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Review

Dairy Waste and Potential of Small-Scale Biogas Digester for Rural Energy in India

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Abstract: In order to reduce emissions of greenhouse gases, related global warming and dependency on fossil fuels, it is crucial to promote the uses of renewable energy, and conversion of biomass and organic waste into energy sources. In many parts of the world, a substantial increase in efforts for the conversion of waste into energy is currently being observed. Specifically, biogas technology has been emphasized for the conversion of animal waste into biomethane/biogas because livestock waste is considered to be a substantial source of ambient greenhouse gases, causing climate change. While biogas technology, an anerobic process to convert livestock waste into biogas, is promoted in both developed and developing countries, this review article is focused on improving our existing understanding of small-scale biogas technology and relevance of this technology in rural environment of India. A thorough review research has been performed to gather the information on livestock population, manure production, and potential of biogas technology in India to provide a wholistic information. A summary of the financial supports facilitated by various agencies, the cost of biogas plants, potential uses, and potential challenges in the dissemination of biogas technology in India has been discussed in this study. We anticipate that the data and interpretation provided here will help in understanding the scope of biogas technology in India and will help in formulating the policies which will support the implementation of biogas technologies in developing countries.

Keywords: biogas technology; rural environment; renewable energy; livestock; greenhouse gases

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1. Introduction

India is the world's second most populous country with more than 1.27 billion people. In terms of land area, India is the seventh largest country in the world with 3.28 million square kilometer [1]. While comparing population densities of the top 5 most populous countries (China, India, United States, Indonesia, and Brazil), the population density of China, India, United States, Indonesia, and Brazil are 149/km^2, 424/km^2, 36/km^2, 145/km^2, and 25/km^2, respectively [2]. Farmers in India are either small or marginal. About 68% of famers own less than 1 hectare of land. Based on 2016 Economic Survey, in many India's states, the average annual income of a farming family is less than 300 USD [3]. The majority of India's population lives in villages. Approximately 70% of India's population resides in small to medium sizes villages, with population ranging from 100–1000. Based on a

2011 Census Report of Government of India, currently 800 million people live in around 600,000 villages [4]. According to a World Bank Report, more than 40% India's workforce is engaged in Agriculture [5]. The average Indian household consisted of 5.4 people in rural areas and 5.2 people in urban areas [6]. India had 192 million households in 2001 [6]. A United Nations report described that economic growth over past several decades in India led to significant declines in poverty, and also resulted in increased economic inequality [7]. For the top 5 most populous countries, Gross Domestic Product (GDP)/capita in 2020 was 10,500 USD, 1900 USD, 63,543 USD, 3869 USD, and 6796 USD for China, India, USA, Indonesia, and Brazil, respectively [8].

Dairy is the top-ranking commodity in India, and based on Food and Agriculture Organization (FAO) report, India has transformed from a country with shortage of milk to a leading milk producer [9]. An Economic Survey Report estimated that approximately 198.4 million tonnes of milk were produced in India in 2019–2020 [10]. FAO reported that per capita milk availability in India was 130 g/day in 1950–51, which increased to 374 g/day in 2017–18 [11]. Dairy animals are a regular source of income and cash in India and women often play a crucial role in milk production in rural areas [12]. In general, milk is produced by smallholders in India, and milk production is crucial for household livelihoods, food security, and nutrition. According to FAO, India is the world's largest milk producer, with 22% of global production followed by the United States of America and China [9]. While New Zealand and United States of America are the highest milk surplus countries, FAO outlined that China, Italy, the Russian-Federation, Mexico, Indonesia are the countries with the highest milk deficit [9].

While milk production is crucial for the economy and food security in developing countries as well in developed countries, it also produces livestock waste such as manure. Livestock affects environment, and for sustainable development in agriculture, it is crucial to understand the linkages between livestock industry and environment, and adopt best practices to reduce livestock's environmental impact [13]. In order to achieve the 2030 Agenda for Sustainable Development and the Paris Agreement, the World Health Organization (WHO) suggests achieving zero hunger, while tackling global warming and climate change by improving livestock system management which involves improving animal waste management [14,15]. Studies showed that integrated manure management that involves optimal handling of livestock manure (collection, storage, and treatment) results in conversion of manure into valuable resource [16–18]. In addition, manure can be source of biogas production, and subsequent uses (Figure 1) [19–25]. Nutrients and organic matter of manure are essential for soil health and fertility. Manure is a valuable soil amendment, and can be used for enriching the soil nutrients [26–32].

