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Review of biogas digester technology in rural Bangladesh

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Abstract

Bangladesh has been facing severe energy crises (lack of electricity and gas supply network) during the last three decades, especially in rural areas. These areas are characterized by their often inefficient use of woody biomass, mainly for cooking purposes. To avoid the resulting environmental degradation and achieve sustainable development, access to clean and affordable energy is essential. Upgrading existing biomass resources (i.e., animal manure, crop residues, kitchen waste and green wastes) to biogas shows significant promise in this respect. This article presents a review of the current status of biogas digester technology in Bangladesh with focus on households in rural areas, covering 75% of the total population. Currently there exists a substantial gap between technical and cost-effective potential and the achievable potential due to lack of technical knowledge, high installation and operation costs, feedstock availability and limited end user applications. As a result only one percent of the overall biogas potential, estimated at $14.5 \times 10^6 \text{ m}^3/\text{yr}$, has been achieved despite government programs for promoting digester installation. Via in-field surveys this review has identified problems in the construction, maintenance and operation of biogas digesters, particularly in overall performance of household digesters. Based on these results a number of operational and technology improvements are suggested. Three digester implementation scenarios are introduced, and performance and cost estimates are projected to 2040. The most ambitious scenario leads to a five-fold increase in biogas output as compared to today's levels; levelized energy costs can be halved with proper choice of digester technology.

Keywords: Anaerobic digestion; Biogas digesters in South-east Asia; Renewable energy; Digesters in rural Bangladesh; Animal and agriculture wastes; Performance forecasting

Contents

1. Introduction and Objectives	4
2. Methodology	6
3. Biogas digesters in South-east Asian countries.....	7
3.1 Biogas in China	7
3.2 Biogas in India.....	8
3.3 Biogas in Nepal	10
3.4 Biogas in Vietnam	10
3.5 Biogas in Cambodia.....	11
3.6 Biogas in Thailand.....	12
4. Renewable energy scenario and biogas potential in Bangladesh	13
5. Biogas digesters in Bangladesh.....	17
5.1 Household digester status in rural areas	17
5.2 Technical aspects of evaluation of existing domestic digesters	19
5.3 Performance analysis of representative biogas plants	24
5.4 Financial support for household biogas digesters.....	27
5.5 Prospects for rural electrification	29
5.6 Major factors affecting the adoption of biogas digesters	29
5.7 Benefits and challenges of biogas plants	30
6. Analysis of expected different biogas production scenarios by 2040	31
6.1 Recommendations	32
6.2 Biogas production scenarios	33
7. Conclusions	36
References.....	37

Nomenclature

AD	Anaerobic Digestion
ADB	Asian Development Bank

AEPC	Alternative Energy Promotion Center
BDT	Bangladesh Taka (currency)
BCSIR	Bangladesh Council of Scientific and Industrial Research
BRAC	Bangladesh Rural Advancement Committee
BSP	Biogas Support Program
BAU	Business as usual
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
FMO	Dutch Development Bank
GEF	Global Environmental Facility
GIZ	Gesellschaft für Internationale Zusammenarbeit-German Agency for International Cooperation
GNI	Gross National Income
GS	Grameen Shakti
HDI	Human Development Index
IDB	Islamic Development Bank
IDCOL	Infrastructure Development Company Limited
KfW	Kreditanstalt für Wiederaufbau-Reconstruction Credit Institute
MARD	Vietnamese Ministry of Agriculture and Rural Development
MLBPs	Medium Level Biogas Plants
MNES	Ministry of Non-Conventional Energy Sources
MSW	Municipal Solid Waste
NBMMP	National Biogas and Manure Management Programme
NBP	National Bio-digester Program
NGO	Non-Governmental Agency
PO	Partner Organization
PSMP	Power System Master Plan

SED	Sustainable Energy Development
SNV	Dutch Development Agency
TS	Total solid

1. Introduction and Objectives

Energy is one of the key components required to reduce poverty, improve the standard of life, and facilitate socio-economic development. The current and continued rapid economic growth of Bangladesh leads to high energy demand with associated challenges and negative impacts. The country has been experiencing a severe energy crisis for about three decades and is third among the top twenty countries where people lack access to electricity [1]. Rural and remote areas of the country have often faced severe crises and have inadequate or no public energy supply. Only around 30% of rural inhabitants have access to national grid electricity while about 75% of the total population (164.2 million, 2012) in the country live in this area, the quality of service is unreliable and the availability of electricity is 23% [2, 3]. Less than 10% of households have natural gas connections via national pipelines, but unfortunately remote and rural areas have no natural gas access [2]. Most recent estimates show that 58% of rural families in the country are officially “energy poor” (i.e. utilization of modern energy services per capita is very low), with shortage of access to even basic energy facilities [4]. In such regions, woody biomass is estimated to cover about 62% of the country’s primary energy consumption [5], mainly for cooking and with very low energy conversion efficiency, 5–15% [6]. It is very clear that many rural and remote villages will not have access to national grid in the near future due to the large capital investments required [7].

The combination of growing energy demand, inadequate natural resource availability, and lack of renewable energy alternatives has led to a burgeoning interest in biogas technology in Bangladesh and other countries. Anaerobic digestion (AD) is a biological process that is used for the efficient conversion of livestock manure and agriculture residues into clean renewable

energy and organic fertilizer. Methane rich biogas (typically 50-70% methane, 30-50% CO₂, with traces of H₂S and other gases) is a clean, efficient, and renewable source of energy, which offers a multipurpose carrier of energy, and can be used as a substitute for other fuels (like firewood and cattle dung) currently used in rural areas [8-10]. Typical calorific values of biogas are 21-24 MJ/m³ or around 6 kWh/m³ [11]. The digestate is highly enriched in ammonium and other nourishment and can be used as an organic compost in the field or as fish feed [9,11]. Tremendous amounts of biomass resources – agriculture residues (crop/tree residue, rice husk, wheat, jute stick etc.), animal dung, woody biomass, tree leaves, municipal solid waste, kitchen waste, vegetation, sugarcane bagasse, poultry droppings, garbage, etc. – have the potential to meet the energy needs of households and small industries. Today, especially in South-east Asia millions of rural families use small-scale digesters to produce biogas for multi purposes (such as cooking, heating, cooling, lighting, CHP-combined heat and power and vehicle fuel) [8,12,13]. Biogas has definite advantages as compared to other renewable energy alternatives: it can be produced when needed, can be easily stored in reasonable quantities, and can be distributed through existing natural gas networks as a natural gas substitute [12].

Despite the advantages of the AD process, the technology as applied in rural areas suffers drawbacks such as low methane yields, incomplete bioconversion, process instability and economically non-viability. Increasing cost of feedstock, poor performance of existing digesters due to technical limitations, and operation of digesters below maximum capacity occur as a result of regional shortages of feedstock [8,14]. Additionally lack of end user productive applications is another major challenge for the technology dissemination. These drawbacks have prevented the full development and smooth operation of rural-based AD technology worldwide [9,10,15,16]. Concerted efforts from both governmental and non-Governmental sectors are absolutely essential in facilitating modernization and dissemination of biogas technology to harness the inherent potential that is currently underutilized and unexploited.

