of carbon sources with other nutrients such as nitrogen, phosphorus, and sulfur is also important. The substrate should be slowly digested, otherwise easily degradable substrates may cause a sudden increase in acid content. The carbon and nitrogen ratio should be around 16:1–25:1. Too much increase or decrease in the carbon/nitrogen ratio affects biogas production. The concentration of solids in the digester should vary between 7% and 9%. Particle size is not an important factor compared to other parameters such as pH and temperature. However, the size of the particles used affects the degradation and ultimately the biogas production rate [28–30].

1.3. A Brief Global View on Small Anaerobic Digesters

Unlike other renewable fuels such as biodiesel and bioethanol, biogas production is relatively simple and can operate under any conditions and is not monopolistic [31,32]. Dung is a potential substrate for biogas production, seen only as a floor polish and fertilizer in the garden for hundreds of years. Biogas for rural energy is sustainable, affordable, and has no negative effect on people's health or the environment, if handled properly [33,34]. Complicated construction, difficult operation of the systems, high investment, and maintenance costs have pushed farmers to adopt cheaper and simpler anaerobic systems [35].

There are currently more than 30 million household digesters in China, followed by India with 3.8 million, 0.2 million in Nepal, and 60,000 in Bangladesh [36–38]. China has increased its investments in biogas infrastructure very rapidly. By 2020, 80 million households in China are expected to have biogas digesters serving 300 million people [39]. India is implementing one of the world's largest renewable-energy programs with different scales of technologies. One of the strategies is to promote biogas plants [40,41]. India began the project half a century ago, and was further supported by the National Project on Biogas Development in 1982. Similar trends were more or less observed in other Asian countries. For instance, SNV, a Non Governmental Organization (NGO) from The Netherlands has installed 23,300 plants in Vietnam [42].

In America, 162 farm scale plants were in operation by 2010, providing energy for 41,000 homes; in addition, 17 plants were operating in Canada. The number of farm scale digesters in Europe has increased drastically. At the end of 2011, the number of these digesters was more than 4000 in Germany, 350 in Austria, 72 in Switzerland, 65 in the United Kingdom followed by Denmark with 20 community type and 35 farm scale plants, and Sweden had 12 plants [43–46].

The level of biogas technology for household purposes is very low in many African countries [47]. Kenya has 1884 household biogas plants and Ethiopia has more than 1140 plants [48]. Small-scale biogas plants are located throughout Africa, but only a few are working. Poor technical quality of construction and material used, inexperienced contractors, insufficient knowledge on the system in practice as well as in research institutes and universities are some of the reasons responsible for the failure [49]. Although the potential need is very high in Africa, the technology is at embryonic stage with the countries struggling to meet their energy demands [2,49,50].

2. Household Digesters

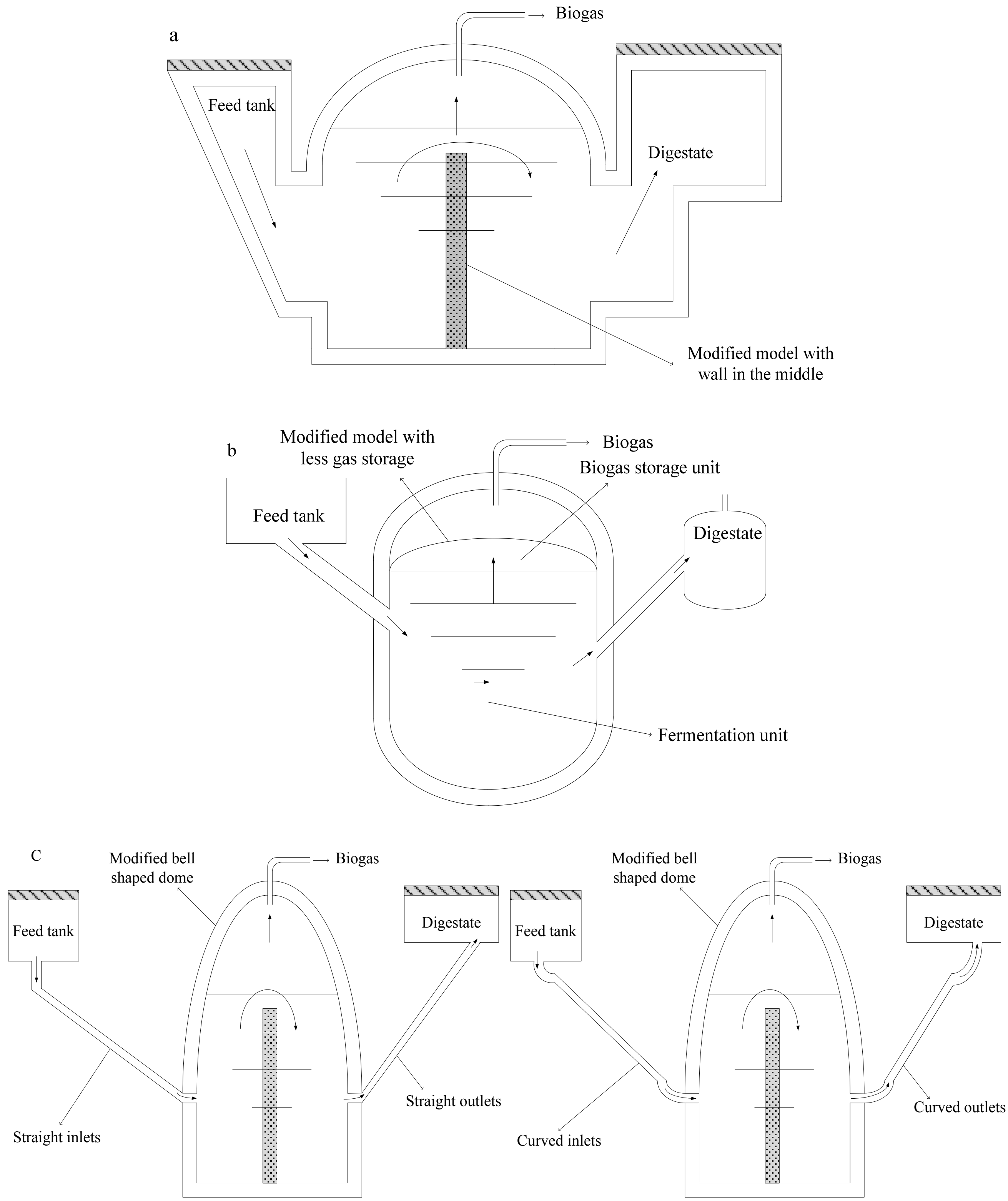
It is always difficult to adopt one particular type of digester for household purposes. Design of the digesters is varied based on the geographical location, availability of substrate, and climatic conditions. For instance, a digester used in mountainous regions is designed to have less gas volume in order to avoid gas loss. For tropical countries, it is preferred to have digesters underground due to the geothermal energy [51]. Out of all the different digesters developed, the fixed dome model developed by China and the floating drum model developed by India have continued to perform until today [52]. Recently, plug flow digesters are gaining attention due to its portability and easy operation.