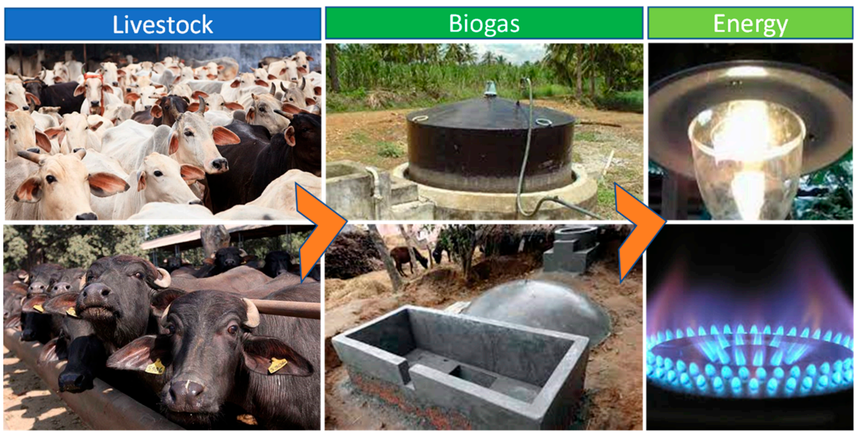

Figure 1. Livestock, manure, and biogas production (integration of livestock waste).

2. Livestock Population and Manure Production in India

The animal-agriculture system, which involves rearing cows, buffalo, sheep, goat, pig, and chickens at a small scale, is an integral part of India. Livestock such as cows and buffalo are the main milk producing animals, which constitutes 59% of the total livestock population in India [33]. Over the past 6–8 decades, cattle population in India steadily increased (Figure 2) [34]. The livestock population in India is approximately 512 million, which involves 200 million dairy cows and 105 million buffalo [35]. Considering dairy cows produces around 10 kg/day of manure, manure production from cows could be around 730 million tonnes annually. Annual production of manure from buffalo could be around 574 million tonnes, considering the manure production from buffalos is around 15 kg/day. Descriptive information considering the total livestock population (top five species) and corresponding manure production is described in Table 1.

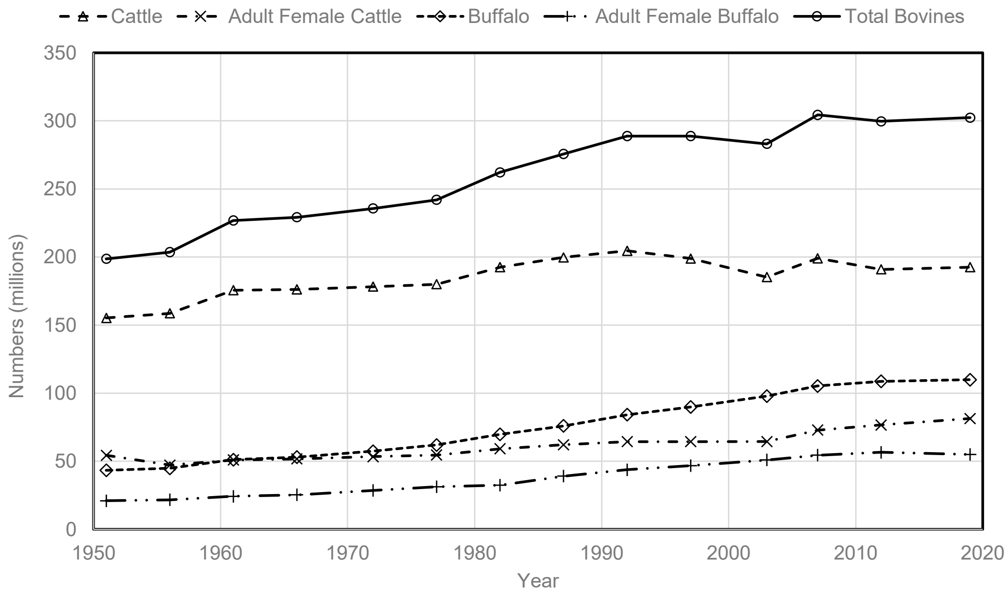

Figure 2. Steady increase in total bovine population (cattle, adult cattle, buffalo, and adult buffalo) between 1950 and 2019 are shown (data source: National Dairy Development Board [36]).

Table 1. Livestock population in India, and manure production (top five species population).

Animal Type	Numbers (Millions)	Manure (Million kg/Day)	Manure (Tonnes/Year)	Remarks and References
Cow	192.5	1405.25	730 million	Annual manure production was calculated based on number of animals and manure production per animals. Average cow numbers were obtained from National Dairy Development Board Database [13,14,36].
Buffalo	109.9	802.27	574 million	Annual manure production was calculated based on number of animals and manure production per animals. Average cow numbers were obtained from National Dairy Development Board Database [13,14,36].
Poultry	851.8	0.0171–0.0219	6.25–8 million	Annual manure production was calculated based on number of animals and manure production per animals. Average cow numbers were obtained from National Dairy Development Board Database [13,14,36].