The objective of this review article is to identify the factors underlying successful and unsuccessful operation of existing domestic biogas plants as applied in rural settings. The present status of household biogas digesters in rural South-east Asia is assimilated in detail, concentrating on current opportunities and constraints in rural Bangladesh along with presentation of various government and private sector initiatives. Best practices and technologies are suggested in different scenarios up to 2040, with the goal of examining various options for increasing digester implementation.

2. Methodology

A literature review was conducted to gain a comprehensive understanding of the structures of rural energy systems and domestic digester technology in Bangladesh. Contact was made with Grameen Shakti (GS), a major non-governmental organization (NGO) in Bangladesh within the energy field. With GS's guidance a number of locations were identified for a field survey. Data collection was conducted-via questionnaires followed by interviews with GS, households, and rural energy providers. Respondee were selected in such a way that they could be representative of average features of households who own and operate the biogas plants. Some focus group discussions with households and local key informants were also organized along with the exploratory survey to get insights on the main driving forces determining the adoption of biogas technology and their overall performance in rural areas in Bangladesh.

Secondary data were collected from different Government offices, NGO's and private entrepreneurs who actively promoted the biogas activities in Bangladesh, all supplemented with scientific research papers. Different biogas production scenarios have been considered in the study, with simple mass and energy balances applied to the overall systems. LCOE (levelized cost of energy) is used as a tool for estimating biogas production costs.

3. Biogas digesters in South-east Asian countries

Domestic biogas digester implementation has gained momentum in countries like China, India, Nepal, Vietnam and Bangladesh, where governments strongly supported the installation of household digesters. During the period from 2007 to 2012, the number of household digesters has increased from 26.5 to 42 million in China and from 4 to 5 million in India [9]. Further related country data is provide in Table 1. Among different digester designs, the Chinese fixed dome digester and the Indian floating drum digester are the most common types in developing countries. These digesters are typically constructed to convert animal wastes of one family (domestic) to biogas for cooking and lighting. Typically, the average volume of the digester is approximately 5–7 m³ and provides about 0.5 m³ biogas per m³ digester volume. The following sub-chapters summarize the status of country-specific biogas programmes.

Table 1

Status of biogas digester in South-east Asian countries in 2012

Country	Year of first digester Installation	Installed	HDI & GNI	References
China	1921	42,000,000	0.891 & 11,477	[9,17-22]
India	1900	5,000,000	0.586 & 5,150	[9,21,22]
Nepal	1974 (1955)	270,000	0.540 & 2,194	[9,21-23]
Vietnam	2006 (1964)	500,000	0.638 & 4,892	[9,21,22,24]
Bangladesh	1972	70,000	0.558 & 2,713	[2,6,21,22]
Cambodia	2006 (1986)	20,000	0.584 & 2,805	[9,21,22,25]
Thailand	1982 (1960)	2,300	0.772 & 13,364	[26,22,27]

3.1 Biogas in China

More than 25% of the Chinese population rely on solid fuels for cooking [17]. Therefore, there is an enormous demand for small scale household anaerobic digesters in China, which permit effective digestion of agriculture and vegetables residues when co-digested with other

feedstocks such as animal dung and kitchen waste (less than 1% of total agriculture residues are presently utilized) [17]. As of 2010, more than 40 million household biogas digesters and 27 thousand Medium Level Biogas Plants (MLBP's) were being used in rural China, and the number of people benefiting from biogas use had reached 150 million [18]. In recent years, the Chinese government has shown increasing preference for MLBP's over household biogas because MLBP's separate livestock farm or energy production from residential areas [19]. The typical digester volume is 8–10 m³, which produces between 0.1 and 0.3 m³ of gases per m³ of digester volume per day [20]. The central government has framed a series of policies and programs to promote the development of biogas energy in rural areas [28-30]. Moreover, the Chinese government issued the Renewable Energy Law insisted on a renewable energy development fund in 2005 to inspire a number of local enterprises to become involved in renewable energy development [31]. Aside from energy policies, the Chinese government also created a series of economic measures to promote the development of biogas energy. It is also notable that establishing household biogas digester is strongly supported both financially and strategically by central and local governments of China. Since 2001, government funding has been increased at both central and local government scales. Financial subsidies from the central government vary across the country (east to west); 800–1000 CNY (US\$123–154) is offered to peasant families intending to build household biogas facilities [32].

3.2 Biogas in India

About 30% of total population is still depending on biomass solid fuels for cooking (thermal efficiency 5-15%) and without access to electricity. Animal dung-fed family size biogas plants are estimated about 12 million in 2010; the maximum potential of digesters is around 22 million with yield ranges from 3400 Mm³/yr to 17,900 Mm³/yr, depending if the whole recovered animal manure is used for biogas production [33,34]. Investigations in various states of India

have found that the percentage of functional domestic digester was from 40% to 81% in 2012 [35,36]. The types of digester involves concrete and plastic floating dome plants along with cheaper, concrete, fixed-dome plants. The floating dome system, fed with animal manure and other organic wastes is arguably more popular in south India, while the fixed dome system fed only with animal manure more common in the north of the country [21]. Moreover, there is a significant prospective for biogas production from wastes such as kitchen waste, sewage, municipal solid waste (MSW), and crop and vegetable residues such as rice husks, bagasse (sugarcane waste) and potato. Recently, a plug-flow digester sized 6-8 m³/day has been successfully designed and investigated in order to convert agriculture waste [37]. A few systems that co-digest toilet waste with MSW and kitchen waste have been reported in southern India [38]. It is encouraging that the rural and urban biogas digester distribution program is supported centrally by the Ministry of Non-Conventional Energy Sources (MNES, formerly DNES) [33,39]. So far a total of seven to eight different types of biogas digester have been officially recognized by the MNES in India.

The National Biogas and Manure Management Programme (NBMMP), initiated in 2005, is a scheme that resulted from the unification of the National Project on Biogas Development and a separate manure management initiative [21]. The NBMMP scheme aims to encourage people in rural areas to implement biogas technologies to meet their daily cooking and lighting needs. Financial support for the biogas program has been distributed into three areas according to the average altitude. The remaining states are enclosed by the third category which is depending on social categories. Farmers who do not own any land receive higher subsidy in the third category, and those who own more than five hectares land receive no subsidy. Recently, the states government and private sectors biogas dissemination have an annual intended goal of more than 8,000 digesters obtain 2.5% of the total sum of investment costs as a subsidy directly.