2.1. Fixed Dome Digesters

The fixed dome digesters (Figure 1) also called "Chinese" or "hydraulic" digesters are the most common model developed and used mainly in China for biogas production [27]. The digester is filled through the inlet pipe until the level reaches the bottom level of the expansion chamber. The produced biogas is accumulated at the upper part of the digester called storage part. The difference in the level between slurry inside of the digester and the expansion chamber creates a gas pressure. The collected gas requires space and presses a part of the substrate into an expansion chamber. The slurry flows back into the digester immediately after gas is released [53].

Fixed dome digesters are usually built underground [27]. The size of the digester depends on the location, number of households, and the amount of substrate available every day. For instance, the size of these digesters can typically vary between 4 and 20 m^3 in Nepal [54], between 6 and 10 m^3 in China [55], between 1 and 150 m^3 in India [56] and in Nigeria it is around 6 m^3 for a family of 9 [57]. Instead of having a digester for each individual home, a large volume digester is used to produce biogas for 10–20 homes, and is called community type biogas digesters. In countries where houses are clustered as in Nigeria, these types of biogas digesters are more feasible [58].

Figure 1. Schematic sketch of (**a**) a janta model fixed dome digester and its modifications, (**b**) a deenbandhu model fixed dome digester and its modifications, and (**c**) a modified fixed dome digester with straight and curved inlet and outlet tube.



Fixed dome models developed in India include the *janta* and *deenbandhu* models. The janta model was introduced in 1978 (Figure 1a). It consists of a shallow well with a dome roof on top. The inlet and outlet were kept above the dome with the gas pipe fitted on top of the dome. The disadvantages of the *janta* model includes short circulating path of the slurry, escape of undigested slurry at the top and less volume of gas produced due to the increased gas pressure [59]. Action for Food Production (AFPRO) launched a modified *janta* model called the *deenbandhu* model in 1984 (Figure 1b). It consists of two spheres of different diameters. The lower sphere acts as a fermentation unit, while the upper one is the storage unit. This model was developed to reduce the price without decreasing the efficiency of the process [1].

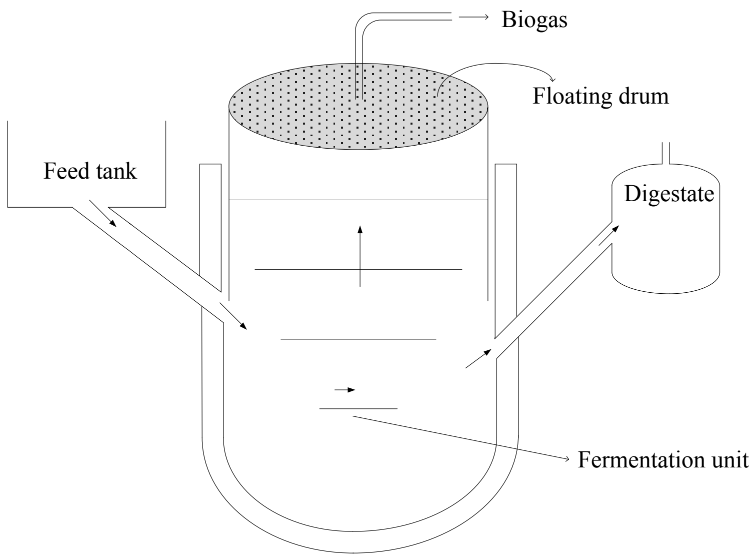
Many countries have modified the basic shape of the fixed dome model. For instance, the Chinese digester was modified into a hemispherical shape with a wall in the middle as shown in Figure 1a [60,61], and the *deenbandhu* model was modified with a smaller gas holding capacity and reducing the diameter of the arch (Figure 1b) [62]. In mountainous regions, loss of biogas during the winter months is less in the modified model than the *deenbandhu* model. Jash and Basu [63] modified the dome with a vertical cylinder and a gas holder in a bell shape. The cylindrical vessel was partitioned into two using bricks. Since the inlet and outlet tubes were long and straight, some of the heavy particles got stuck, resulting in a modification with a bent inlet and outlet tube (Figure 1c). Fixed dome digesters were surrounded by a steel drum containing biomass to avoid the loss in temperature, which is also called French type digesters [64]. Another modification is to cover the gas storage part of the fixed dome digester with an expanding plastic bag. A wood roof is placed on top of the cover in order to protect the fragile plastic bag against the sunlight and at the same time increase the gas pressure by its weight [53].

2.2. Floating Drum Digesters

Khadi and Village Industries Commission (KVIC) is the name of a floating drum digester model developed in 1962 (Figure 2). Even though the model is pretty old, it is one of the most widely accepted and used designs for household purposes in India. The design includes a movable inverted drum placed on a well-shaped digester. An inverted steel drum that acts as a storage tank is placed on the digester, which can move up and down depending on the amount of accumulated gas at the top of the digester. The weight of this inverted drum applies the pressure needed for the gas flow through the pipeline for use [1].

Floating drum digesters produce biogas at a constant pressure with variable volume [33]. From the position of the drum, the amount of biogas accumulated under the drum is easily detectable. However, the floating drum needs to be coated with paint in a constant interval to avoid rust. Additionally, fibrous materials will block the movement of digester. Hence, their accumulation should be avoided if possible [65]. In Thailand, the floating dome has been modified with two cement jars on either side of the floating drum. The average size of these kinds of digesters is around 1.2 m^3 [66]. For a small-medium size farms the size varies from around 5–15 m^3 [65]. Singh and Gupta [67] compared 14 different biogas plants with a floating drum model. The size of each digester was about 85 m^3. The ratio of the waste fed to the plant in one day to the capacity of the plant is called plant utilization factor (PUF), and it was found to be 0.36. This result suggests that the full capacity of the plant was not utilized.

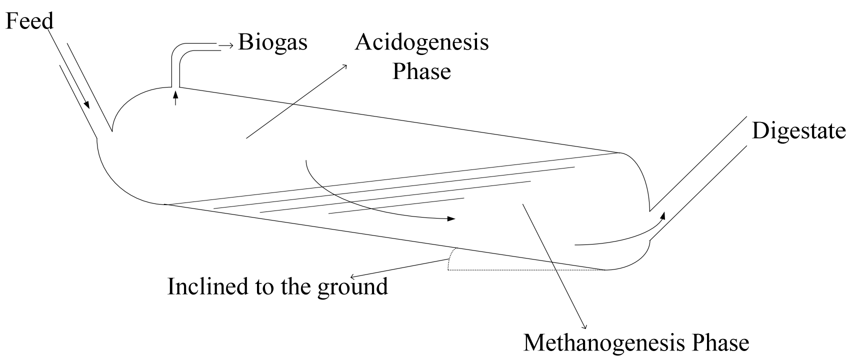
Figure 2. Schematic sketch of a floating drum digester.