Table 1. *Cont.*

Animal Type	Numbers (Millions)	Manure (Million kg/Day)	Manure (Tonnes/Year)	Remarks and References
Sheep	74.3	1.81	3.2833 million	Annual manure production was calculated based on number of animals and manure production per animals. Average cow numbers were obtained from National Dairy Development Board Database [14,36].
Goat	148.9	0.625	93.0625 million	Annual manure production was calculated based on number of animals and manure production per animals. Average cow numbers were obtained from National Dairy Development Board Database [36].

3. Utilization of Livestock Waste and Renewable Energy Consumption Pattern in Rural India

Conventionally, livestock waste is used for various purposes such as a source of fuel for cooking, and fertilizer. More recently, livestock waste has been used to feed small-scale biogas digester for producing biogas (Table 2). Subsequently, biogas is used as source of energy for cooking and lighting [37,38]. Substantial untapped potential exists in rural areas in terms of livestock, which can be further explored through biogas technology [37]. Biogas, which contains 60–70% methane is not only useful as a cooking fuel but also can be utilized as a transportation fuel [37,39,40]. While the use of biogas as a transportation fuel has been explored, currently biogas uses for transportation is limited [41,42]. In rural India, energy consumption can be disintegrated into 3 sectors: (1) domestic/household; (2) agriculture; and (3) transportation [41,43–47]. Traditionally, livestock and livestock waste has contributed to all three sectors (Figure 3).

In the domestic sector, the major tasks which require energy are cooking and lighting. For cooking purposes, wood, dung, and agriculture residues are used often [41,47]. However, when available, biogas might be used for cooking purposes. For lighting purpose, the two other sources of energy in rural areas are electricity and kerosene (Figure 3).

In the agriculture sector, water pumping and agricultural operations such as plowing and harvesting are major drivers for energy demand in rural India. For water pumping, electricity and diesel are two major energy sources [37,41,48]. The use of biogas for water pumping has been explored when available. Conventionally, the use of livestock for agricultural operations such as plowing, harvesting, and more recently the uses of diesel and electricity has increased. In the transportation sector, bullock carts (based on livestock power) were popular in India, in addition to the limited uses of tractors (run by diesel). Recently, the uses of animal for transportation have declined substantially, replaced by the uses of internal combustion engine-based transportation vehicles that requires diesel. Considerable potential exists for the uses of biogas as transportation fuel in India [42–44].

In the past two decades, the use of electricity has increased, and it has surpassed the use of kerosene in rural areas. In rural areas, between 2006–2007, the use of electricity and kerosene in terms of energy were 56% and 42%, respectively [6]. In rural households, average electricity demand is about 39 kWh/month, which is 50% of India average residential consumption [47].

A study by the World Bank reported that about 65.53% of population live in India, and 92.9% of the rural population has access to electricity (in 2018), and 41% of rural population has access to clean fuel-based technologies for cooking purposes [48]. In 2015, India obtained 15.34% of total electricity from renewable sources. Electricity demand in a village is about 1826 kWh/day, and the majority of it is used for household activities. The low consumption of electricity in rural areas in India is potentially due to the uses of fewer appliances, which require electricity such as refrigerators, electric burner, and mixer/grinders [42,47,48].

In agriculture purpose, electricity is mainly used for irrigation. More than 18 million irrigation pumps are working across India, which are run by electricity [48,49]. In cases where electricity is not available, pumps are run by diesel fuel (Figure 3) [50]. As shown in Figure 3, in each sector of energy consumption (domestic, agriculture, and transportation), biogas can play a substantial role in the use of existing technologies currently available for converting biogas produced from animal waste into electricity (with the help of generator) and transportation fuel (i.e., bio-CNG). The use of compressed natural gas (CNG) produced from biogas (bio-CNG) can be used as an alternative fuel to transportation fuels. Further, bio-CNG causes low greenhouse gas emission.