3.3 Biogas in Nepal

Based on the number of available animals, there is a prospect for installing up to 1.9 million household-sized biogas digester in Nepal. However, while the technology was first introduced in the year 1955, until 1985 interest in biogas digester remained limited due to high capital costs and lack of technical knowledge. Local governments decided to offer support of 25% on the investment cost and 50% on the interest imbursement to meet the goal of 800 installed digesters per year. With the backing of the Biogas Support Program (BSP), a significant number of digesters were put in place beginning in 1992. Additionally with the financial support of some 167 micro finance institutes which provide biogas credit fund, nearly 7,000 digesters were successfully installed during the first phase of the Alternative Energy Promotion Center (AEPC) Program [40], which was established in 1997 under the Ministry of Science and Technology. Subsequently, the number of biogas digesters dissemination has been constantly growing. Up to now, a total of 189,122 biogas digesters have been constructed in 66 out of 75 districts in the country [36, 40]. In the next phase, 135,000 household biogas digester are to be installed, mainly domestic- sized digesters (6 m³ volumes are most common, however sizes of 4, 8, and 10 m³ can also be found). In the socio-economic context of Nepal, subterranean Chinese-style fixed dome digesters are widespread [40,41]. The digested slurry has been demonstrated as a useful compost for agriculture. Up to now, with some exemptions, cow manure has been used principally as a major feed for the digester. There has been inadequate use of digester feed for agriculture waste, vegetable waste, kitchen waste, municipal waste and slaughterhouse waste [23]. In addition it is estimated that about 80,000 rural households in Nepal have latrines that are attached to domestic biogas digesters, helping to improve sanitation [41,23].

3.4 Biogas in Vietnam

In Vietnam, the present development, introduction and dissemination of biogas digesters technology is far below the potential for utilizing available livestock and agriculture wastes.

The nation has considered mostly the Chinese fixed dome digester model, mainly for handling animal manure. There are varieties of biogas digesters now implemented in the country, due to a diverse influence of technology transfer. Nowadays, the number of digesters is also growing due to economic provision from national and international aid agencies as well as self-financing. Up to now, the total number of installed small scale biogas digesters is more than 500,000 (sizes are less than 10 m³). Due to lack of knowledge and technology transfer, intermediate and large scale biogas plants have not been successfully developed in Vietnam to a significant extent. It is estimated that less than 1% of the medium and large scale pig farms are presently served by AD systems [42]. The biogas programme initiated by the Dutch Development Agency (SNV) and the Vietnamese Ministry of Agriculture and Rural Development (MARD) aimed to build 140,000 biogas digesters between 2006 and 2011; the target was reached, and digesters serve over 600,000 people with cooking fuel with CO₂ savings of around 260,000 tonnes per year [43]. Here limited number of plug flow digesters were employed in the program, as opposed to the smaller fixed dome digesters. The daily volume loaded into the system ranges between 0.6 and 4 m³ corresponding to a digester volume of 50 to 500 m³. Recently, 10 low cost and medium scale plug flow digesters (150 to 500 m³ size) installed by SNV and more than 215 plug flow biogas digesters (Low Carbon Farm) will be installed by four to five years' time in 35 provinces. On the other hand, access to financing is sometimes difficult due to complicated administrative procedures and limited support from the state budget. Moreover, economic support guidelines are not vibrant and do not hugely support the stockholders.

3.5 *Biogas in Cambodia*

Cambodia has very favorable environment and conditions for dissemination of biogas technology, yet this potential has not yet been achieved. The prospective and benefits of household digesters are significant in at least six of 25 provinces, and approximately 500,000

rural households could potentially install digesters. From 1986 to 2005 a total of 400 domestic digesters were built in Cambodia by international aid agencies. Most of these digesters were plastic tube type, which were either comprehensively subsidized or completely paid for by contributors or foreign agency [25]. Unfortunately, presently the large majority of these type of digesters are out of operation, because the digester have a very short life span, are difficult to maintain, and lack technical support and a practical marketable model. Under the National Bio-digester Program (NBP), a total of 20,000 domestic digesters (fixed dome type, 6 m³) were installed between 2006 and 2012, and forecasts for 2016 and 2018 call for an additional 45,000 and 20,000 units, respectively (a fixed dome type design, which is a modified Indian-model digesters) [44]. Chandararo and Dannel [45] reported that only 16% of digester owners have the ability to pay the necessary investment (after subsidy) for a 6 m³ bio-digester (total cost about US\$800). The digester credit system, sponsored by FMO (a Dutch development bank), provides soft loans to two local banks PRASAC MFI and Amret MFI (Micro Finance Institute), aimed to cope with local farmer financial demand and improve the accessibility of rural digester technologies and providing special loans for digester construction costs from 2007 onwards.

3.6 Biogas in Thailand

Thailand has the lowest utilization digesters in the South-east Asian region, which can be linked in part to its relatively high level of development (see HDI and GNI data in Table 1). There were already 1000 biogas plants in country in 1982, but until 1992, only 150 large scale pig farm digesters were in operation. However, by 2000 these activities had largely terminated, due to lack of economic support and technical knowledge [46], even though consequently larger biogas systems have become more common in livestock farms as a means to treat wastewater or slurry, with an overall volume of 60,210 m³ constructed in 2001 [47]. But recently, the country has experienced a significant increase in the deployment of digesters in different industries like starch, breweries and palm mills. Moreover, biogas resources are from

industrial wastewater and live stocks manure, which have potential of 7800 and 13,000 TJ/y, respectively [46,47]. Currently, the financing issues have been solved by several local banks but the achievement of biomass and biogas energy program in Thailand is still uncertain. The total potential of domestic digester is estimated to be approximately 200,000 in five of 76 provinces [47].

4. Renewable energy scenario and biogas potential in Bangladesh

Renewable technologies offer opportunities to provide electricity, cooking gas and heating in areas not served by domestic energy grids. However, due to technological, political and economic restraints, at present the contribution of renewable energy to overall power generation in the country is less than one percent [48]. The Ministry of Power and Energy has decided to harness the enormous potential of renewable energy to generate 5% of total electricity (about 800 MW from baseline scenario, Power System Master Plan-PSMP 2010) from renewable energy by 2015 and 10% (about 2000 MW) by 2020 [48,49]. Table 2 summarizes the main targets by energy source.

Table 2

Renewable energy potential for installed electricity capacity in Bangladesh

Renewable energy	Technical potential (MW)	Achievement (MW) in January 2015	Target (MW) by 2015- 2020	References
Solar	3000-5000	About 165	200 - 800	[48-51]
Wind	100 (resource mapping required)	2	200 - 500	[48,50,51]
Biomass and biogas	1200	18-20 (mostly cooking gas), 6 MWe	90 - 255	[48,49,51]

Mini and micro hydro	200	0.06-0.08	15 - 40	[48,51]
Tidal	5	0	1 - 2	[48-50]

The government framed a Renewable Energy Policy in 2008, but it has not been ratified as a law yet, therefore, responsible authorities are not obliged to follow through. Different government and international organizations have been working individually and in concert to spread renewable energy technologies, mostly in rural areas as described in recent literature [52-57]. However, proper planning and broad understanding is required, and additionally the sector should be continually scrutinized [58]. The major concern is initial investments; it is estimated that the primary investment is about 372 million USD for 197 MW electricity capacity (i.e. 10% of total projected electricity generation by 2020) [59].

