Environmental Science and Pollution Research (2024) 31:1841–1862
https://doi.org/10.1007/s11356-023-31328-4

REVIEW ARTICLE

Zone-wise biogas potential in India: fundamentals, challenges, and policy considerations

Pradeep Kumar Meena[1] · Amit Pal[1] · Samsher Gautam[2]

Received: 1 June 2023 / Accepted: 28 November 2023 / Published online: 8 December 2023

Abstract

The current manuscript focuses on the advancements made in establishing zone-based biogas plants in India from 1990 to the present. India generates various types of waste from agricultural, industrial, and human activities. Several methods are available to manage and derive energy from these waste materials, such as incineration, gasification, and anaerobic digestion (AD). Among these options, AD stands out as one of the most viable and environmentally friendly alternatives for biogas production, thanks to its low energy consumption. However, developing biogas plants in developing countries faces significant challenges, primarily due to governments' inadequate application of policy, financial, social, market, information, and technical constraints. To compile this information, data from various agencies in India have been gathered, revealing that 1.81 million biogas plants are currently installed in the West Zone, 1.48 million in the South Zone, 1.106 million in the North Zone, and 0.65 million in the East Zone. These biogas plants across the zones generate 7.02 lakh m^3 per day. Additionally, 22 bio-CNG plants produce 84,759 kg/day of compressed biogas, and 201 waste plants generate 330.935 MW of electricity. Recently, the government has emphasized several initiatives, including GOBAR-DHAN, New National Biogas and Organic Manure, Sustainable Alternative Towards Affordable Transportation, and the waste-to-energy program. These initiatives aim to enhance the utilization of waste, promote cleanliness in villages and towns, and support the Swachh Bharat Mission and Atmanirbhar Bharat campaign, leading to tremendous overall success.

Keywords Biogas plant · Barriers, Policies and plans · Waste management · Environmental sustainability · Renewable energy · Energy production

Introduction

India, the world's second-most populated country with 1.38 billion people, covers a total area of 3.28 million km^2 and is divided into four zones: West, North, South, and East (Ministry of Home Affairs 2021; MSME 2021). The country faces numerous environmental challenges due to its growing population, rapid urbanization, and the generation of a significant amount of waste. Additionally, India relies heavily on Gulf countries to meet its escalating energy demands, resulting in a fuel crisis and highlighting the need for alternative energy sources (Prabakar et al. 2018). Fossil fuels dominate global energy consumption, accounting for approximately 84% of the total (Shafiee and Topal 2009). However, finding sustainable and environmentally friendly solutions for waste management and renewable energy generation has become crucial for long-term viability (Bajić et al. 2015).

A substantial percentage of the global population lacks access to electricity and relies on solid fuels like firewood, agricultural wastes, cow dung, and coal for cooking (WHO 2009). As a developing country, India produces a substantial amount of waste annually, estimated at around 62 million tons, with a 4% annual growth rate (Bhatia et al. 2020). Proper management of municipal organic waste, which has significant potential as a biogas plant substrate, is essential to prevent environmental hazards (Pandyaswargo et al. 2019). Unfortunately, more than 90% of waste streams in India are disposed of in uncontrolled landfills, burned openly, or composted inefficiently (The World Bank 2019). Effective

Responsible Editor: Ta Yeong Wu

✉ Pradeep Kumar Meena
pradeep_2k18phdme08@dtu.ac.in

[1] Department of Mechanical Engineering, Delhi Technological University, Delhi, India

[2] Harcourt Butler Technical University, Kanpur, India

waste management technologies, particularly biogas, can help reduce India's reliance on fossil fuels and convert massive amounts of garbage into electricity (Masera et al. 2015). Biogas production from waste biomass is considered a crucial alternative worldwide, given the negative environmental impacts and greenhouse gas emissions associated with fossil fuels (Bhatia et al. 2020).

Promoting biogas production would contribute to developing renewable energy sources, reducing greenhouse gas emissions, and improving the economic conditions for underprivileged populations, especially farmers in rural India (MNRE 2019). Biogas is produced through the anaerobic digestion of biodegradable organic matter, such as animal waste, producing methane (Mukeshimana et al. 2021). The calorific value of raw biogas ranges from 21 to 23 MJ/m^3 and consists of 50–70% methane, 30–50% carbon dioxide, and other residual gases (Dieter Deublein 2011; Akinbami et al. 2001). Biogas utilizes the residue as fertilizer and soil conditioner as a renewable energy source, reducing waste and enhancing agricultural efficiency. Anaerobic digestion of organic wastes, including food, manure, and wastewater sludge, is a global focus for this technology (Di Maria et al. 2017). Composting organic wastes reduces groundwater and soil contamination and local air pollutants like carbon dioxide and methane (Lewis et al. 2017). Replacing fossil fuels and untreated solid biomass with clean fuels like biogas helps to mitigate greenhouse gas emissions and indoor air pollution (Pathak et al. 2009). While biogas energy is well suited for households and small-scale farms, especially in hot climates, it is increasingly recognized as a viable technology for industrial applications, providing heat and cogeneration (Kothari et al. 2010). Biogas energy generation can transform a costly issue into a profitable solution (Walekhwa et al. 2009). Biofertilizers produced from biogas plants can partially or fully replace chemical fertilizers, addressing the high energy demand during fertilizer production in agricultural lands (Saidmamatov et al. 2021). Domestic biogas digesters offer economic, social, and environmental advantages to rural households, addressing the lack of clean cooking energy and crop fertilizer supply (Ahmad Romadhoni Surya Putra et al. 2017; Diouf and Miezan 2019).