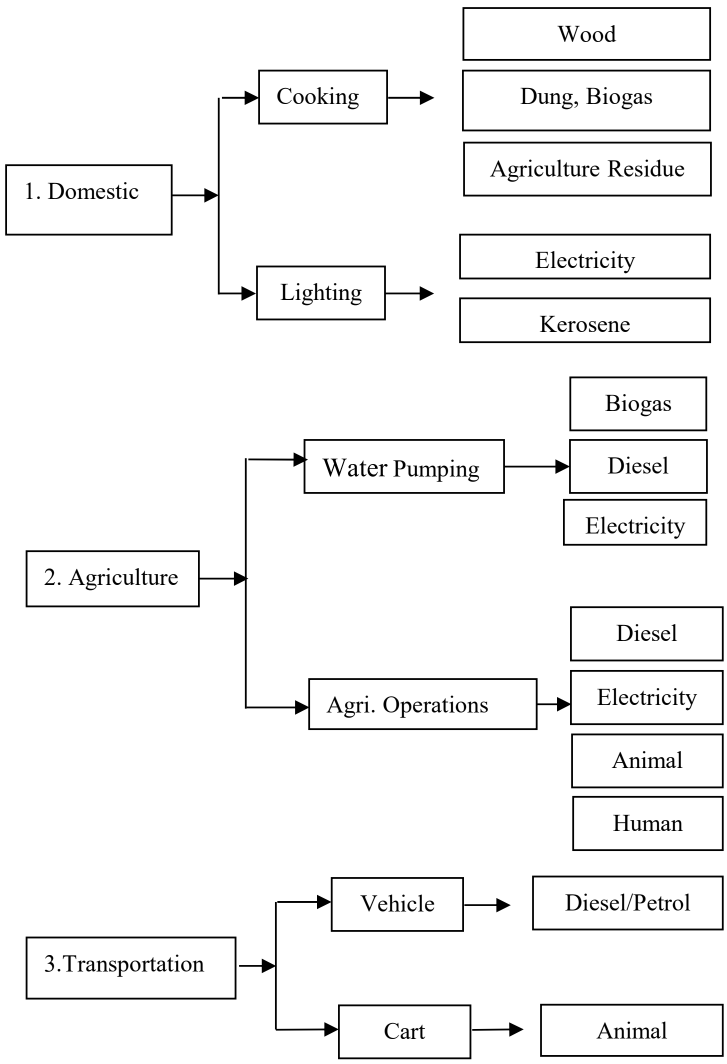

Figure 3. Energy consumption in domestic, agriculture, and transportation sectors of India, and livestock contribution (data source: [42,43,45,48,50].

Table 2. Livestock waste and waste utilization for various purposes in India.

Livestock Type	Production of Manure (Million Tonnes/Year)	Waste Use as a Source of Cooking Energy	Waste Use as a Source of Fertilizer	Waste Use for Biogas Production Using Biogas Digester	Source
Cow	730	Yes	Yes	Yes	[51]
Buffalo	574	Yes	Yes	Yes	[51]
Chicken	6.25–8	No	Yes	Yes	[52]
Sheep	3.28	No	Yes	Yes	[53]
Goat	93.06	No	Yes	Yes	[54]

In addition, bio-gasification, which is a conversion of biomass into biogas, could assist further in meeting the energy demand for domestic, agriculture, and transportation fuel purposes. For bio-gasification, the required biomass is abundantly available in the majority of the rural regions in many countries. One of the challenges in the implementation of bio-gasification is the level of technology expertise required for the operation of bio-gasification plants. Compared to anaerobic digesters, which have minimal moving parts and require minimal maintenance, the bio-gasification process involves multiple thermo-chemical reactions and successful operations requires advanced scientific and technological skills, particularly when gaseous products of bio-gasification are converted into electricity using generator. In many developing countries, attempts to install of bio-gasification plants were not very successful because plants were often dysfunctional or below the optimal capacity due to the lack of maintenance of the gas engines.

4. Biogas Promotion and Various Biogas Model Types Population in India

In India, the substantial uses of biogas energy and installations of biogas plants started in 1981–1982, when a National Project on Biogas Development (NPBD) was launched by the Ministry of Non-Conventional Energy Sources (MNES) [55,56]. Under this program, the installation of small-size biogas plants, which can be operated using 2–4 livestock were popularized. Substantial portions of expenditures incurred during installations of these plants were covered by the MNES [55]. The NPBD projects incentivized households to accept biogas technology, workers help in construction, and implementing agencies support the dissemination of biogas technologies in India. This was a crucial initiative by MNES since fossil fuel-based energy sources such as liquid petroleum gas were not commonly available in rural areas of India [57,58].

The nation-wide implementation of NPBD project helped in the installation of biogas plants across India. The top five provinces, which have the largest number of small size biogas plants are Maharashtra, Karnataka, Uttar Pradesh, Gujarat, Madhya Pradesh. Biogas plant numbers and livestock populations in these provinces are shown in Table 3. The largest number of biogas plants (about a million) are installed in various rural parts of Maharashtra. In Madhya Pradesh, the number of biogas plants are approximately 376,221 [58–60].

Table 3. Top five provinces with largest number of biogas plants in India.