Animal dung from cattle, buffalo, goat, sheep, horse and chicken is the most widely utilized feedstock for biogas production in Bangladesh. Total livestock production in Bangladesh has grown at 3.7 per cent annually from 2000-2013 [60-62]. It is calculated (see Table 3) that more than five billion m³/year of biogas could be achieved from the livestock wastes of the country.

Table 3

Major livestock and biogas production potential in Bangladesh in 2013 (head count in Million)

Animals	Heads in million [55,60,61]	Residue generation rate kg dry matter/animal/day [9,21]	Biogas production rate in m ³ /kg dry matter [9,21]	Total biogas potential (10 ⁶ m ³ /year)
Cattle	24.0	2.86-1.8	0.30-0.33	4510
Buffalo	1.465	2.52-2.0	0.31-0.33	0.87
Goat	55.60	0.55	0.32-0.34	4.51
Sheep	3.12	0.33	0.40-0.42	0.32
Poultry	291.50	0.05	0.31-0.32	0.92

Table 3 summaries the potential local feedstocks for digesters in Bangladesh on the basis of number of livestock. The total biogas production potential was calculated using average values for specific biogas production by animal type (Table 3). According to Wim et al. [63], more than three million households could conceivable employ domestic digesters, but according to other recent estimates a potential maximum of more than 4.5 million household units could be realized, based on an assumption of five cows per digester [9,51,55,60,64]. The manure generated by five cows is adequate to feed a domestic digester with gas yield of about 3 m³ per day. At least four cows are required for a household using the smallest digester, with production capacity of 1.2 m³. Equally, poultry litters were also identified to be a worthy feeding material for biogas production, and poultry husbandry is perceived as a large industry in Bangladesh [65]. On the other hand, the number of poultry birds used for poultry-litter based plants ranges from 250 to 1212, and averages at 1180. A household biogas user survey report [61] mentioned that out of the 300 plants, 232 use a one-to-one ratio of raw materials and water more than 80% of the plants need to be loaded only once in a day. Table 4 summarizes the situation for households in terms of cattle and poultry numbers.

Table 4

Number of household with cattle and poultry birds

Livestock	Size of cattle/poultry farm [51,60,65]	Number of household [50,66]
Cattle	With 1-2 heads	6 806 994
Cows and buffaloes	With 3-4 heads	4 211 498
	With 5 heads and above	1 072 872
Poultry	Less than 249	65 000
	With 250-999	140 000
	With 1000 or more	91 250

Agriculture production in Bangladesh has grown at 4.2 per cent annually from 2000-2013 [60]. Table 5 includes a list of major crops along with biogas production potentials from agriculture residues. Agricultural crops produce large quantities of field and process residues, which represent an important source of energy both for domestic as well as industrial purposes in rural areas. In the Table 5, it shows that the agricultural residues represent the major portion of the total recoverable biomass and biogas production potential is much higher than the livestock's waste. The total biogas production potential was calculated using average values for specific biogas production by crops type (Table 5).

Table 5

Annual yields of agricultural crops and biogas potential in Bangladesh in 2013

Crops	Production rate Ktonne/year [55,60]	Residues generation ratio		Biogas production potential, m ³ /kg dry matter [9,21,56,67]	Total biogas production potential, (10 ⁶ m ³ /yr)
		Field residue	Process residues		
Rice	51500	1.7	0.35	0.50-0.62	8994
Wheat	1255	1.75	-	0.65-0.75	89.64
Vegetables	13221	0.4	-	0.3-0.9	115
Sugarcane	7300	0.3	0.29	0.4-0.7	127
Jute	1657	3.0	-	0.3-0.4	750
Pulse	767	1.9	-	0.4-0.5	5.7
Cotton	473	2.75	-	0.3-0.35	46.8
Maize	2042	2.0	0.47	0.4-1.0	381.2
Groundnut	126	2.3	0.477	0.4	239.6

Bio-slurry from digester is an environmentally friendly organic fertilizer and can play an important part in re-establishing the richness of the soils. Potential of organic fertilizer/bio-

slurry only from cow dung and poultry droppings is about 92×10^6 tons/year [68,69]. From above analysis of the agriculture feedstock's (Table 5), it can be estimated that the potential of bio-slurry from agri-residues could be much higher than animal wastes. The nutrient quality of the bio-slurry is much higher compare to other compost manure and chemical fertilizer. Several field investigations showed that the positive effects of digested-slurry in increasing the products of cabbage, brinjal, tomato, onion, potato and papaya [68].

5. Biogas digesters in Bangladesh

5.1 Household digester status in rural areas

Currently fixed-dome digesters are most popular in the country. About 90% of digesters are cow dung based, with 6% utilizing poultry waste and 1-2% other substrates. The first domestic digesters (size 3 m^3) were built in 1972. Initially the dissemination rate was very poor due to high initial investment requirements, lack of proper technical knowledge and no subsidy or support. In early 1980, there were some limited initiatives taken by governmental sectors to accelerate the dissemination of household digesters in rural areas. In 1994 the government formed a public limited company called Infrastructure Development Company (IDCOL) with economic aid from the World Bank and major emphasis on the energy sector. In 1995 an important dissemination push was provided by the Biogas Pilot Plant Project, organized by Bangladesh Council of Scientific and Industrial Research (BCSIR). More than 25,000 fixed dome biogas digesters that principally use cattle manure were constructed under this project up to 2008. Additionally 37,269 domestic biogas digesters were financed by IDCOL, under the National Domestic Biogas and Manure Program between 2006-2012 [61,66,69,70]. Figure 1 shows the progressing of digester implementation between 1985 and 2015.

Fig. 1. Total number of installed digesters in Bangladesh from 1985 to 2015 [53,54,71,72]

Major governmental organizations like IDCOL (with the help field based local organization), BCSIR along with NGO's like Grameen Shakti (GS) and Bangladesh Rural Advancement Committee (BRAC) are currently engaged in dissemination of domestic biogas plants (1.2 - 4.8 m³ digester size) [51,57,7,73]. As up to June 2015, a total of around 77,500 biogas plants have already been built in Bangladesh. Table 6 shows the number of domestic biogas plants installed by major organizations in Bangladesh as of June 2015. (Data for 2013 is also included as a reference; the growth rate between 2013 and 2015 is about 10%). From several field surveys in different areas of Bangladesh, it is quite clear that the locally made digester is mostly fixed dome type. Other designs include floating-dome and plastic-dome digesters, with fiberglass sometimes used as a construction material. The most popular sized AD plant is 3.2 m³ plant (50% of plants installed). A report on annual biogas user survey [61] showed that out of the 300 household plants, 253 are cow-dung based and the remaining 47 are poultry-litter based. Best results had been observed when poultry litter is mixed well with cattle manure for AD. When using only poultry litter as a feed for digester there is a risk of high

ammonia concentration, which also may reduce the specific biogas production per kg fresh substrate.