The concept of anaerobic methane digestion was first implemented in India in 1939 at the Indian Agricultural Research Institute (IARI) in New Delhi. The first biogas plant was developed in 1946, followed by the construction of the Gramalaxmi gas plant by Patel in 1951, producing approximately 5.7 m^3 of gas per day. An improved version of the Gramalaxmi gas plant was developed in 1954, known as the KVIC design. It gained recognition for its trouble-free operation, stable gas pressure, and efficient cast iron burners. The Khadi and Village Industries Commission (KVIC) popularized this design, and by 1963, India had over 6000 biogas plants. The KVIC design, colloquially known as the "Janta plant," with over 100,000 installations, remains India's most widely utilized design (Qureshi 1985).

The National Project on Biogas Development (NPBD), initiated in 1981–1982, promoted advanced digester designs and provided financial assistance, training, and development activities. During the 1980s and 1990s, government subsidies at the state and federal levels ranged from 30 to 100% for residential bioreactors (Tomar 1995). By 1999, India had over three million family-sized biogas plants, and by the end of 2007, government subsidies had supported the construction of around four million family-sized biogas plants (Bond and Templeton 2011). The country has over five million biogas plants (Statista 2021). The simplicity and versatility of biogas technology have facilitated its widespread adoption in India (Amigun and Von Blottnitz 2010). However, further research is required to create more efficient and cost-effective anaerobic digestion systems for waste-to-biogas conversion, including biogas, biohydrogen, and biomethane. Providing incentives and GST (goods and services tax) exemptions to individuals and biogas-related enterprises can ensure the success of waste-to-renewable energy projects (Surendra et al. 2014). These endeavors contribute to energy generation from waste biomass and environmental protection (Bhatia et al. 2020), with ongoing research focusing on optimizing biogas production methods and the quality of the generated residue (Angelidaki et al. 2018).

While the European Union (EU) currently produces approximately half of the world's biogas, developing countries have shown inadequate biogas output due to various factors such as climate conditions, technology availability, developmental levels, natural resource endowment, and socioeconomic factors (Gu et al. 2016). Developing countries often rely on small-scale and home-based biogas facilities (Chen et al. 2010). In contrast, emerging countries increasingly establish medium- and large-scale biogas facilities (Patinvoh and Taherzadeh 2019). Limited research has been conducted on the barriers to rural bioenergy adoption (Rao and Ravindranath 2002), stakeholder perspectives, and bioenergy possibilities (Kumar et al. 2015), and the performance of biogas development efforts through rural case studies (Raha et al. 2014). The potential for biogas diffusion in developing countries is significant, but infrastructure, funding, and policy gaps have hindered widespread adoption (Patinvoh and Taherzadeh 2019).

A review article was conducted to gain insights into the biogas plant scenario in India, particularly across different states and regions. The review aimed to cover five main areas:

1. Analysis of the increase in biogas plants over the last 30 years regarding the number of states, union territories, districts, wards, population, and areas.

2. Assessment of the current status of biogas plants in different zones, including the achieved targets by states and zones, and identification of the best and worst-performing conditions in each zone.
3. Examine the number of waste-to-energy plants in each zone, the proportion of plants producing biogas or bio-CNG, and the overall power generated.
4. Discuss the obstacles faced in installing and developing biogas plants in a developing country like India.
5. Overview of new schemes and policies aimed at boosting biogas plant installations.

By addressing these areas, the review article aimed to provide a comprehensive understanding of the biogas plant landscape in India, including its growth, challenges, and potential strategies for further development.

Zone-wise biogas plant growth rate (%) from 1990 to present

West Zone

In the West Zone of India, there are a total of 151 districts and 21,265 wards. However, only 7273 wards have access to door-to-door waste pickup services. Among the states in this zone, Goa is the only one that provides 100% door-to-door waste collection from all its wards. The West Zone has the highest number of biogas plants installed, with a total of 1.81 million plants (Table 1).

There is no biogas plant in Lakshadweep, but population = 64,473, one district, area = 32 km^2, density = 2013/km^2 is added in the south zone, and data for Telangana in Andhra Pradesh has been added. Presently, J&K is a union territory, but we considered all those data till 2019–2020, when it used to be a state. Source: Subramanyam 2015; Census of India 2011; Census of India 2008; Planning Commission of India 2019; Statista 2021; Lohan et al. 2015; MSME 2021

Maharashtra alone accounts for approximately 0.92 million biogas plants, nearly 50% of the total in the West Zone. On the other hand, Dadra Nagar Haveli and Daman Diu have the lowest number of biogas plants among this region's states and union territories. Examining the growth rates of biogas plants from 1990 to 2002, Rajasthan, Madhya Pradesh, Gujarat, Dadra Nagar Haveli and Daman Diu (Union Territory), Maharashtra, and Goa experienced growth rates of 90.89%, 446.71%, 278.59%, 27.06%, 82.15%, and 131.69%, respectively. The average growth rate of biogas plants in the West Zone during this period was 176.18%. From 2002 to 2010, the growth rates for biogas plants in these states were 1.19%, 44.82%, 17.11%, 0%, 15.6%, and 16.03%, respectively, with an average growth rate of 15.29% for the entire region.

From 2010 to 2020, the growth rates for biogas plants in these states were 7.64%, 27.28%, 5.66%, 302.95%, 18.39%, and 8.55%, respectively. The average growth rate during this period was 61.74%. Over the 30 years from 1990 to 2020, the states in the West Zone experienced an average growth rate of 84.57% for biogas plants. Among the states, Madhya Pradesh had the highest growth rate at 172.93%, while Maharashtra had the highest increase in biogas plants.