State/Province Names	Biogas Plant Number	Livestock Number (Million)	Sources
Maharashtra	924,092	33	[37,55,59,60]
Karnataka	510,942	29	
Uttar Pradesh	440,949	67.8	
Gujrat	435,287	26.9	
Madhya Pradesh	376,221	40.6	

In India, multiple types of small-scale biogas digesters have been promoted. These can be divided into two major types: (1) floating type biogas plants; and (2) fixed dome types. Both floating and fixed dome types of biogas plants are semicontinuous types (Figure 4). A typical floating drum type biogas plant (Figure 5) involves a floating chamber, a manure chamber, feed inlet, and effluent outlets. In fixed dome-type biogas plants, a chamber/head space, which holds biogas, is fixed type (Figure 6). These fixed dome-type biogas plants also involve feed inlet, effluent outlets, and a chamber to house manure in anaerobic environment.

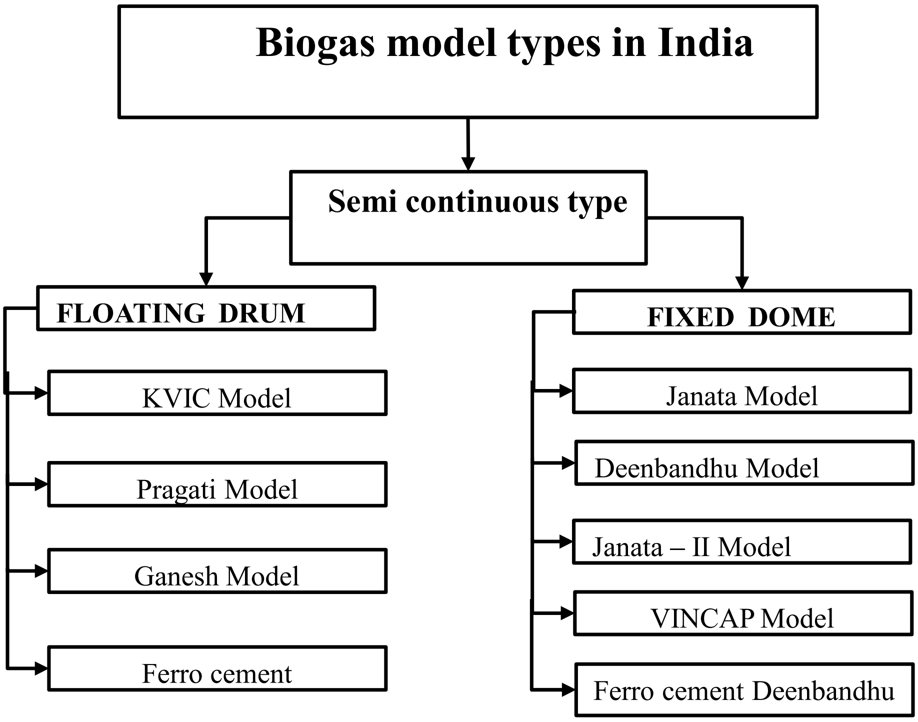

Figure 4. Classification of various types of biogas plants in India.

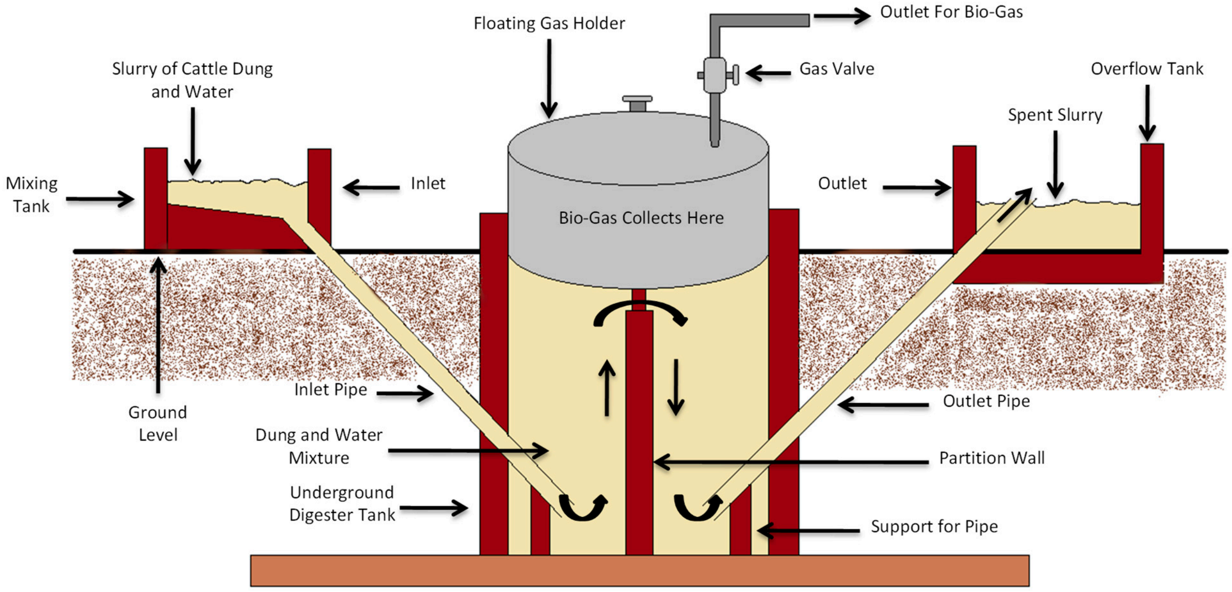

Figure 5. Floating dome types of biogas plants in India.