2.3. Plug Flow Digesters

The disadvantage with the fixed dome and floating drum models is, once installed they are difficult to move. Hence, portable models built over the ground called tubular or plug flow digesters were developed (Figure 3).

Figure 3. Schematic sketch of a plug flow digester.



Plug flow digesters have a constant volume, but produce biogas at a variable pressure [33]. The size of such digesters varies from 2.4 to 7.5 m^3. Plug-flow digesters consist of a narrow and long tank with, an average length to width ratio of 5:1. The inlet and outlet of the digester are located at opposite ends, kept above ground, while the remaining parts of the digester is buried in the ground in an inclined position. As the fresh substrate is added from the inlet, the digestate flows towards the outlet at the other end of the tank. The inclined position makes it possible to separate acidogenesis and methanogenesis longitudinally, thus producing a two-phase system. In order to avoid temperature fluctuations during the night and maintain the process temperature, a gable or shed roof is placed on top of the digester to cover it, which acts as an insulation both during day and night [68–74].

The popularity of tubular digesters has increased recently in Peru, due to its portability and low cost [68]. The usefulness of these digesters includes easy installation, easy handling, and adaptation to extreme conditions at high altitudes with low temperatures. The transportation costs for the material to build the digester in hilly areas are high, leading to a high capital cost. On the other hand, plug flow digesters are easy to transport, which ultimately reduces the cost of the digester [68]. It is also difficult to dig a large volume under the ground to build digesters in high altitudes [75].

51% of all digesters installed by United States Environmental Protection Agency (USEPA) were plug flow digesters [76]. Plug flow designs are suitable for manure, and operating semi-continuously with a HRT between 20 and 30 days, and a solid contents varying between 11 and 14%. These digesters do not have moving parts, reducing risks for failure [77–79]. Out of 99 digesters installed by the Bureau of Animal Industry in the Philippines, only one did not produce gas, and three had delayed gas production [80].

2.4. Comparisons of Different Digesters

Hamad *et al*. [81] compared the performance of the modified Indian digester and the Chinese fixed dome models for the conditions prevailing in Egypt. None of the digesters were suitable for the local conditions, and for the conditions present in Egypt, the plug flow digester and the digester with a solar heater were reported to be more efficient. Biogas production decreased by 70% in the rubber balloon digester compared to 17% in the *deenbandhu* model during winter. It is not advisable to use the rubber balloon model in hilly areas as it is affected by the ambient temperatures. The fluctuation in temperature changes the microflora in the reactor between lower mesophilic in summer to psycrophilic in winter, affecting the process parameters. Compared to the conventional plant (fixed dome digesters), rubber balloon reactors in hilly areas maintain 2–3 °C lower temperatures during the winter and 2–3 °C higher temperatures during the summer [82]. Mohammad [64] compared the vertical plant (modified floating drum), horizontal (with two partitions), community type, Chinese dome, French type, rubber tube, and polyethylene bag using a common substrate (buffalo dung). The results suggest that the community model was somewhat expensive, but it was very effective.

2.5. Other Digesters

Singh and Anand [83] aimed to decrease the water consumption in domestic digesters. Thus, a solid-state digester (SSD) was built out of a cylindrical vertical vessel with a cone at the bottom. This digester was welded to a tripod for balance. Lagoons with a floating cover could also be used as a digester, which is very cheap for farmers [84]. Qi *et al*. [85] designed and studied an integrated system of biogas production, using a greenhouse for growing vegetables and a pigsty for feeding the pigs in Laiwu, Shandong province, North of China. The biogas produced from swine manure and urine was used for cooking, lighting, or to maintain the temperature inside the greenhouse for optimum vegetable growth and the digestate were used as a fertilizer to replace chemical fertilizers. During winter, the low temperature and sunlight levels increases the application of chemical fertilizers. This frequent use of chemical fertilizer not only increased the cost of expenses but also decreased the vegetable quality during the winter. However, the substitution of chemical fertilizer with digestate increased the vegetable yield by 18.4% and 17.8% for cucumber and tomato respectively.

3. Parameters in Digesters Operation

3.1. Materials for Construction

Materials for construction of household digesters depend on geological, hydrological, local conditions, and locally available materials [18]. With technological advances, different materials with improved properties and lower costs have been introduced to the market in recent years. In India, underground biogas household digesters are very popular. Stone or bricks are used as the material for construction of these kinds of digesters [86]. High investment costs are required to build fixed structure digesters, which is the main constraint to low-income farmers. Taiwanese engineers in 1960 started to develop digesters from cheaper, locally available materials. Although nylon and neoprene were used initially, this proved to be expensive. With the development of technology, PVC and polyethylene were used instead, since they are relatively cheap [72]. Different construction materials with their advantages and disadvantages are summarized in Table 1.

Table 1. Different materials used for construction of digesters with their advantages and disadvantages.

Material	Modifications	Advantages	Disadvantages	Reference
Poly vinyl chloride (PVC) Polyethylene (PE)	Red mud PVC (mixed with aluminum) PE with UV filter	Less weight Easily portable PE is much cheaper compared to PVC	Short life span of plastics	[59,68,70,72,73,87–90]
Neoprene and rubber	Reinforced with nylon	Weather resistance elastic	Expensive Low pressure Less life span	[72,82,91]
Bricks and concrete	Pre fired earthen rings, lime concrete, slag concrete, fired clay, bricks, reinforced concrete, Ferro cement (crack proof)	Everlasting, less maintenance costs	Gas could escape through concrete pores when pressure increases. Built underground. Difficult to clean. Occupies more space.	[18,52,63,86,92,93]
Bamboo and wood supports	Usually a support material, Reinforced with flax	Locally available material	Can break easily	[54]
Steel drum		Produce gas at a constant flow Leak proof	Corrosion Heavy weight of gas holder	[64,91]

3.2. Effect of Temperature

One of the important and difficult parameters to maintain in domestic biogas digesters is the temperature. Methanogens are active, even at a very low temperature [70,94–96], while the biogas production increases by tenfold upon increasing the temperature from 10 to 25 °C. According to some observations, the amount of biogas produced by high temperature (mesophilic) and low HRT is comparable to the biogas produced with low temperature (psycrophilic) and high HRT [70]. People living in mountain valleys or outside of tropical regions suffer from low digestion rates during the winter season, when the temperature drops below 15 °C [86]. Different techniques and methods have been developed around the world to maintain the temperature inside the digester. Solar energy could be used as a heating source to increase the temperature of the digester [18]. Misra *et al*. [97] developed a solar-based heating device, but the efficiency decreased during the wintertime in hilly areas. To keep the temperature as constant as possible, most of the digesters were built underground [98]. Ramana and Singh [99] reported that geothermal energy helped in maintaining the temperature in the digester when buried underground.