North Zone

In the North Zone of India, which includes states like Himachal Pradesh, Jammu and Kashmir, Uttarakhand, and Uttar Pradesh, the climate conditions are considered cold, with an annual average temperature ranging from 15 to 20 °C. Uttar Pradesh is the largest state in population, districts, wards, and land area. On the other hand, Jammu and Kashmir is the smallest state in terms of land area in this zone. Out of 18,473 wards in the North Zone, only 4327 wards have access to door-to-door waste collection services. Chandigarh is the only one that provides 100% door-to-door waste collection in all 26 wards among the union territories in the North Zone. Regarding biogas plants, 1106 million are erected in the North Zone. Uttar Pradesh has the highest number of biogas plants, accounting for nearly 40% of the total number in the zone.

On the other hand, Jammu & Kashmir and the Union Territory of Chandigarh have established the most diminutive biogas plants in the region. Looking at the growth of biogas plants from 1900 to 2002, Jammu and Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh experienced growth rates of 177.54%, 110.99%, 364.43%, 25.97%, 1547%, 143.58%, 16.95%, and 104.76%, respectively. The average annual growth rate during this period was 311.40%. It is worth noting that Uttarakhand experienced significant growth during this period as it was established as an independent state after being split from Uttar Pradesh. From 2002 to 2010, the growth rates of biogas plants in these states were 26.66%, 4.05%, 53.15%, 0%, 579.25%, 22.47%, 0.44%, and 14.05%, respectively, with an average growth rate of 87.5% for all states. Interestingly, no new biogas plants were built in Chandigarh during this time. Continuing from 2010 to 2020, the growth rates for biogas plants in the states of this zone were 28.56%, 4.35%, 76.26%, 42.6%, 3369.56%, 17.29%, 14.87%, and 4.42%, respectively. The average growth rate during this period was 441.02%. However, during this time, existing biogas plants in Delhi were shut down, resulting in a negative growth rate for biogas plants in Delhi. Overall, the average annual growth rate of biogas plants in the North Zone over the 30 years from 1990 to 2020 was 279.97%.

Table 1 Details of the growth rate of biogas plants, geographical location, and the population status in the states of all zones

	State/Uts	Districts	Total no. of wards	Population	No. of wards with 100% Door-to-door collection	Area (km^2)	Density	Biogas plant (1990)	Biogas plant (2002)	Biogas plant (2010)	Biogas plant (2020)
(a) West Zone	Rajasthan	35	5247	68,548,437	1300	342,239	201/km^2	34,864	66,552	67,348	72,497
	Madhya Pradesh	50	6999	72,626,809	3602	308,245	236/km^2	37,332	204,100	295,580	376,221
	Gujarat	26	1730	60,439,692	1658	196,024	308/km^2	92,908	351,745	411,950	435,287
	D & N Haveli and Daman Diu	3	43	585,764	13	603	970/km^2	133	169	169	681
	Maharashtra	35	7054	112,374,333	508	307,713	365/km^2	370,662	675,177	780,527	924,092
	Goa	2	192	1,458,545	192	3702	394/km^2	1448	3355	3893	4226
	Total	**151**	**21,265**	**316,033,580**	**7273**	**1,158,526**	**412/km^2**	**537347**	**1,301,098**	**1,559,467**	**1,813,004**
(b) North Zone	Jammu and Kashmir	22	1163	12,267,032	989	42,241	297/km^2	708	1965	2489	3200
	Himachal Pradesh	12	502	6,864,602	167	55,673	123/km^2	20822	43,933	45,716	47,706
	Punjab	22	3065	27,743,338	2000	50,362	551/km^2	14802	68,745	105,289	185,583
	Chandigarh	1	26	1,055,450	26	114	9252/km^2	77	97	97	169
	Uttarakhand	13	706	10,086,292	90	53,483	189/km^2	0	1547	10,508	364,582
	Haryana	21	1449	25,351,462	332	44,212	573/km^2	18129	44,160	54,083	63,436
	NCT of Delhi	8	272	16,787,941	232	1484	11,297/km^2	578	676	679	578
	Uttar Pradesh	75	11,290	199,812,341	491	240,928	828/km^2	180806	37,0219	422,269	440,949
	Total	**174**	**18,473**	**299,968,458**	**4327**	**488,497**	**2888/km^2**	**235922**	**53,1342**	**641,130**	**1,106,203**
(c) South Zone	Andhra Pradesh	23	5356	84,580,777	4697	275,045	308/km^2	89,327	334,054	457,938	574,988
	Karnataka	30	5252	61,095,297	3962	191,791	319/km^2	65,968	340,270	418,759	510,942
	Kerala	14	2096	33,406,061	1280	38,863	859/km^2	23,471	79,532	126,463	152,771
	Tamil Nadu	32	12,802	72,147,030	9182	130,051	555/km^2	127,096	201,295	216,516	223,894
	Puducherry	4	129	1,247,953	81	479	2598/km^2	447	573	578	17,541
	A & N Islands	3	24	380,581	18	8249	46/km^2	98	137	137	97
	Total	**107**	**25,659**	**252,857,699**	**19220**	**644,478**	**780/km^2**	**3,06407**	**955,861**	**1,220,391**	**1,480,233**

Table 1 (continued)