Table 6

Organization-wise digester installation in 2013 and 2015

Organizations	Number in 2013	2015	References
IDCOL	31,258	about 35,000	[53]
BCSIR	22,334	23,000	[72]
Grameen Shakti (outside of IDCOL)	7,200	8000	[71]
NGOs and others	9,850	11530	[54]
Total	70,642	77,530	

5.2 Technical aspects of evaluation of existing domestic digesters

Typical small-scale dome type digesters (single feedstock) in Bangladesh feature a retention time of about 40-50 days and a daily feed supply of 60 kg of manure (corresponding to 5-6 cows). Plastic pipes are used overwhelmingly as the gas distribution device, and for gas transmission, overhead method is preferred to underground method. Average distance of biogas plants from the nearest water source is about 18 meters. Only 13 of the surveyed plants [61,74] have toilet attached, which is a reflection of the prevailing social customs. The majority of the surveyed plants have one slurry pit [74]. The plants (72 plants) having no slurry pit dispose the bio-slurry directly to nearby water-body. The size of slurry pit is positively correlated to the size of biogas plants as expected. Almost half of the plants have no pit boundary and 60% lack a pit shed. Through the field investigations and the interviews with local stake holder and technical personal, different performance data was collected on the quality of the installation materials necessary for the biogas digesters. Inlet tanks of household digesters were made of bricks and completed with plaster. Biogas was supplied to the point of end users use mainly for

cooking purposes through flexible 19 mm diameter plastic. One annual survey report has shown that single burner is the dominant form of using biogas in the surveyed households (216 out of 300) [74]. The daily average use varies from 4.42 hours for single burners and 3.72 hours for double burners [74]. Most of the biogas stoves were made in the vicinity and delivered to the user by the organization in charge for dissemination the digesters.

A technical survey report [75] (66 biogas plants under analysis in three different regions in Bangladesh) found that three percent of digesters were working without any fault, 76% were malfunctioning but working and 21% were out of order and not functioning during the time of field investigation. The causes for malfunctioning digesters were low availability of feeding materials and poor and inefficient digester performance and operational activities like ineffective digestion process, short circuiting, higher water-feed mixing ratio, and improper design, size and construction.

Another case study on biogas plants survey [76] reported that the most of local users used a lower daily feedstock compared to the required dose – 33% less as recommended in the GS Handbook. Insufficient number of cows was the key cause to be given. It was also identified during the digester visit that the owner failed to charge the digester appropriately; therefore the microbial growth was affected. Most of the time, lack of knowledge seemed to be the major cause for such type of ineffective management. Additionally, this survey compared data from the GS Handbook in terms of biogas rate and composition percentage; outcomes showed that the small cattle farm and poultry farm digesters were 57% and 29% efficient, respectively (biogas production efficiency). Nearly all of the NDBMP 2010 surveyed biogas plants (300 biogas plants) are operating below their promised daily biogas production design capacity (best performance is about 33% efficiency), which is a serious barrier for the technology dissemination [74]. Another recent survey [77] studied 70 household digesters and found that 83% of the digesters were malnourished/underfed, with 50% of the digesters getting lower than

half of their necessary feedstock. According to the observation report, improper feeding usually occurs when the farmers sell their livestock after the digester is built. Another key reason for improper feeding (water/feed mixing) is lack of appropriate training. Other malfunctions were caused by ineffective workmanship or sub-standard construction materials [77]. Large variations exist in dimensions; some may be explained due to rocky underground or high ground water table during construction, so depth instructions were not followed, and volumes and diameters have been changed. The outcome of surveyed biogas digesters field reports suggested as follows in Table 7.

Temperature is the most significant factor that has a substantial impact on biogas production throughout the digestion process. Most importantly, rural people suffer from very low biogas production rates or in stagnation during the winter period, when the temperature goes under 12°C. Biogas yield efficiency normally rises with temperature, roughly doubling for every 10°C rise between 15°C and 35°C (cow manure as a feedstock) [78,79]. But the average inside temperature of a biogas digester in Bangladesh remains at 19°C–26°C [80], which is close to the ideal situation [81] for psychrophilic condition but the measured digester temperature do not promise higher gas yield.

Table 7

Field survey data of existing domestic biogas digester and evaluation of their design parameters [74-77]

Digester parameter	Proportion of surveyed digesters within range of standard	Variations	Deviation
Diameter	8% diameter	22% plants smaller than standard and 69% plants larger than standard diameter	-20% to +25%

Height of effective gas storage (pressure height)	9% with proper height	42% lower than standard and 49% higher than standard	-26% to +50%.
Dome height (gas storage tank)	5%	63% lower than standard and 32% higher than standard	-24% to +25%.
Outlet diameter	17%	37% had shorter and 46% had longer	-25% to +19%.
Height of outlet tank up to overflow	20%	47% less than needed and 33% more than standard	-40% to +58%.
Tank volume	4%	53% smaller than standard and 43% larger than standard	-40% to +48%

Maintaining correct operating parameters are also critical for obtaining the maximum biogas yield from the digesters. C/N ratio i.e. carbon nitrogen ratio is one of the guiding factor in the process of biogas production. Usually, a C/N ratio of 20 - 30: 1 is appropriate for biogas production [5,14,16]. One technical study in Bangladesh [82] revealed that the C/N ratio from poultry manure is within the lowest range of an optimal C/N, which will reduce the optimal substrate specific biogas production capacity (see Table 8) [74]. pH is another key parameter ,as pH values between 6.8 and 7.2 yield the best production of biogas [5,14]. Usually pH of a digester is self-regulating, so any deviations tend to be corrected to the reference value on its own. But there could be cases where pH needed to be controlled if too much deviation is observed. Usually lime water is introduced to the digester to maintain pH. For locally made digesters there are no arrangements for periodic measurement of pH. One more aspect that might affect biogas yield very badly is the quality of the animal dung. Periodic loading and unloading are very important for maximizing the biogas production. The dome type digester faces various problems related to floating, scum formation and segregation of feed.

In the digestion process C, H and O components of feedstocks are lost in the form of CH₄, CO₂ and H₂O, and all the other necessary nutrients such as moisture, N, P and K and trace elements are remained within the slurry [74,82]. A survey of digesters found that the pH value of slurry ranged between 6.9-8.2 with an average value of 7.3 (see Table 8) [74,82]. These findings indicate that actual pH levels are generally suitable for an effective AD process. In terms of slurry consistency this survey noted a highly diluted (watery) slurry in 52% of the plants, with 10% exhibiting thicker consistencies (the remaining 38% were average).