Anand and Singh [86] proposed using a charcoal coating on top of the digester. This method increased the temperature by 3 °C and gas production by 7%–15%, but the digester had to be coated every one and a half months. This method is however economical as farmers can prepare charcoal by burning wood pieces. To maintain the temperature in the reactor, it is not enough to only blacken or glaze (coating). Some part of the biogas produced should also be burnt to maintain the temperature in the digester [100]. Paddy husk placed on top of the digester can also help in maintaining the temperature during winter [101]. Singh *et al*. [102] reported that the decrease of biogas yield during winter could be overcome by providing insulation on the inner surface of the gas holder. A shallow, solar-pond water-heater also reduced the heat loss inside the digester.

The French type digester covered with a polyethylene bag containing municipal solid waste did not affect the temperature drop [64]. Anjan [59] compared the *janta* model and the plug flow type of digester. The biogas production was more in the summer than in the winter, and the plug flow digester was less influenced by the temperature. Hamad *et al*. [81] compared the Indian model and the Chinese fixed dome digester. The Chinese dome digester had better insulation properties compared to the Indian type. In the Indian model the temperature decreased with decrease in height. A long-term testing of a biogas digester shows that the digester worked in the lower mesophilic range for almost eight months out of the year and in the psychrophilic range for the remaining part of the year [75].

In order to maintain the temperature in the reactor, the digester is covered by certain insulation materials. The insulation materials include: composites made of glass wool, sawdust, and plaster of Paris in ratio 1:2:2; black cloth coated with pitch, sodium peroxide, glass wool, and a mixture of thermocol and sawdust. The composite and black cloth coating was able to hold the temperature for more than 70 h, but the thermocol-sawdust mixture could only maintain it for 36 h [97].

3.3. Substrate Consumption

Almost all biomass is degraded to biogas in theory [103]. However, the choice of substrate will depend on the availability of the raw material, type of the digester, and its operating conditions. [64]. Cattle manure was a traditional source for biogas production in the past. The methane content was high in pig manure, around 60%, followed by cow dung with 50% [89]. Kitchen wastes and crop residues are some underexploited substrates for the domestic biogas production. Kitchen wastes contain a high amount of fat in the form of animal fat and cooking oil. This high-fat content can enhance the biogas production [90,103].

Combinations of different substrates often have a synergistic effect on biogas production [104,105]. Co-digestion can improve the nutrient balance, maintains the pH, and results in positive synergisms [106–108]. Moreover, in several studies co-digestion had a higher methane yield compared to mono substrate digestion [90,109–113]. Different substrates used for biogas production, dry matter, ash content, total digestible nutrients and biogas yield for household digesters are listed in Table 2.

Table 2. Different substrates with corresponding dry matter, ash content, total digestible nutrients and biogas yield used in the household biogas digesters [28,65,114].

Main substrate	**Substrate classification**	**Dry matter (%)**	**Ash (%)**	**Total digestible nutrients (%)**	**Biogas yield**	**References**
Manure	Cow	38	14	92	0.6–0.8 m^3/kg TS	[54,60,61, 66–68,75,86, 89,92,110,112, 113,115]
	Pig	20–25	NA	NA	0.27–0.45 m^3/kg TS	[70,89,112, 116,117]
	Buffalo	14	NA	NA	NA	[81,89]
	Poultry	89	33	38	0.3–0.8 m^3/kg TS	[64,118,119]
	Horse	28	NA	NA	0.4–0.6 m^3/kg TS	[120]
Fecal matter	Human excreta	20	NA	NA	NA	[27,54]
	Night soil	NA	NA	NA	NA	[93,94,121]
Agricultural residues	Rice straw	91	13	40	0.55–0.62 m^3/kg TS	[93]
	Wheat straw	91	8	43	0.188 m^3/kg VS	[64,122]
	Maize straw	86	NA	NA	0.4–1.0 m^3/kg TS	[28]
	Grass	88	6	58	0.28–0.55 m^3/kg VS	[55,118,119]
	Mango leaves	NA	NA	NA	0.6 m^3/kg TS	[92]
	Foliage of parthenium	NA	NA	NA	NA	
	Coffee pulp	28	8	NA	0.300– 0.450 m^3/kg VS	[118,119,123]
	Corn stalk	80	7	54	0.350–0.480 m^3/kg VS	
	Cassava peels (residues)	NA	NA	NA	0.661 m^3/kg VS (0.132 m^3/kg VS)	[88,124–126]
Food wastes	Household grease					[111]
	Whey	94	10	82	NA	
	Vegetable waste	5–20	NA	NA	0.4 m^3/kg TS	[16,54,69]
	Fruit wastes(apple)	17	2	70	NA	[64,69]
	Kitchen/restaura nt wastes	27/13	13/8	NA	0.506/0. 650 m^3 CH_4/kg VS	[110,111, 127–131]
	Left over's food	14–18	NA	NA	0.2–0.5 m^3/kg TS	[28]
	Egg waste	25	NA	NA	0.97–0.98 m^3/kg TS	[28]
	Cereals	85–90	NA	NA	0.4–0.9 m^3/kg TS	[28]

Table 2. *Cont.*

Main substrate	Substrate classification	Dry matter (%)	Ash (%)	Total digestible nutrients (%)	Biogas yield	References
Aquatic plants or sea weeds	Algae	NA	NA	NA	0.38–0.55 m^3/kg VS	[132]
	Water hyacinth	7	NA	NA	0.2–0.3 m^3/kg VS	[93,133]
	Giant kelp	NA	NA	NA	NA	[118,119]
	Caboma	NA	NA	NA	0.221 m^3/kg VS	[133]
	Salvinia	NA	NA	NA	0.155 m^3/kg VS	[133]

* NA- Not Available.

3.4. Loading Rate and Yield of Biogas Produced

The solids concentration in the household biogas digesters varies between 5% and 10% [64,69,89,92,103]. Increasing the solids concentration to 19% decreased the biogas production considerably [92]. The common organic loading rate (OLR) of the digester is 2–3 kgVS/m^3/day under mesophilic conditions. Nevertheless, it could be possible to achieve higher OLRs if the sludge concentration is over 10% [101]. Anjan [59] reported a maximum of 10.4–10.6 kgVS/m^3/day in the *janta* model and the modified plug flow reactor. The average biogas production in the domestic biogas digester was in the range of 0.26–0.55 m^3/kgVS/day [67,84,89].

Hydraulic retention times (HRT) vary between 20 and 100 days for mesophilic household digesters [70,71,89,103]. Studies show that decreasing HRT from 90 days to 60 day and increasing the OLR by diluting the substrate from 1:4 to 1:2 would be beneficial for the better performance of the digester [68]. Many household digesters do not have a stirrer to mix the digester content, which creates stagnant regions in the digesters. Due to these stagnant regions, the digester HRT is decreased compared to its calculated HRT, leading to wash out of the microorganisms [81,134,135].

3.5. Biogas Storage and Maintenance of Digesters

Storing the biogas produced is often a major concern. Biogas can be transported directly to the kitchen or stored in a pressurized tank, floating drum storage, gas cylinders, and gasbags. Storing the biogas reduces the problem of low flow rate during cooking. Biogas can be transported from one place to another by using gasbags [18,52,72,136–138]. The excess pressure in the storage container can be released using a 'T' shaped valve [72,139].