	State/Uts	Districts	Total no. of wards	Population	No. of wards with 100% Door-to-door collection	Area (km^2)	Density	Biogas plant (1990)	Biogas plant (2002)	Biogas plant (2010)	Biogas plant (2020)
(d) East Zone	Bihar	39	3229	104,099,452	519	94,163	1102/km^2	58,553	121,913	125,888	129,925
	Sikkim	4	48	610,577	4	7,096	86/km^2	364	3475	7333	9044
	Arunachal Pradesh	16	42	1,383,727	18	83,743	17/km^2	24	1514	2957	3609
	Nagaland	11	234	1,978,502	165	16,579	119/km^2	124	1667	4153	7953
	Manipur	9	315	2,570,390	130	22,327	122/km^2	339	1956	2128	2128
	Mizoram	8	193	1,097,206	66	21,081	52/km^2	591	2818	3820	5856
	Tripura	8	244	3,673,917	0	10,486	350/km^2	114	1719	2793	3710
	Meghalaya	7	114	2,966,889	6	22,429	132/km^2	167	2309	6661	11,156
	Assam	27	883	31,205,576	45	78,438	398/km^2	8557	51,269	81,592	138,483
	West Bengal	19	2875	91,276,115	1130	88,752	1029/km^2	40,474	203,669	318,510	1072
	Jharkhand	24	815	32,988,134	161	79,714	414/km^2	0	400	4933	7855
	Odisha	31	1012	41,974,219	456	155,707	269/km^2	48,407	185,690	239,818	271,690
	Chhattisgarh	27	3232	25,545,198	739	135,191	189/km^2	0	3047	32,050	59,700
	Total	**230**	**13,236**	**341,369,902**	**3439**	**815,706**	**329/km^2**	**157,714**	**581,446**	**832,636**	**652,181**

Uttarakhand witnessed the highest annual growth rate of 1831.93% during this period, mainly due to the establishment of biogas plants in the state.

South Zone

The South Zone of India is the third-largest zone in terms of land area but has the smallest population. It consists of five states and three union territories. However, Telangana is considered together with Andhra Pradesh for data purposes, and the data of Lakshadweep union territory is added. Therefore, a total of four states and two union territories are included in this zone. The South Zone has a total of 25,659 wards, out of which 19,220 wards have 100% door-to-door waste collection. Among the states, Tamil Nadu has the most significant number of wards and districts, while Kerala has the smallest number.

Examining the growth rates of biogas plants in the South Zone from 1990 to 2002, Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Puducherry, and Andaman and Nicobar Islands experienced growth rates of 273.96%, 415.81%, 238.85%, 58.38%, 28.18%, and 39.79%, respectively. This growth is illustrated in Fig. 1c. During this same period (1990–2002), the average growth rate of biogas plants in the South Zone was 175.82%. From 2002 to 2010, the average growth rates for these states and union territories were 37.08%, 23.06%, 59%, 7.56%, 0.87%, and 0%, with an overall average growth rate of 21.26%. It is worth noting that no new biogas plant was built in the Andaman and Nicobar Islands Union territory during this period, resulting in a 0% growth rate for the region. Additionally, from 2010 to 2020, the growth rates in these states and union territories were 25.65%, 22.01%, 20.8%, 3.4%, 2934.77%, − 29.19%, with an average growth rate of 496.24% for the 10 years. During this later period, some existing biogas facilities in the Andaman and Nicobar Islands Union territory were closed down, leading to a negative growth rate in the sector. Overall, from 1990 to 2020, the South Zone experienced an average growth rate of 231.05% for biogas plants. Among the states, Karnataka had the highest growth rate at 153.62%, while Puducherry had the highest increase in biogas plants with a growth rate of 987.6%.

East Zone

The East Zone of India encompasses several states and has a total of 13,236 wards, out of which 3439 wards have 100% door-to-door waste collection. However, it is worth noting that Tripura is the only state in this zone where no society has implemented door-to-door waste collection. Examining the growth rates of biogas plants in the East Zone from 1990 to 2020, the states of Bihar, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, Assam, West Bengal, Jharkhand, Odisha, and Chhattisgarh experienced growth rates of 108.2%, 854.67%, 6,208.33%, 1244.35%, 476.99%, 376.81%, 1407.89%, 1282.63%, 499.14%, 403.2%, 400%, 283.6%, and 3047%, respectively. These growth rates are illustrated in Fig. 1d. The average growth rate across the East Zone for this period was 1276.37%.

From 2002 to 2010, the growth rates of biogas plants in these states varied. They increased by 3.26%, 111.02%, 95.31%, 149.13%, 8.79%, 35.55%, 62.47%, 188.47%, 59.14%, 56.38%, 1133.25%, 29.14%, and 951.95%, respectively, with an average growth rate of 221.83% over the 8 years. Moving on to the period from 2010 to 2020, the growth rates of biogas plants in the region were as follows: 3.2%, 23.33%, 22.04%, 91.5%, 0%, 53.29%, 32.83%, 67.48%, 69.72%, − 99.66%, 59.23%, 13.29%, and 86.27%. The average growth rate for these 10 years was 32.5%. It is important to note that no new biogas plants were built in Manipur during this time, and the existing biogas plants in West Bengal saw a shutdown rate of 99.62%, resulting in a decrease in the number of biogas plants in the East Zone from 2010 to 2020. The average growth rate of biogas plants in the East Zone over the past 30 years is 510.23%. Arunachal Pradesh experienced the highest growth rate during this period at 2108.56%. Among the states, Odisha has the highest number of biogas plants installed.

Present status of estimated and cumulative achievement of biogas plants in states of different zones

West Zone

Rajasthan has installed only 7.89% of its potential biogas plants in the West Zone. In contrast, Madhya Pradesh, Gujarat, Dadra Nagar Haveli, and Daman Diu & Goa have installed 25.02%, 78.52%, 34.05%, and 52.83% of their potential, respectively. On the other hand, Maharashtra has installed 102.36% more biogas plants than expected, making it the state with the highest number of biogas plants in this zone and the entire country (Fig. 2).

North Zone

In the North Zone, Jammu, Kashmir, Delhi, and Chandigarh have installed biogas plants at just 2.49%, 4.48%, and 12.07% of their anticipated capacity, respectively. Himachal Pradesh has installed 38.14% of its potential biogas plants, while Punjab, Haryana, and Uttar Pradesh have installed 44.72%, 20.94%, and 22.72%, respectively. Uttarakhand is the only state in this zone that has exceeded expectations, with 438.09% more biogas plants than anticipated.