Table 8

C/N and pH contents in animal feedstocks and slurry [61,74,82]

Manure	pH	C/N	% moisture	N%	P%	K%
Cow dung	7.48	20:1	12.28	1.03	0.53	0.75
Cow dung slurry	7.63	18:1	11.09	1.20	0.63	0.85
Poultry	7.76	19:1	12.14	1.80	0.95	1.35
Poultry slurry	7.89	16:1	10.22	2.15	1.20	1.55

Biogas slurry is one of the two end products of the AD inside biogas plants. Bio-slurry can be used for a variety of purposes, the main being use as organic fertilizer in farms. To optimize benefits from biogas plants it is important that the users realize nutrient values of bio-slurry and use it to enhance agricultural productions. The field survey findings revealed that 72 out of 104 households were using bio-slurry in some way [74]. About 50% of the interviewed farmers are using bio-slurry in the production without any problem in handling or storage; if the farmers have not enough pit volume for storage, they dry the slurry, or compost it with other agricultural waste, are selling it as fertilizer or as cooking fuel, or feed fish. Finally, Table 9 summarizes the reasons for failure or partial failure in the operation of locally made fixed domed digesters.

Table 9

Major reasons behind the failure and partial satisfaction with functioning of bio-digester [61,74,78,79]

Functioning of plants	Reasons
Failure	<p>Poor design and construction</p> <p>Low quality construction materials</p> <p>Poor operation (improper feeding, more water, more feed)</p> <p>Ineffective maintenance or, no maintenance service available</p> <p>Non-availability of spare parts</p> <p>Natural/man-made disasters</p> <p>Slurry entered into the gas pipe</p> <p>Water collected in pipe, clogged it</p> <p>Higher water level/overflowing during rainy season</p>
Partial satisfaction	<p>Less gas for cooking/lighting</p> <p>Gas leakage through pipelines</p> <p>Low gas during winter</p> <p>Difficult to operate</p> <p>Problems with slurry flow because plant was too deep</p> <p>Problems with main gas valves and mixture machine</p> <p>Cracks in dome and outside walls</p> <p>Often run into technical problems</p> <p>More additional effort</p> <p>Technicians not available on demand</p> <p>Others</p>

5.3 *Performance analysis of representative biogas plants*

In order to illustrate the existing biogas digester operational conditions, survey information was analyzed on current status of biogas plants. The present condition of different components of biogas digesters was observed in detail during a field investigation to assess the features of

construction and effectiveness of operation and maintenance activities carried out. Both primary and secondary data were composed from household digesters schemes. A total of 11 biogas household digesters were visited throughout the interval of this work. Eight out of the 11 plants visited used poultry waste as feedstock (dome type, psychrophilic condition, and single feed, HRT 50 days). From the field survey, it was observed that the owners did not monitor the volume of feedstock recommended in the provided handbook; as a substitute they used a smaller volume of substrate daily compared to the most favorable one, so the substrate had loaded and unloaded periodically. The feedstock feeding rate to the digester was once per two days. Total solid (TS) in the feed slurry was typically used as the material unit to indicate the biogas production rate (TS values of about 8% are desirable). In the surveyed digesters it was found that there was no control of TS. For optimal C/N ratio (carbon and nitrogen ratio) different substrates (organic wastes) are mixed for which maximizes the production of biogas. For locally made digesters there are no arrangements for periodic measurement of pH which could reduce the biogas production but for the cases of imported digesters there are arrangements for periodic pH measurement.

The variation of temperature will reduce biogas yield and methane content of the gas. Neither biogas yield or methane content nor electricity generation is monitored for locally made dome type digesters. But methane content of biogas was monitored for Nazim Poultry Farm (local digester, fixed dome type) at Rangpur, but not tabulated. The methane content during the hotter part of the year varies among 60% to 65%. But during the winter season it can fall as low as 40% or sometimes no more gas production [81]. The performance of (biogas production rate in-terms of feedstock potential and digester size) different digesters are shown in Fig. 2 and Table 9;

- Local digester (fixed dome type without digester heating or temperature and pH control, poultry litter as feed),

- Imported digesters (paragon poultry digester heating under constant temperature, poultry litter),
- Low ambitious digester (fixed dome type but better management with feedstock and mixing, poultry litter and cow manure), and
- New plug flow digester with heating and co-digestion (animal wastes and agriculture residues)

It was observed that the biogas production rate all around the year was constant for the temperature control imported digester. The imported digester inside temperature is maintained about 35-38°C all around the year with help of engine exhaust gas (temperature about 500-650°C) via heat exchanger.

Fig. 2. Variation of biogas yield for different type digesters and system throughout the year

Table 10

Comparisons between two types of digesters in Bangladesh

Biogas plants	Animal waste (t/day)	Total solid (kg)/HRT(days)	Biogas (m ³ /kg TS)	Electricity (kWh/day)	Digester efficiency (%)	Digester inside temperature
Paragon Poultry (CSTR)	20	6000/20	0.7	6300	86-90	35-38
Nazim poultry (Fixed dome)	0.08	16/40	0.4	10	50-55	22-27

There are notable seasonal variations in the aspects of availability of raw materials, gas availability and quantity of slurry produced. Rainy season is generally better for gas availability whereas the flow really shrinks during the winter. The field data and information revealed that the quality control procedures being practiced were not effective. Though there was standardized quality control procedure in place, however, detailed guidelines on how to monitor the compliance of the procedure was lacking.

5.4 Financial support for household biogas digesters

The Bangladeshi government established the regulatory body IDCOL for monitoring, evaluating, issuing, and distributing subsidies and credits to the biogas users. Funding of IDCOL comes from different organizations, including World Bank, GEF (Global Environmental Facility), KfW (Kreditanstalt für Wiederaufbau-Reconstruction Credit Institute), GIZ (Gesellschaft für Internationale Zusammenarbeit-German Agency for International Cooperation), SNV (Netherlands Development Agency), ADB (Asian Development Bank) and IDB (Islamic Development Bank). The investment support for the owner was increased to USD 96 per digester, and about 50 local agencies were identified in the regions (mostly districts) receiving a fee of USD 64 per digester.

GS, a partner organization of IDCOL, providing two types of financial facilities for digesters owner. The owner can construct digester with own funding under GS technical

supports but has to pay 10% of total construction cost for supervision and technical support for GS biogas model. Otherwise the owner has to pay 5700 BDT (Bangladeshi Currency) (1 USD = 80 BDT) for technical and supervision support for IDCOL digester model. Another financial facility from GS provides the digester owner with 5000 BDT as a subsidy, with 15% of construction costs covered by the owner as down payment and remaining costs paid in 24 monthly installments with a flat rate service charge 6%.