The amount of biogas produced in the digester depends on the material fed, type of the material, C/N ratio, digestion time, and temperature [50,140,141]. For instance, highly concentrated influent slows down the fermentation, and diluted influent causes scum formation. To keep the solids concentration, the amount of water and biomass added should be in equal proportion [11,142–144]. The digester should be fed every day. However, free fermentable carbohydrates will increase the volatile fatty acids concentration, which affects the methane forming bacteria. Usually, the steady state of biogas production is observed after two months of operation with a constant OLR [33,145].

4. Applications of Biogas in Household Digesters

4.1. Cooking and Heating

Biogas produced from the household digesters is mainly used for cooking [54,70]. The amount of biogas used for cooking purposes usually varies between 30 and 45 m^3 per month. This number can be compared with other commonly used fuels such as kerosene where the consumption is between 15 and 20 L, and Liquefied Petroleum Gas (LPG) between 11 and 15 kg per month, respectively. The energy equivalent was around 300, 200, and 150 kWh for biogas, kerosene, and LPG, respectively [66,146,147]. The surplus biogas in the domestic digester could be used for water and space heating [148–150].

4.2. Biogas Stoves

Biogas burning is not possible in commercial butane and propane burners because of its physiochemical properties. However, it is possible to use these burners after some modifications [103]. Burners are changed in the gas injector, its cross-section, and mixing chambers. The biogas burners are designed to meet a mixture of bio-gas and air in the ratio of 1:10 [101]. Different burners like vertical flame diffuser, horizontal flame diffuser, and no diffuser with biogas have been examined. A vertical flame diffuser had a high heat transfer efficiency compared to other diffusers [68]. The efficiency is obtained by calculating the heat gained by the water subjected for heating and the amount of fuel consumed during this process. The efficiency of the heat entering the vessel from the stove was high for biogas with 57.4%, followed by LPG, kerosene, and wood with 53.6%, 49.5%, and 22.8%, respectively [151]. The biogas consumption and the thermal efficiency in the biogas stoves varied between 0.340–0.450 m^3/h and 59–68% [67,145,152–154].

4.3. Fertilizer

The digestate left over from the digester is rich in nitrogen, phosphorus, and potassium, and can be used as a fertilizer [54,73]. Digestate increased the potato cultivation by 27.5% and forage by 1.5% compared to no added fertilizer. Due to the anaerobic digestion of organic matter, these nutrient concentrations were easily taken up by plants [71,116]. The effluent can be directly used as a fertilizer in farming [92]. Digestate has a high commercial value when exported. The dried effluent could also be used as an adsorbent to remove lead from industrial wastewater [155]. Biogas slurry could be helpful in growing algae, water hyacinth [101], duck weed [156], and fish poly-aquaculture [157,158].

4.4. Lighting and Power Generation

The other major application of household biogas is for lighting and power generation. In many developed countries, biogas from the digesters is sent to a combustion engine to convert it into electrical and mechanical energy [64]. Biogas requires a liquid fuel to start ignition [13]. Diesel fuel can also be combined with biogas for power generation [159–163]. For instance, in Pura (India), a well-studied community biogas digester can fuel a modified diesel engine and run an electric generator [164]. Bari [160] reported that carbon dioxide up to 40% will not decrease the engine performance using biogas as a fuel. Biogas can also be used to power engines when mixed with petrol or diesel, and it can also help in pumping water for irrigation [66,165–167]. Cottage/small scale industries use biogas for pumping, milling, and for some other production activities [168].

For a medium-sized farm in Jordan, the monthly energy consumption for various purposes is about 1282 kWh. The biogas required for producing 982 kWh is around 6.7 m^3/day, and for water-heating 2 m^3/day. The use of 1 kW generator proved that half of the energy needed could be met by using a domestic digester. Satisfactory results were observed when tested for water-heating and electricity generation from biogas [60,61]. In Earth University (USA), electricity from biogas is used for milking operations [169]. Biogas is blended with jatropha oil in a 12 kW diesel engine generator to act as a dual fuel for rural electrification. Jatropha seeds remain as a waste product after oil production. This waste gets converted into biogas. The oil and biogas is combined in a duel fuel engine for electricity generation [13]. The fertilizer from biogas is used for jatropha plantation. Hence, the nutrients are in the closed cycle, which can act as a bio-refinery [170]. Biogas conversion into electricity using fuel cells is a hot research topic nowadays. However, it is not commercially affordable due to the requirement of clean gas and the cost of fuel cells [103].

Biogas lamps are more efficient than the kerosene powered lamps, but the efficiency is quite low compared to electric-powered lamps. However, the light intensity of the biogas lamp compared to a kerosene lamp or an electric light bulb, was in the power range of 25–75 W [145]. One cubic meter of biogas is equal to lighting 60–100 watt bulb for 6 h, or cooking three meals a day for 5–6 persons. In contrast, 0.7 kg of petrol can run 1 hp motor for 2 h or generate 1.25 kW for electricity [171]. To provide electricity for a home with a family of five, about 0.25 to 0.5 m^3 biogas is needed [66]. Until recently, many of the rural areas in India depended on kerosene lamps for lighting due to the energy shortage. Using these kerosene-powered lamps was inefficient as well costly. Battery-operated solar panels were also an expensive means for lighting. This resulted in research to design a digester, which could provide lighting to a home. A mini-biogas digester developed especially for lighting purposes. This digester could produce 0.5 m^3/day biogas which is enough for 4 h of use [63].

4.5. Other Applications

Besides common applications, domestic biogas is also utilized for other purposes. Gas-powered refrigerators or a chicken incubator can run on household biogas, which is a well known application in Kenya [98,145]. In India, around 4600 public toilets are connected to biogas digesters by a local NGO to improve social living conditions of the people. Similarly, in Nepal, public toilets are connected to biogas digesters to light these toilets [98,172].

5. Disadvantages

Despite the various advantages of household biogas digesters, there are a few disadvantages to overcome as well. Anaerobic digestion is a slow process, and it requires a long HRT (>30 days) [16]. This increases the volume and cost of the digester. Low loading rates and slow recovery after a failure are other limitations in biogas production [173]. Another limitation is the fluctuation in temperature throughout the year. The decrease in biogas production during the winter months makes it difficult for cold countries to adapt this technology [30]. In the long-run, people often stop using the household digesters due to lack of knowledge, gas leakage, slow recovery, low gas production, and inadequate supply of substrate [174]. Research into these issues is needed. For instance, straw is a potential substrates for household biogas digesters, but it demands more research and development [175].

Leakage from biogas digesters increases emissions of methane and carbon dioxide into the environment. Fire explosions in households are another disadvantage when methane leaks from the digester [40].

Individual economic status is also a concern in biogas technology [176]. Sibisi and Green [98] installed a floating drum digester in a school to meet their energy needs. However, it was impossible for the school to spend a capital investment unless a governmental subsidy was provided. In Thailand, high investment, lack of financial resources, lack of information, and lack of skilled labor are barriers towards adopting biogas stoves, and household biogas digesters [177,178].