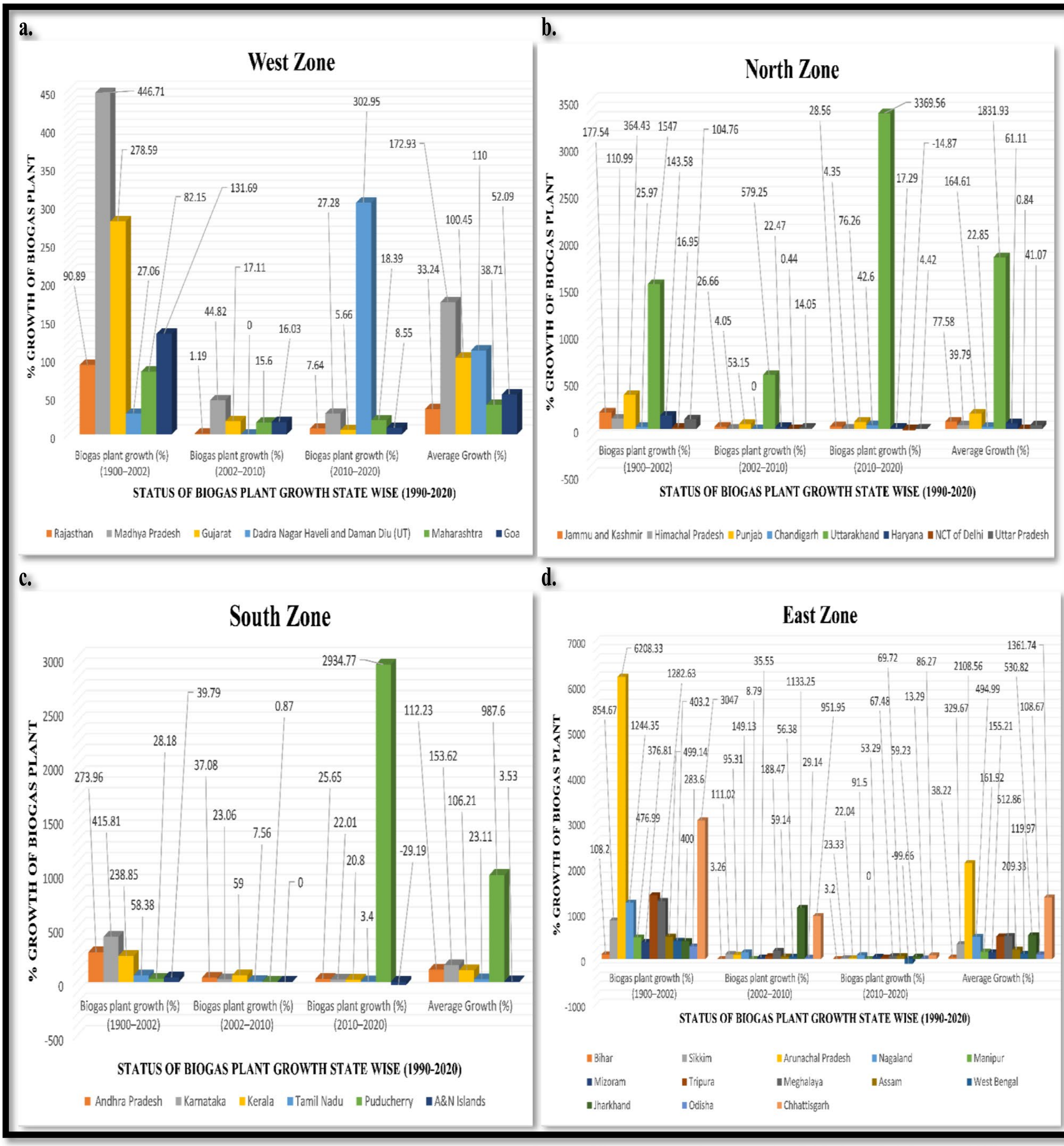

Fig. 1 Status and growth rate of biogas plants from 1990 to present: **a** West Zone, **b** North Zone, **c** South Zone, and **d** East Zone

South Zone

In the South Zone, AP & Telangana, Karnataka, Tamil Nadu, and A & N Islands have installed 53.98%, 74.1%, 36.36%, and 4.4% of their potential biogas plants, respectively. Kerala and Puducherry have exceeded their estimated potential, installing 101.34% and 407.93% of their respective capacities.

East Zone

In the East Zone, states like West Bengal, Jharkhand, and Manipur have installed 0.13%, 7.82%, and 5.6% of their potential biogas plants, respectively, falling far below their expected capacities. Bihar, Arunachal Pradesh, Tripura, Meghalaya, Assam, Odisha, and Chhattisgarh have also struggled to establish biogas facilities, building only a