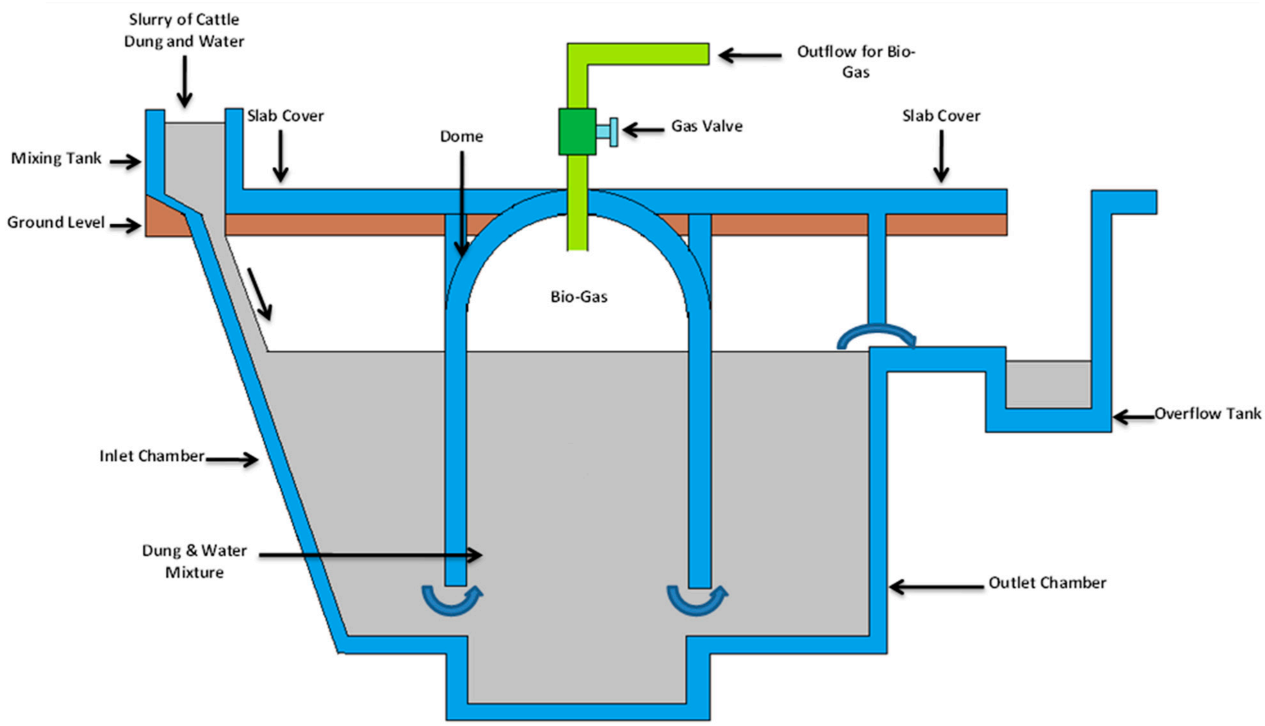

Figure 6. Fixed dome types of biogas plants in India.

Figure 5 shows a typical floating drum type biogas plant, which can vary in size between 1–10 m^3. This is also known as KVIC type. There are 4 different types of floating drum-based biogas plants (Figure 3): (1) KVIC; (2) Pragati; (3) Ganesh; and (4) ferro cement floating drum. A biogas collector, which is under floating conditions and collects the gas; depending on the biogas volume and pressure, it moves upwards and downwards, which regulates biogas pressure at the biogas outlets (Figure 4). In general, floating drum is built of metals, and concrete is used to build chamber for housing livestock waste under anaerobic conditions.

Fixed dome biogas plant design is shown in Figure 6. In contrast to the floating drum, in the fixed dome gas the chamber/head space is fixed and an outlet is provided in the top of fixed dome for gas. The anaerobic chamber, which houses livestock waste in anaerobic conditions, is built using concrete. Inlet and outlets of fixed dome and floating drome are similar in nature.