Developments in technology can help to rectify these problems by making biogas sustainable for rural energy production. However, low functionality of biogas plants due to defective components, lack of technical knowledge, not adopting a proper size and model based on locality and availability of raw materials, poor supervision, and lack of NGO involvement continue to present obstacles to technology dissemination [91]. It is important to spread basic knowledge among farmers and local people in order to train and educate them about the potential of biogas technology [179].

6. Economics and Policies

Most biogas digesters have lifetimes of 25–35 years [180,181]. The cost of these digesters varies from 200 to 400 USD. For instance, in Thailand a fixed dome model called cement water jar with a size of 1.2 m^3 costs around 180 USD [66], in Peru a PVC tubular digester of volume 0.225 m^3 costs around 250 USD [70] and a plug flow digester with a size of 0.250 m^3 costs 300 USD in Costa Rica [90]. In India, the floating drum model of size 1–6 m^3 costs from 200 to 400 USD respectively [66,70,88,90,182]. The payback period (PBP) for different digesters, including *deenbandhu*, KVIC, and *janta* models was calculated. The *deenbandhu* model had a lower PBP around 4.7 and 1.6 years for a digester of size 1 and 6 m^3, followed by the *janta* model with 11.3 and 3.2, PBP and years, respectively, for the same size. The floating drum model had a high PBP of 26.6 for a 1 m^3 digester [1]. Amigun and von Blottnitz [47] calculated the capital cost for different sizes of biogas digesters by using the Lang factor (f_L). The results revealed that the f_L value of 2.63 and 1.79 gives a better prediction for small/medium digesters and large plants, respectively. Rubab and Kandpal [183] calculated the capital cost using different methodologies, including economies of scale, ratio of size of a reference plant cost, cost of constituents, and the last method included factors like retention time and other important factors for capital cost calculations.

Different economic models to predict the cost of a digester and the cost of benefits obtained using a household biogas digester have been developed in the recent past. An economic model to assess the cost-effectiveness of domestic biogas plants was developed by [35,184,185], which is summarized in Equations (1), (2) and (4). The cost calculation of a biogas digester based on a reference plant is given in Equation (3). In Laboratory of Agricultural Structures (LAS) of the Agricultural University of Athens, an improved version of the original Basic Economic Evaluation Model were developed called Modified Basic Economic Evaluation Model (MBEEM). This model involves many parameters and a computer model was developed in order to facilitate the application of the MBEEM. According to the model, the optimum retention time from an economical point of view would be 20 days. The net present benefit increases with the increase in government subsidies, increase in fuel wood cost, and decrease in the cost of the digester. However, net present benefit gets affected if the interest rate is high. The financial stability of the digesters is increased with the increase in digester size. Cooking with firewood suppresses biogas cooking if the efficiency is more than 25%. The biogas plants will be in a critical position, if the cost of wood fuel decreases or the cost of dung increases. Ciotola *et al.* [169] conducted an energy analysis to assess the sustainability and environmental impact of small-scale digesters. They found that it was better to use biogas for cooking, but not for producing electricity using a generator. Environmental Sustainability Index (ESI) is a way to measure the total sustainability of a process and Environmental Loading Ratio (ELR) is a method to estimate how much impact a process has on the environment. A high ELR corresponds to a high environmental stress. ESI was reduced from 5.67 to 2.22 due to production of electricity from biogas. At the same time, ELR was increased from 0.52 to 0.93.

Equation 1. Model for net present benefit for the digesters in Bangladesh, where PW- present worth of the incremental net benefit, A_g—Annual incremental benefit from using biogas as cooking fuel, A_f—Annual incremental benefit from using treated slurry as fertilizer, C—Cost of digester, N—Plant life, and W—Inflation rate/Interest rate [184]:

$$PW = (A_g + A_f)\sum_{n=1}^{N} W^n - C - \sum_{n=1}^{N} m_n W^n \tag{1}$$

Equation 2. Model for the cost benefit analysis in India for floating drum model, where NPV—Net Present Value, A_b—Annual benefits, A_c—Annual operating costs, i—interest rate, t—life time of the plant, C—Cost of the digester [185].

$$NPV = \frac{(A_b - A_c)[1-(1+i)^{-t}]}{i} - C \tag{2}$$

Equation 3. Generalized cost calculation for a biogas digester, C—Cost of the digeter, C_O—Cost of the reference plant, a and b are constants, V—Volume of the digester, V_o—Volume of the reference digester [185]:

$$c = C_0[a + b\left(\frac{V}{V_0}\right)] \tag{3}$$

Equation 4. Modified basic economical evaluation model for Greece, where NPV—Net Present Value (Euro), NCF—Net Cash Flow, r—discount rate, j—operational life span of installation (year), I—capital investment [35]:

$$NPV = \sum_{j=1}^{n}[NCF_j \times (1 + r)^{-j}] - I \tag{4}$$

Pütz *et al.* [186] developed a morphological matrix to sell the biogas produced from the digester to the low-income farmers. Using the right methods to transport and sell biogas can yield a profit to both the seller and the buyer. Li *et al.* [5] calculated the ecological and environmental benefits by building a biogas digester by using a quantitative model. The equation to calculate economical and environmental benefits is given in Equations (5) and (6), respectively. The results showed that families that have a biogas digester could benefit by about 100 USD/digester. Peter *et al*. [187] developed an empirical model for the adoption of biogas technology, and the results showed that the adoption of technology is increasing with high income, more cattle owned, bigger homes and hike in fuel price. However, the adoption for biogas technology decreased with an increase in remote location and area of the household. Van Groenendaal and Gehua [188] analyzed the internal benefits which revealed that 58.5% of people who used a biogas digester could cook three meals a day and most of the people had improved health conditions. Feng *et al*. [189] calculated the efficiency of energy use for the rural households in Tibet. The comparison of the present scenario and the futuristic change revealed the importance of the biogas not only economically, but also by building a healthier and sustainable society.

Equation 5. Calculation for economical benefits of a digester, T_c—cost of economical benefits for a household, m—items consuming energy, n—kinds of energy resources, j—type of usage, i—type of resource, C_i—unit price for the type of energy [5]:

$$T_c = \sum_{j=1}^{m} \sum_{i=1}^{n} C_i x_{ij} \; (i = 1,2 \ldots n, j = 1,2 \ldots m) \quad (5)$$

Equation 6. Calculations for environmental benefits of a digester, T_s—cost of environmental benefits for a household, m—items consuming energy, n—kinds of energy resources, j—type of usage, i—type of resource, S_{1i}—Environmental costs in a hill, S_{2i}—environmental costs in a slope [5]:

$$T_s = \sum_{j=1}^{m} \sum_{i=1}^{n} x_{ij} \, (S_{1i} + S_{2i})(i = 1,2 \ldots n, j = 1,2 \ldots m) \quad (6)$$

Politicians and policymakers must promote efficient ways to meet energy needs in rural areas [190]. By having government subsidy plans and loan or credit schemes, the biogas program for rural households will be more attractive to people [33]. In China, the government pays two-thirds of the digester cost and the farmer pay the remaining amount. However, the construction of digesters decreased when the government reduced the subsidy to one-third of the cost [55]. Millions of people have benefited from this technology, and its popularity is still increasing [54]. Domestic biogas digester programs could be alive with the microfinance schemes available in the developing countries. This could help farmers and poor people to reduce the burden on capital cost investments [191].