The IDCOL biogas user survey [80] showed that almost all the surveyed users (except 5 out of 300 biogas plants) received grants from IDCOL or its POs. The grant covers on an average about 22% of the total investment costs required. The rest have to be incurred by the users. Although the grant size is officially about 9,000 BDT (provided by IDCOL), it varied a little bit according to the amounts reported by the users (see Table 11), which appear to be somewhat correlated to the plant size (the differences are of course not significant except for the smallest plants of 1.6 m³).

Table 11

Financing mechanism of household biogas plants by IDCOL or its POs [61,71]

Plant size in m ³	Total expenditure in BDT	Average amount of grant in BDT	Expenditure by plant owner	Average amount of loan
1.6	28,403	7,000	21,265	16,428
2.0	29,007	8,175	21,012	15,901
2.4	32,732	8,562	24,161	18,331
3.2	38,108	8,741	27,380	21,919
4.8	68,961	8,885	59,897	24,683

The financing mechanism of 6 m³ commercial biogas plant could be explained briefly that the PO's share is 25,200 BDT out of the total cost of 45,000 BDT for constructing a biogas plant which is done on a credit basis. Dissemination strategy of commercial biogas plants total amount by monthly installment with interest. Moreover, PO gets 5,000 BDT for after sale service up to 5 years. The PO also gets an amount of money for promotional activities like

printing leaflet, brochure etc. The main difference between these (SED and IDCOL) two programs is that size and design. Another important difference is that SED provide revolving funds to PO's which strengthening financial capacity. IDCOL provides soft loan to PO's which they have to return to IDCOL.

5.5 Prospects for rural electrification

In the field investigation of biogas plants, it has been seen that some digester holders set up petrol, diesel, and natural gas generators to run with biogas for electricity use in the plants. At present about 300 engine are using biogas for electricity of size up to 260 KW [72]. Currently total 750 kW electricity is being generated from biogas by the direct observation and technical assistant of SED program [83]. According to survey report from IDCOL, the country has more than 215,000 poultry farms and 15,000 dairy farms and by installing biogas plants in these farms, more than 1,000MWe electricity can be generated.

5.6 Major factors affecting the adoption of biogas digesters

Various reasons actively motivate the household toward biogas adoption: environmental, economic, technical, and social aspects. Environmental reasons refer to health benefits, forestation, and soil fertility. Economic reasons consist of subsidies, credits, income generating and number of livestock (number of cattle and poultry birds owned by a household is likely to be an important factor in the biogas adoption process). Technological reasons related to time and energy savings, fuel shortage, service provider and technical training. Finally, social reasons include neighbor plant owners' inspiration, NGOs motivation, advertisement attraction, and local government activities.

One recent case study [84] on 150 biogas plants stated that environmental (63%) and economic (59%) benefits are the major reasons motivating households for adopting the biogas plant. Another field survey study [85] showed that about 90% of biogas users were motivated

for adopting the biogas technology by NGOs. These NGOs indeed are actively working to promote renewable energy use with new technology in rural areas of Bangladesh. Neighbors played also an effective role in households' decision making process toward biogas technology. However, this study shows that socio-economic features of the target receivers are vital in the popularization of new technology such as the biogas one.

5.7 Benefits and challenges of biogas plants

The overall performance assessment of biogas digesters of the Biogas Pilot Plant Project investigated by DPC Group [85] is the most dependable source of for an impression of the benefits provided by the disseminated biogas digesters. This survey considered 620 digesters spread across six regions in Bangladesh. Socio-economic benefits are obvious, as most of the plant owners used biogas for cooking, and cooking demand was largely met. Decrease in bad smell of feedstocks like animal dung currently fed to the digesters stated by the farmers. Around 10% of owners use biogas for lighting, which reduces kerosene demand. Other benefits come from saved time and money for cooking (no more collecting or purchasing wood). Most of the bio-digester owners use bio-slurry commonly as fertilizer but also as fish feed. Another biogas user survey report [61] claimed that the 300 households in one year have saved 23,816 workdays through reduced time necessary for cooking and management of fuel. Switching to biogas also reduces greenhouse emissions owing to reduced wood fuel usage and lower methane emissions emanating from unused manure. Katuwal and Bohara [23] reported that a household size biogas digester can replace the direct burning of 3 metric tons (6600 pounds) of fire wood and 576 kg (1270 pounds) of manure annually, consequently reducing 4.5 metric tons (9900 pounds) of CO₂ emissions. Bio-slurry from the biogas digester can be used in horticulture, pisciculture, and agriculture. The average saving per digester amounted to BDT 759 per month [68]. A case study [23] in Nepal also showed that 68% of the family observed

an increase in crop yield and 42% of households stated increase in revenue from vegetable production after the use of bio-slurry.

Turning to challenges, feedstock availability a major hurdle. Several studies have indicated that some existing biogas plants have been facing severe difficulties due to lack cattle dung or poultry litter. Only cooking energy needs cannot meet because all rural household does not have the required number of cattle or poultry and the availability of animal dung has been finite and limiting. Household biogas plant using cattle dung can be feasible when eight cows are available per family [78]. The main barriers to dissemination of the technology is the existing law for marketing slurry as organic fertilizer and the lack of awareness of the people using slurry. Social and non-pay attitude problems have been identified as barriers in rural areas, which in turn have made private investors reluctant to be active in biogas projects. The major challenge of rural energy business in a poor country is (i) high upfront cost associated with the technology (ii) low incomes and (iii) lack of access to credit [78].

There is a necessity to establish specialized plans that convey awareness and constructive understanding to a wide stakeholders, farmers and owners through a diversity of mass media and multi-stakeholder dialogs, more importantly, programs for technology and knowledge transfer from the countries.

6. Analysis of expected different biogas production scenarios by 2040

The Bangladesh government has prepared PSMP-2010 to meet the demand with reasonable reliability, installed capacity to be increased to 24,000 MW and 39,000 MW by 2021 and 2030 respectively [47]. The renewable energy share will be in total about 3,168 MW and 10 MW will be added through biogas by 2021 [47]. Moreover, IDCOL has a target in 2012 of financing 100,000 biogas plants by 2018 of which 37,700 biogas plants have been constructed under the program up to March 2015. But there is a doubt about fulfilling the target by that time.

Among the surveyed biogas plants, five types of plant sizes ranging from 1.6 m³ (smallest) to 4.8 m³ (largest) are found and medium size plant of 2.4 m³ seems to be the most demanded one (about 45% of total surveyed cow feed plants). But for the poultry fed digester, the bigger size (4.8 m³, about 60% installed) is more preferable. It can be seen from Table 3 and Table 5, the yearly biogas potential with only animal wastes as feed is about 5000x10⁶ m³ and additional 10500x10⁶ m³ could be obtained from agriculture residues. But the present biogas production rate is about 14.6x10⁶ m³/yearly (in 2015) which is definitely very low compare to the potential. Fig. 1 showed that the installation of digester is moderately increasing by about 4000-5000 per year in between 2005 to 2015. If it considered that the rate of local digester installation is similar, the forecasted cumulative number of digester will be about 215000 by 2040 (Fig. 3).