While comparing the efficiency of the fixed dome and floating dome biogas plants, studies showed that gas losses are higher in a floating dome type of digester, particularly when biogas was used to run a diesel engine. Fixed dome type of biogas plants has lower biogas losses. Further, the cost of construction of the floating drum digesters are almost twice to that of fixed dome type of digesters. In addition, the constructions of floating drum type of digesters require advanced technical skills in operations and maintenance. This could be one possible reason for the more popularity of fixed dome digester compared to the floating drum digester. One advantage of floating drum digesters is that this they do not often require mixing/agitation. Due to the inherent mixing in floating type digesters, the biogas production in floating drum digesters are expected to be slightly superior compared to fixed dome type. However, a detailed comparative study where these two different types of digesters (floating and fixed domes) of various sizes are compared for rates of biogas production and efficiencies is yet to be conducted. Both in India and China, the majority of the biogas plants (small sizes) are fixed dome type digesters.

5. Limitation in Biogas Production and Future Biogas Potential in India

While biogas technology is a robust and well-proven technique for converting animal waste into biogas, multiple challenges exist in India for large scale adaptations. Both technical and non-technological barriers exist [41], which hinders the dissemination of biogas technology in India. One of the major barriers is economic in rural areas. Biogas technology adaptations in urban areas are limited because, previously, the majority of livestock populations were in rural areas. However, currently a large number of small to medium size dairy industries, which house 10–100 dairy cows, are located in the vicinity of urban areas, where biogas digesters can play crucial role in treating animal waste, removing odor problems, creating a better environment for livestock, and converting livestock waste into biogas, a source of renewable energy.

Here, it is important to clarify the definition of rural versus urban areas in the context of India because the definition of rural and urban areas differ from one country to the next. In India, rural areas are defined (based on national sample survey organizations) as the living environment where the population density is up to 400 per square kilometer. On the other hand, urban areas are defined cities with a population of more than 5000. An additional criteria for urban areas is that 75% of male workforce in the city should be engaged in non-agriculture activities. In urban areas, the availability of livestock waste could be low, however, combining the food waste (often available abundantly) with livestock to operate these digesters can also improve the biogas production as it can enhance the food waste recycling and control the excessive influx of food waste into landfills.

Currently, livestock living environments and sanitation in livestock housing requires improvement in many dairy farms in India. A new National Biogas and Organic Manure Program (NNBOMP) has been launched to promote the installation of biogas plants of sizes between 1 and 25 m^3 with the objective of providing green and clean renewable energy source for domestic purposes [61,62]. Considering the livestock population in India, a substantial potential exists for producing biogas and organic fertilizer generated by biogas plants. An estimation showed that around 302.23 million livestock heads can produce 33,000 million m^3 biogas considering collection recovery of cattle dung of 70%. Recently, multiple biogas-based projects with the aim of producing power have been installed, with power generation capacities of 212 kW and a corresponding biogas generation capacity of 1805 m^3/day, which can be seen as positive development in terms of biogas technology adaptions. Recently waste-to-energy projects are commissioned, and existing capacity is to produce biogas of 702,508 m^3 per day and 84,759 kg per day of compressed biogas, and 141 MW of biogas-based electric power per day [62,63]. Currently, the cumulative total of 316 biogas-based projects are in operation with a total power generation capacity of 7.166 MW, however, considering the potential of biogas productions existing capacity is substantially low [55–57]. Relatively, the cost of constructions of biogas plants in India vary between $102 USD to $479 for 1 m^3 to 25 m^3, respectively, which is an affordable investment considering the benefits of biogas plants [63]. Large-scale biogas plants (>5000 m^3), which can use livestock waste and other organic waste including municipal waste can be used for converting organic waste into renewable energy is yet to be explored in India at large scale [41]. The use of biogas for transportation requires additional processes such as scrubbing, compression and upgradation of biogas, which can replace existing fossil-based transport fuel is yet to be achieved [42,43]. In terms of manpower, for the construction and operations of biogas plants, substantial resources exist, however, strategies for training relevant personal, and long-term planning are required in order to trap this underutilized potential in India.