7. Environmental and Social Aspects of Biogas Digesters

Climate change is one of the major environmental challenges facing the World today. Unsustainable energy consumption in past has contributed to global warming that needs to be addressed [192]. Household digesters could reduce the pressure on the environment by reducing deforestation and greenhouse gas emissions, soil erosion, loss of cultivable land [54].

A major contributor to global warming are greenhouse gases (GHG), emitted to the atmosphere mainly from burning fossil fuels such as coal, oil and natural gas. Rural biogas production can partially reduce global warming [193]. By utilizing biogas for rural households, environmental, economical, and social benefits were obtained [194]. Even though, both methane and carbon dioxide are major contributors to the greenhouse effect, the global warming potential of methane is 21 times higher than that of carbon dioxide [195]. However, the comparison of the houses equipped with and without biogas systems, including the leakage of gases in the biogas systems revealed that the households with biogas plants have 48% less emissions compared to households without biogas systems [196]. It is worth mentioning that only 10% of households had methane leakage [194]. Studies show that by replacing firewood and coal with biogas, the emission of CO_2 and SO_2 would be reduced by 397–4193 thousand tons, and 21.3–62.0 thousand tons, respectively [193]. Pathak *et al*. [193] reported that the global warming mitigation potential from a 3 m^3 family size biogas plant in India using dung from four cattles was about 9.7 tons CO_2 equivalent per year. The government of India targeted to install 12.34 million digesters by 2010. This target mitigation potential is equal to 120 million tons CO_2 equivalent per year.

Hamburg [197] did a pilot-scale study on the emission of H_2S and SO_2 by using crop stalks, coal, and biogas for cooking in the regions of Henan province in China. The study revealed that the emission of SO_2 using crop stalks and coal for cooking was four times higher than that of biogas. Additionally, no significant level of H_2S was found. Khoiyangbam *et al*. [198] compared the methane emission effect of fixed dome biogas plants installed in the hilly areas of India. The studies showed that methane emission was higher for the *janta* model compared to the *deenbandhu* model. A family size biogas plant is a substitute for 316 L of kerosene, 5535 kg of wood and 4400 kg of cattle dung as fuels reducing emissions like NO_x, SO_2, CO, and volatile compounds into the atmosphere by 16.4, 11.3, 987.0, and 69.7 kg/year, respectively [199].

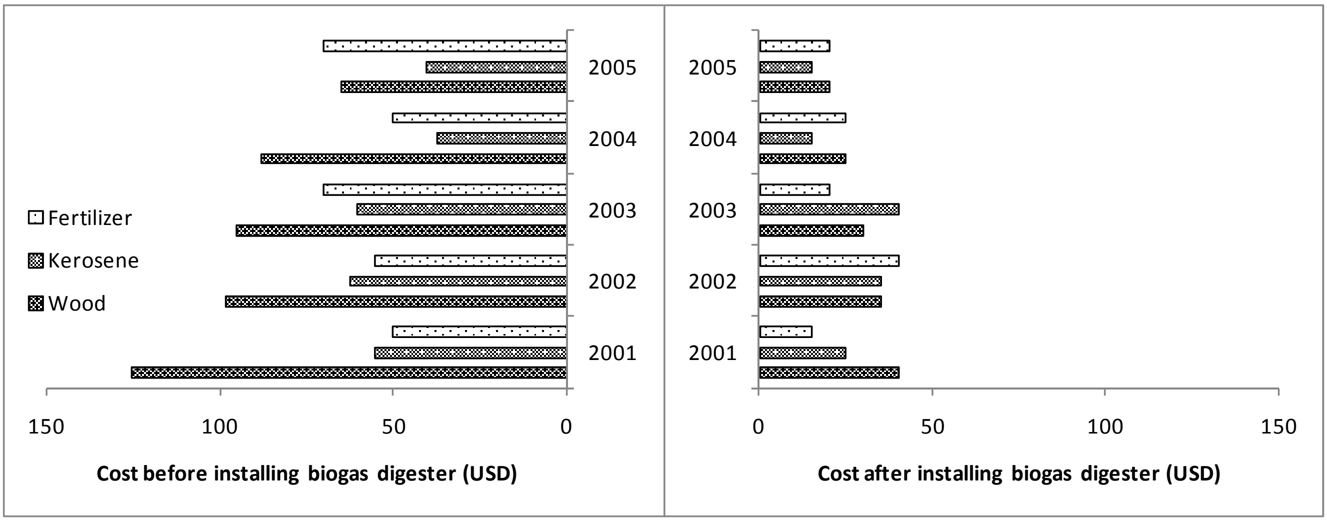
The slurry from the biogas digesters, if not used properly, becomes an active place for insects to spread diseases [200]. Biogas slurry could be used as a valuable resource for earthworm culture. Slurry mixed with plant rich materials, is also a suitable substrate for vermicomposting [201,202].

A comprehensive study to analyze the rural energy development in China using household-scale biogas digesters and green house gas emission reduction was done by Yu *et al* [22]. The greenhouse gas emissions from energy sources including straw, fuel wood, coal, refined oil, electricity, LPG, natural gas, and coal gas were compared to emissions from biogas. Biogas as a substitute for other energy sources reduced the greenhouse gases by 73.157 megatons CO_2 equivalents based on the amount of consumption between the years 1991 to 2005.

Another study in the Peruvian Andes by Garfi *et al* [88] involving 12 rural families in a project to substitute biogas with firewood, showed a decrease of firewood consumption by 50%–60% and cooking time by 1 h. The results are based on a survey which included technical aspects such as type of fuel and time for cooking, environmental aspects such as number of cows in the households and amount of firewood used to cook and economical aspects including income of the family and the expenditure for fuel and fertilizer and social aspects such as time for collecting wood. The effect of the price on firewood, kerosene and fertilizer before and after installing the biogas plant from 2001 to 2005 in India is shown in Figure 4.

Cattle dung is usually used as compost or dung cakes for cooking, which is neither hygienic nor economical [1]. Burning dung cakes does not only creates pollution but also leads to loss of a valuable fertilizer. On the other hand, if the dung cake is applied directly to the field it would also cause total loss of fuel, besides the pollution [184]. Anaerobic digestion is a secure and high-profit yielding way to dispose of this cattle dung [1].