6.1 Recommendations

To further develop the biogas industry in rural Bangladesh, the authors recommend that scientific and technological support be strengthened to promote household biogas development in rural areas, especially for small holder biogas digesters in remote areas;

- Selection of new digester technology:

The plug flow (or channel) digester has ability to handle larger volume efficiently compare to dome type digester; perhaps the simplest and least expensive digester, it is able to produce gas with wide variety of feedstock's with high percentage of solids content, and it does not need any internal mixing [78,86-90].

- Co-digestion of animal manure and agriculture residues:

One of the methods for the economic viability of biogas plants is to increase their biogas yield up to 40-60% by co-digesting the animal dung with more degradable organic wastes (agriculture and vegetable wastes) as long as such wastes are accessible in the locality [91-93].

- Mesophilic condition (35-37°C) and other parameters:

Biogas yield efficiency normally rises with temperature, roughly doubling for every 10°C rise between 15°C and 35°C (cow manure as a feedstock) [78,79]. For optimal pH and C/N ratio (carbon and nitrogen ratio) different substrates (organic wastes) are mixed for which maximizes the production of biogas.

6.2 *Biogas production scenarios*

When deciding upon the most cost effective and efficient digester system, multiple alternatives were evaluated. Three different scenario cases incorporating various recommendations have been considered for comparing the biogas production rate versus number of installed digesters by 2040 (see Table 12 and Fig. 3). These three scenarios and digester installation trends are used to forecast the biogas production in 2040 for rural areas of the Bangladesh (Table 12 and Fig. 3). These scenarios are presented below:

Scenario 1: Business as usual (BAU) case – Fixed dome type (psychrophilic condition, single feedstock, cow/poultry dung) inefficient digesters, poor and uncontrolled operating parameters (daily feeding, feedstock and water mixing, temperature, pH, TS concentration, insulation). In the first scenario, it is considered as present case (which is available in survey data) in rural Bangladesh with inefficient dome type digester and uncontrolled operating parameters and poor maintenance

Scenario 2: Easily obtainable or low ambitious case – Fixed dome type (psychrophilic condition, combined animal wastes as feedstock) inefficient digesters, proper feedstock supply and mixing with water but uncontrolled operating parameters (pH, temperature, insulation, TS concentration).

Scenario 3: High ambitious/advanced case - modern digester (plug flow, mesophilic condition (35-37°C) and co-digestion of agriculture residues and animal wastes, high TS value), multiple feedstock's with controlled operating parameters and proper maintenance.

Table 12

Yearly biogas production rate scenarios by 2040

Scenarios in 2040 (total digesters 215,000)	Feedstocks	Type of digesters and conditions	Efficiency of digester	Biogas production rate (10 ⁶ m ³ /year)
BAU case	Single feed (cow dung/poultry waste)	Dome type, psychrophilic (10-27 °C), poor operation and maintenance	29% for cow dung, 57% for poultry litter	46
Low ambitious case	Mix feed (cow and poultry waste)	Dome type, psychrophilic (10-27 °C) condition, properly mixing and feed supply	50-60% for mix animal manures as feed	66
High ambitious (advanced) case	Co- digestion (animal and agri wastes)	Plug flow, mesophilic (35-37 °C) condition, pH (6.8-7.2), TS 14- 16% and controlled parameters	More than 95% for combined agri- animal wastes feedstock's	106

Fig. 3. Biogas production rate and number of digester installation scenario in 2040 for three cases

Fig. 3 shows that the future biogas production rate is double in advanced case compare to BAU case with same amount feedstock input. The higher biogas production in 2040 for the advanced case is mostly due to new type digester (plug flow), proper mixing of multiple feedstock, maintenance of mesophilic conditions and control of pH and TS value. In the analysis, it has been considered that the dome type digester installation will start declining from 2015 and new type digester (plug flow) construction will take place instead. Fig. 3 shows that the dome type digester will be replaced by new plug flow digester and completely phase out at 2030.

The economic viability of each system was also evaluated, with levelized cost of biogas chosen as the figure. The levelized cost include capital costs (C_c), operation and maintenance cost (C_{om}); replacement cost (C_r), and fuel cost (C_f). If the amount of useful energy produced

over the total life period of the system is (E_l) then LCOE is represented by Equation (1) as follows:

$$\text{LCOE} = \frac{C_c + C_{om} + C_r + C_f}{E_l} \quad (1)$$

The economic analysis shows that the levelized costs for biogas are varying widely in three different scenarios. The analysis showed that the levelized costs of existing dome type digester is about 0.37 USD/m³ while the cost of biogas (0.17 USD/ m³) is less than half in the plug flow digester with heating and co-digestion (animal and agriculture wastes) facilities. The advanced scenario (plug flow digester with heating and co-digestion) appears to be more effective and less costly than BAU scenario (fixed dome type digester) and Low ambitious scenario (fixed dome type but better maintenance), biogas levelized cost is 0.33 USD/m³.

7. Conclusions

The development of biogas sector is generally recognized as a success to Europe and America but not in developing country like Bangladesh. Despite huge feedstock potential until now biogas plants are not economically feasible for most of the cases. One of the main purposes of this study is to analyze the factors affecting the overall performance of existing biogas technology in rural areas in Bangladesh. It has been found that most of the biogas plants lack schemes for controlling the operating parameters like temperature, pH, TS control, agitation, loading and unloading apart from few of the biogas plants which are imported. Hence the imported biogas plants produce up to 75% more biogas than the locally available biogas plant. Biogas energy potential from available biomass residues (animal wastes and agriculture residues) in rural Bangladesh has been estimated in this paper. However, the biogas recovery technologies reliance only single feedstock on animal manure will need to be overcome by extensively using other agriculture residues in co-digestion mode. Moreover, the huge potential of biogas can be used for decentralized electricity generation and other productive purposes like

heating, lighting and cooling in rural areas in the country. The government sectors and NGO's could play a vital role to encourage the digester owner to install of new efficient type digesters technology, optimization of major operating parameters (like temperature, TS, C/N ratio etc.), better management of digesters and locally available feedstocks. A gradual shift in attitudes and policy toward replacing chemical fertilizer subsidy program is essential. This research work represents the impact of different factors on production of biogas and the paper also analyzed three different biogas production scenarios by 2040. Since biogas is mainly competing with (free) solid biomass in rural Bangladesh, financial investment for biogas in some cases fail to breakeven over long period of time. So, another purpose of this study is to investigate the economic viability of biogas plants in rural Bangladesh by comparing different scenarios. After all, achieving a sustainable energy system on biogas sector in rural areas requires comprehensive reforms in all techno-economic, social and policies aspects which represent one of the most crucial investments in future.

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