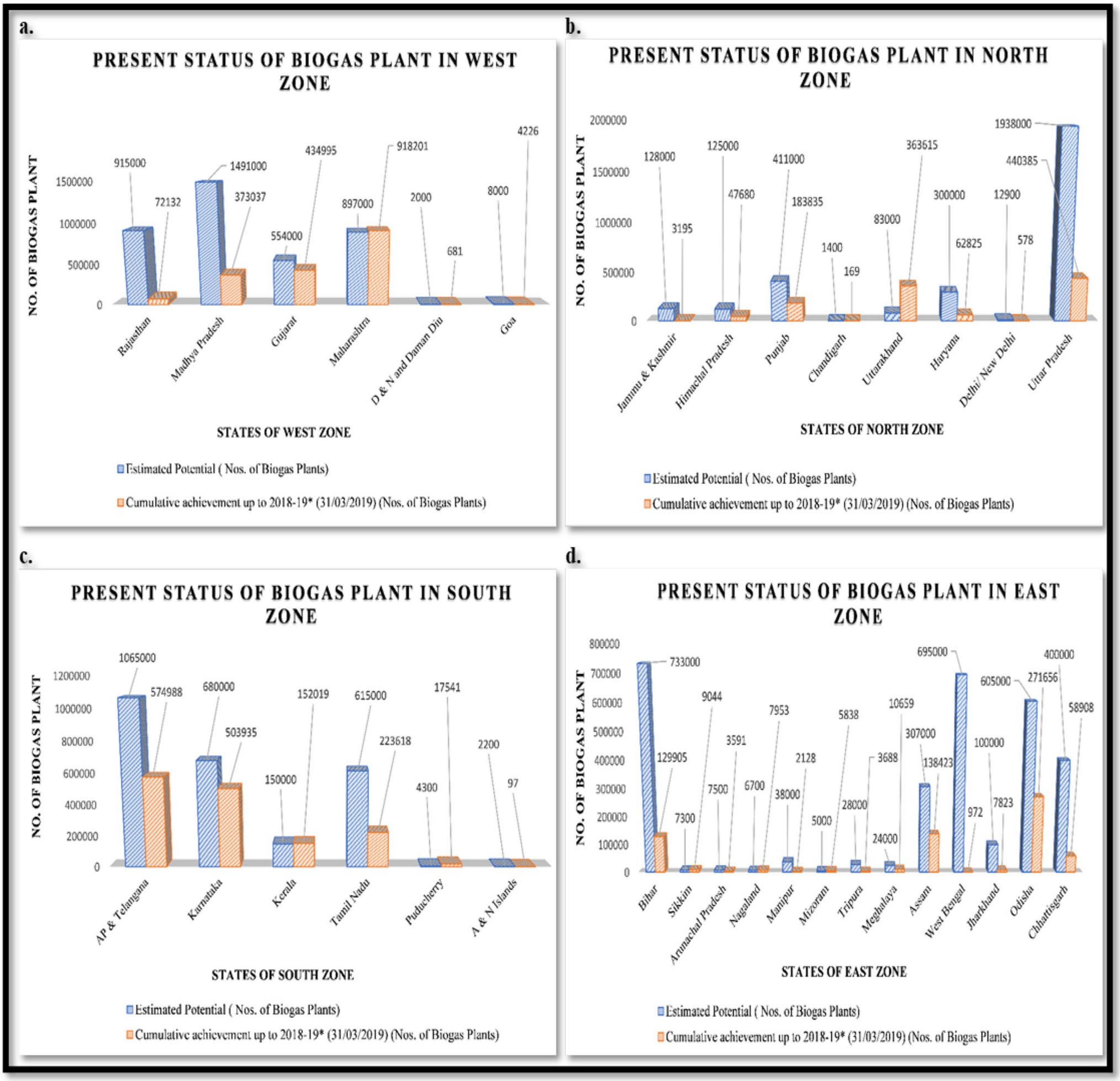

Fig. 2 Estimated potential and cumulative achievement of biogas plants in **a** West Zone, **b** North Zone, **c** South Zone, and **d** East Zone (MNRE 2021a)

fraction of their capacity. However, Sikkim, Nagaland, and Mizoram have surpassed their projected potential, installing 123.89%, 118.7%, and 116.76% of their biogas facilities. Overall, most states in the North and East Zones have established less than half of their anticipated biogas capacity, while some states in the West and South Zones have exceeded their expected potential. These variations in achievement can be observed in Table 2, with different states categorized based on their performance.

Status of waste-to-energy plants and biogas production in different states of the regions

Maharashtra generates the highest power in the western region, producing 43.63 MW from 29 garbage facilities. It yields 1.6 lakh m^3 of biogas daily from 19 biogas facilities, with 12 units producing over 61,000 kg of bio-CNG gas daily. The West Zone has 60 waste plants generating 84.61 MW of energy. Moving to the northern

Table 2 Worst, moderate, and excellent categories in biogas installation by states in different zones

	0–50% Biogas plants established by states/UTs (worst condition)	51–100% Biogas plants installed by states/UTs (moderate condition)	51–100% Biogas plants installed by states/UTs (moderate condition)
(a) West Zone	Rajasthan	Gujarat	Maharashtra
	Madhya Pradesh	Goa	_
	D & N and Daman Diu	_	_
(b) North Zone	Jammu & Kashmir	_	Uttarakhand
	Delhi/New Delhi	_	_
	Chandigarh	_	_
	Himachal Pradesh	_	_
	Punjab	_	_
	Haryana	_	_
	Uttar Pradesh	_	_
(c) South Zone	A & N Islands	AP & Telangana	Kerala
	Tamil Nadu	Karnataka	Puducherry
	_	_	_
	_	_	_
(d) East Zone	Manipur	_	Sikkim
	West Bengal	_	Nagaland
	Chhattisgarh	_	Mizoram
	Jharkhand	_	_
	Tripura	_	_
	Bihar	_	_
	Arunachal Pradesh	_	_
	Meghalaya	_	_
	Assam	_	_
	Odisha	_	_

part of Uttar Pradesh, six units produce 62,320 m^3 of biogas daily using organic waste. One waste plant generates 2000 kg of bio-CNG gas daily, while the other twenty-two waste plants utilize solid waste. This zone generates around 44.63 MW of electricity, with a total of 54.24 MW generated by 29 waste facilities.