6. Future Perspective for Biogas Technology in India

Considering the livestock population in India and growing demand for milk production, technologies which help treating animal waste and converting animal waste into renewable energy have substantial scope for development and implementation, and biogas technology is one of them. One of the major advantages in using biogas technology for treating animal waste is that it is relatively simple to develop, easily scalable, and produces a source of energy, and demand for energy in India is consistently increasing. Research showed that biogas potential in India ranges from 310–655 billion m^3 per year by 2040 [64]. Reports indicate that India may require more than 5000 compressed biogas plants (CPG) by 2023 [65]. Currently, the limited infrastructure of building large-scale biogas plants and compressing of biogas exist in India. The primary purpose of the planned CPG biogas plants is to increase the availability and affordability of renewable transport fuels and identify sustainable alternative energy source [65]. Approximately 600 million tons of biowaste is produced in India, which has the potential to increase compressed natural gas (CNG) production by 25 times and replace 50% of the total fuel imports [66]. In India, 3 different sizes of biogas plants are installed: (1) small size biogas plants; (2) medium size biogas plants; (3) large-scale (i.e., industrial size biogas plants. The current trend of dairy farms in India showed that dairy farm structure is evolving, and medium-size dairy (up to 50 cows) farm numbers are increasing, while smaller size (conventional) dairy farms with 1–5 milking animals are decreasing [67]. In many regions, the growth in medium-size dairy farms is about 30% per year [67,68]. Often when sizes of dairy farms increase, it requires improved manure management, and anaerobic digesters/biogas plants can play a crucial role in improving the manure management. The number of dairy farms in India is more than 75 million, which are more than any other countries in the world [69,70]. Based on a report by FAO, South Asia (including India) and European Union (EU)-25 are the largest dairy regions accounting for more than 44% global milk production [70,71]. The largest population of bovine in the world live in India, which accounts for 22% global milk production [70,71], and the production of animal waste in the dairy industry is unavoidable. A recent 19th Livestock Census reported that livestock population in India is about 512 million, which potentially produces 1095 million metric tons (MT) manure per year [71,72]. When manure management in the livestock environment is poor, it negatively affects livestock health, milk production, and poses risk to public and animal health [73,74]. In many developing countries such as India, substantial improvement in manure management is needed to enhance livestock living conditions and reduce the negative impacts of manure in environment and mitigate the public and animal health risk, and anaerobic digester/biogas plant technology can assist in improving the manure management and reducing the adverse impacts of manure in environment [74,75].

To disseminate biogas technology for conversion of animal waste, food waste, and biomass/organic waste into biogas (a renewable energy source), the availability of technologies can be considered sufficient. A range of technologies for converting biogas into electricity and transportation fuels are currently available. Challenges, however, in the adaptation of biogas technology include the required investment, operational cost, and economic benefits of biogas production. The use of biogas as a transportation fuel is relatively new and yet to be adapted at a large scale, however, it is an attractive alternative [76] to improve the biogas market and consumptions, which can provide a better financial return compared to the use of biogas as a source of heat.

The cost of biogas plant construction/production, operational cost of biogas plants, and cost/benefits of biogas plants is likely to change substantially from one country to the other and, particularly, there could be a huge difference in the cost of construction in developing countries versus developed countries due to the cost of labor and required materials. Existing reports suggest [77] that total production cost for a biogas plant (i.e., essential installations except land) is about 50–75 USD/m^3. Out of this, approximately 30–40% of the total cost is the digester. The running cost is equally important because operation of large-scale digester requires more human hours in supervision, disposal, gas distribution, administration, acquisition of parts, and feeding of the digesters. With the help of technology, automation can reduce the requirement of human hours, however, it will increase the production and installation costs. While calculating the capital costs, it is important to consider interest rate and lifetime of biogas plants (which is around 15–20 years) [77]. Studies available for biogas plants in California, USA suggest that the estimated total cost for dairy biogas to biomethane plants can vary from $8.12 USD–$11.82 USD/1000 ft^3 [78]. Life-cycle cost analysis of the operations of anerobic digesters in Iowa, USA, suggest that the capital cost of the digester attached to a 2400 head of cattle operation is about $3.12 million USD. Internal rate of return was 4.56%, when cattle waste was co-digested with glycerin and corn husk that has 950 kW of electric generation capacity [79]. The operational cost was mainly due to the labor and maintenance, which is about 67% of the cost of the digester.

In developing countries such as India, the high capital cost is the key barrier to adapt the biogas technology in rural areas [41]. The cost involves for the construction, labor, and equipment to complete the installation is high considering rural household incomes, which is low. Currently, the installation cost of family size biogas plants is approximately $348 USD, and government often provides $123–$200 USD subsidies (20–40% of the total installation cost) [80]. Without financial supports many households may not be able to adapt the biogas technologies in many developing counties. The large-scale adaptation of biogas technologies in both developing and developed countries is likely to be driven by subsidies and support from various government agencies under current situations.

7. Conclusions

This study was conducted to improve existing understating of biogas program in India. Both small-scale and large-scale biogas potential have been reviewed in considering with livestock population and livestock waste. Livestock waste production in India is enormous, and currently only a small fraction of this waste is used for biogas productions. This limited capability and untapped biogas not only reduces the renewable energy source in the forms of biomethane but also the emission of biogas into the air causes greenhouse gases in atmosphere, which are reportedly responsible for global warming and climate change. In general, biogas technology is mature and has been developed for small dairy farms as well as large-scale dairy farms, and biogas can be converted into various forms of useful fuel (i.e., electricity, transportation fuel, and natural gas). Improvement in existing planning, financial support, implementation, and evaluation and monitoring is needed to use the potential of biogas technology and livestock waste in India.

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