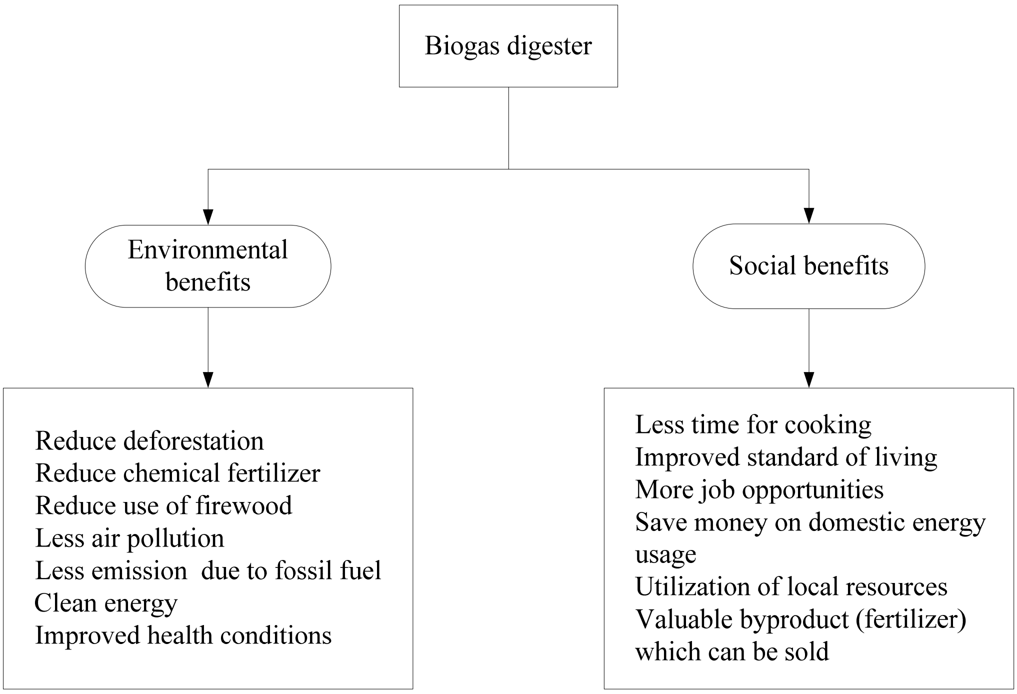
Figure 4. Costs of firewood, kerosene and fertilizer before and after installing the biogas digester from 2001 to 2005 in India [190].



In addition to environmental benefits, there are a number of social and health benefits using biogas as a fuel. Improved health conditions and change in lifestyle for women in the households were observed after installation of a biogas digester [33]. Hiremath *et al*. [203] mentioned that India could meet their energy demands by a decentralized energy planning. Using the locally available materials, they could fulfill their energy needs in a sustainable way. One of the possible alternatives to producing energy for rural India is biogas. The basic seven goals are: cost minimization, efficiency maximization, employment generation, system reliability, minimization of petroleum product, maximization use of local resource, and minimization of emissions. Biogas can improve sanitation considerably, when linked to a public toilet where waste is no longer stored [204,205]. Green foods (crops grown using fertilizer from biogas plants) were developed by connecting a biogas plant to a toilet and pigpen. This kind of integrated model is very popular in southern China [175]. One-third of the dung produced in India is enough to run 12 million biogas plants [206]. Use of biogas digesters by the rural people could help them financially as well as improve the living conditions such as improved air quality for the health benefits of the people [66].

For instance, burning firewood for cooking also creates a lot of smoke and soot particles. The smoke and soot contributes to air pollution which in turn causes health issues such as respiratory illness [54]. However, Zhang *et al*. [10] reported that more than 420,000 premature babies died in China every year due to indoor air pollution. Most of the pollution is due to poor combustion fuels and emitted greenhouse gases. The main reason for infant mortality and deaths in developing countries is respiratory diseases. Most of these diseases are due to pollution emission from cooking. In contrast, biogas is a clean fuel compared to biomass or coal combustion. Cleanliness here refers to the cooking vessel not turning black in the bottom of the vessel, when biogas is used for cooking. Air pollution in biogas will be less because they have few larger hydrocarbons. Increase in the concentration of hydrogen sulfide leads to headaches, dizziness, blurry vision, nausea, and vomiting. Sulfur dioxide emissions lead to choking and sneeze-inducing effects [197]. Sustainable energy production for rural-needs and proper sanitation has a significant difference on control of parasitic diseases [204,205]. Figure 5 shows the environmental and social benefits obtained by using a biogas digester.

Figure 5. Environmental and social benefits in using biogas digesters.



8. Discussion

Access to energy resources, economic development and environmental pollution, which in turn threaten human health, are major challenges facing developing countries today [207]. Economically feasible and efficient small scale biogas digesters could be the answer of solving some of these problems and needs. By enhancing energy availability and simultaneously protect the surrounding environment such as soil, water and air, a lots of benefits could be gained. Most of small-scale digesters are concentrated in developing countries with India and China as leading countries accounting for the highest share.

More or less, every biodegradable organic waste can be treated in a biogas digester, providing energy for cooking, lighting and heating along with increased of dissolved nutrient concentration in the digestate, thus, providing farmers with an improved organic fertilizer. Many of small scale digesters do not require high maintenance and are more or less adaptable to the climate and condition of many of developing countries [73]. However, adopting of biogas digesters is low in many countries despite the great potential to gain a wide verity of benefits, both from socioeconomic and environmental point of View. Possible negative impacts are suggested such as the potential for pathogens, limitation of economic and material resources, and pollution through losses from damaged digesters, and possible leakage of incomplete combustion of methane to CO_2. Additionally several practical problem have also been suggested as limiting the uptake of small-scale digesters including unaffordable initial investment costs, accessibility of proper materials to avoid leakage in digester construction, lack of efficient functioning digesters in different climate condition, sufficient production of fuel to meet the needs, social acceptability of the fuel produced, *etc*. [208].

Studies showed that political measures are required to support adoption of the household digesters, by subsidy plans, including training and capacity building to keep up the interest in adopting the household digesters. However, the interesting paradox is, despite all the benefits that could be gained, the interest fades as soon as the governmental subsidy support is reduced, as the case in China which is the one of leading countries in adopting the biogas digesters. It seems the benefit from implementation of biogas digester alone is not enough to increase the attention. Further, full analysis are needed with a new approach to facilitate communication between the experts from different fields such as engineering, hydrology, biology, social science, economics and systems-modeling to identify and find the best possible optimum solution and strategies needed in implementing household biogas digesters in rural communities [208]. Furthermore, interest is growing slowly in many poor countries and effort should be made to increase the awareness and to introduce affordable and more efficient digesters tailored to take full advantage of the local possibilities in order to succeed.

9. Conclusions

Household digesters represent a boon for farmers and rural people to meet their energy needs. These digesters help in two ways: one is to reduce waste, and the other is to provide valuable energy. Although they have been used for many years, modernization is needed to overcome the drawbacks in the long run. The awareness by people of their technical issues, and governmental subsidy plans could provide even more benefits from household digesters.

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