Delhi generates a maximum of 52 MW of electricity using three waste facilities, while Himachal Pradesh generates up to 1 MW. The North Zone states collectively generate 36,670 metric tons of trash, which produces 1.7 lakh m^3 of biogas from 17 plants. An additional 7117.44 MW is made from 36 waste facilities, resulting in 135.06 MW of electricity generated by 60 waste facilities, the highest in all zones.

Table 3 Status of biogas production, MSW generation, and power generation from waste to energy plants in the states of different zones

In the South Zone, Andhra Pradesh generates 6141 metric tons of waste daily, producing 90,540 m^3 of biogas from seven biogas plants. Fifteen waste plants generate 40.81 MW of electricity. Tamil Nadu generates 1.5 lakh m^3 of biogas daily from 28 biogas plants and 22.97 MW of electricity from 34 waste plants, using 15,272 metric tons of municipal solid waste (MSW). Kerala generates less biogas, providing only 0.23 MW of power from 2760 m^3. The South Zone has 77 plants generating 108.775 MW of electricity.

In the East Zone, West Bengal has experienced the shutdown of most of its biogas facilities, leaving only two plants producing 14,000 m^3 and generating 1.17 MW of power. Bihar has one biogas plant generating 12,000 m^3 and 1 MW of energy. Chhattisgarh has a single waste energy plant generating 0.33 MW of power. Overall, the East Zone has four waste facilities generating 2.5 MW of power from the three biogas plants, producing 26,000 m^3 of biogas.

In summary, there are 83 biogas plants across all zones, generating 7.02 lakh m^3 of biogas daily. Additionally, 22 plants produce 84,759 kg of bio-CNG per day. Power is generated by 96 waste facilities, totaling 254.33 MW. The combined output of all 201 regional waste facilities is 330.93 MW of electricity.

Table 3 Status of biogas production, MSW generation, and power generation from waste to energy plants in the states of different zones

State/UT		Municipal waste generation (metric tons/day)	Biogas generation plants M^3/day (no. of plants) (A)	Bio-CNG generation plants kg/day (no. of plants) (B)	Power generation plants MW (no. of plants) (C)	Total MWeq (A + B + C)
(a) West Zone	Rajasthan	5247	-	4000 (2)	3.0 (1)	3.83 (3)
	Madhya Pradesh	5079	27,014 (5)	1200 (1)	15.4 (3)	17.90 (9)
	Maharashtra	26,820	109,636 (10)	27,723 (4)	28.713 (15)	43.63 (29)
	Gujarat	9277	24,800 (4)	28,338 (5)	11.275 (10)	19.25 (19)
	Total	**46,423**	**161,450 (19)**	**61,261(12)**	**58.38 (29)**	**84.61 (60)**
(b) North Zone	Delhi	8400	-	-	52.00 (3)	52.00 (3)
	Haryana	3490	-	4250 (3)	4.0 (2)	4.89 (5)
	Punjab	3900	34,800 (5)	1847 (1)	14.92 (7)	18.20 (13)
	Uttarakhand	1400	67,260 (5)	5880 (2)	1.89 (2)	8.72 (9)
	Himachal Pradesh	300	12,000 (1)	-	-	1.00 (1)
	Uttar Pradesh	19,180	62,320 (6)	2000 (1)	44.63 (22)	50.24 (29)
	Total	**36,670**	**176,380 (17)**	**13,977 (7)**	**117.44 (36)**	**135.05 (60)**
(c) South Zone	Andhra Pradesh	6141	90,540 (7)	-	40.82 (15)	48.365 (22)
	Karnataka	8784	58,060 (3)	9521 (3)	7.8 (5)	14.62 (11)
	Kerala	1576	2760 (1)	-	-	0.23 (1)
	Tamil Nadu	15,272	150,218 (28)	-	10.45 (6)	22.97 (34)
	Telangana	8634	37,100 (5)	-	19.5 (4)	22.59 (9)
	Total	**40,407**	**338,678 (44)**	**9521 (3)**	**78.57 (30)**	**108.775 (77)**
(d) East Zone	West Bengal	8675	14,000 (2)	-		1.17 (2)
	Bihar	3703	12,000 (1)	-	-	1.00 (1)
	Chhattisgarh	1896	-	-	0.33 (1)	0.33 (1)
	Total	**12,378**	**26,000 (3)**	**-**	**0.33 (1)**	**2.5 (4)**

Source: International Institute of Health and Hygiene 2020

Challenges or barriers to biogas implementation in developing countries

Technical barrier

According to several studies, the establishment of biogas facilities in underdeveloped countries is hindered by several technical barriers. These include a lack of information and training among householders, leading to inadequate maintenance of biogas digesters and insufficient knowledge of feedstock compatibility (Raha et al. 2014). Inappropriate garbage disposal, insufficient waste collection, and defective supply chains can impede biogas generation (Mittal et al. 2018). In rural areas where not all households have livestock or poultry, biogas generation is further hampered by the shortage of animal manure (Khan and Martin 2016). Farmers in agro-biogas plants need to be educated so that biogas slurry can be utilized for organic farming in addition to biogas utilization (Uddin et al. 2016). However, a lack of technical expertise among biogas operators, including experienced and qualified personnel, presents significant challenges to establishing long-term biogas plants.

Moreover, most operators lack the necessary technical training and course certificates, making connecting biogas with eco-agriculture and reducing biogas output challenging (Chen et al. 2010) Table 4. As a result, most biogas plants are shut down before their full operational potential due to a lack of setup and operation expertise (Ghafoor et al. 2016). In addition to technical barriers, the failure of biogas initiatives due to poor management, lack of technical knowledge, and lack of experience have led to an overly pessimistic view of biogas technology (Surendra et al. 2014). A lack of R&D to manufacture high-quality digesters, a lack of information about effective digester management, and a failure to embrace technology on time are other causes of digester failure (Rupf et al. 2015a).

Larger-scale biogas production has proven to be a substantial impediment in many countries due to water scarcity experienced by many developing nations (Patinvoh and Taherzadeh 2019). In addition, the daily organic waste-to-water ratio in a biogas digester is crucial to producing biogas. It can be completely stopped when the quantity is too much or too little (Rupf et al. 2015a). In metropolitan environments, where organic and inorganic

Table 4 The primary roadblocks to biogas program acceptance in developing nations (India) are summarized below

Categories	Barrier description	References
Technical barrier	• Substrate toxicity/inhibitor	Zhang et al. (2019)
	• Land availability (sufficient amount of space required to construct the AD reactor)	Gülzow (2010), Tanto and Wiratni (2018) Mittal et al. (2018)
	• Water supply (no issue of water scarcity)	Roopnarain and Adeleke (2017)
	• Technical assistance during the construction	Yasar et al. (2017), Lora Grando et al. (2017)
	• Standardized/regulated/appropriate plant design	Auburger et al. (2017)
	• Reliable transportation and infrastructure for supply stability	Rupf et al. (2015b)
	• Inadequate supply of feedstock (low output in winter)	Bansal et al. (2013)
	• Lack of technical services	Planning Commission (2014a)
	• Poor quality of feedstock	Bedi et al. (2015)
	• Lack of waste storage and treatment facilities	Kabera et al. (2016)
	• Lack of standards and quality control measures	Mulinda et al. (2013)
	• Insufficient local research and development work	Rupf et al. (2015b)
	• Poor design and construction	Clemens et al. (2018)
	• Lack of technical skills and training	Rupf et al. (2015b), Mulinda et al. (2013)
	• Low rate of functional installed biogas systems/short lifespans	
Financial barrier	• Fertilizer pricing system	Tyagi et al. (2018)
	• Electricity market	Teymoori Hamzehkolaei and Amjady (2018)
	• Project technology transfer scheme for large-scale AD	De Clercq et al. (2017)
	• Private investment public-private partnership	Surendra et al. (2014)
	• Support for Initial investment (donor/subsidies)	Kabir et al. (2013)
	• Expensive initial investment	Bansal et al. (2013)
	• Excessive transaction fees	Rao and Ravindranath (2002)
	• Lack of financial mechanism	Tigabu et al. (2015)
	• Inadequate subsidy	Mengistu et al. (2016)
	• Extensive payback time and limited rate of return	Bedi et al. (2015), Landi et al. (2013)
	• High-risk perception by financial institutions	Rupf et al. (2015b)
	• Poor financial conditions and purchasing power for household	Roopnarain and Adeleke (2017)
	• Competition from firewood –where the wood collection is free and available	Mwirigi et al. (2014)
Social barrier	• Local laborers and technicians are included.	Terrapon-Pfaff et al. (2014)
	• Guarantee for safety	Casson Moreno et al. (2016)
	• Ease of operation	Yasar et al. (2017)
	• Aesthetic consideration	Lüker-Jans et al. (2017)
	• Ethical obstacles or sociocultural taboos	Hirmer and Cruickshank (2014), Gabriel (2016)
	• Leadership (attitude of the leader toward renewable energy)	De Clercq et al. (2017)
	• Working with a variety of stakeholders	Ghimire (2013), De Clercq et al. (2017)
	• Technology adoption is more difficult due to low literacy levels.	Akinbami et al. (2001)
	• A lack of understanding of the technology's advantages.	Mwirigi et al. (2014)
	• Objections to utilizing animal or human waste on social, cultural, or religious grounds	Rabezandrina (1990) Akinbami et al. (2001)
	• Preference for conventional cooking methods, such as using a wood stove rather than a biogas burner.	Kabera et al. (2016)
	• Women are underrepresented in the biogas adoption process.	
Market barrier	• Competition from other fuels	Bansal et al. (2013)
	• Other technologies, such as Refuse Derived Fuel (RDF) and composting, pose a threat.	Planning Commission (2014b)
Institutional barriers	• Government policies or support for biogas are insufficient.	Parawira (2009), Karagiannidis (2012)
	• Biogas system ownership and accountability are not correctly defined or understood.	Walekhwa et al. (2009) Njoroge (2007), Avery et al. (2019)
	• There is a lack of current information, knowledge sharing, and translational biogas research at the national, continental, and international levels.	Kabera et al. (2016), Tigabu et al. (2015) Bag et al. (2016)
	• Coordination and collaboration between institutions are lacking.	
	• Limited municipal capacities in cities	
Information barrier	• Inadequate transmission of information about government-sponsored technology and incentives	Ravindranath and Balachandra (2009), Rao and Ravindranath (2002)
	• A lack of knowledge about alternative biogas substrates to cow dung	Raha et al. (2014)
Policy barrier	• Inadequate government incentives and poor policy execution	Roopnarain and Adeleke (2017)
	• Monitoring and follow-up services are lacking.	Landi et al. (2013), Rupf et al. (2015b)

waste segregation is not done appropriately, biogas production is also negatively impacted.

Furthermore, due to municipal and government neglect of trash collection and segregation, there are insufficient waste-to-energy facilities in India's cities, towns, and villages. Adopting biogas technologies is also a difficult challenge. Many private enterprises are reluctant to invest in new construction and technology for biogas plants due to the costly investment and market risk associated with biogas technology (Amuzu-Sefordzi et al. 2018; Chen and Liu 2017).

Financial barrier

According to several studies, financial barriers pose a significant challenge to adopting and proliferating biogas systems. Biogas systems are expensive to install and maintain, making them unaffordable for low-income individuals and households. A self-built home-scale biodigester with a daily input capacity of 50 kg can cost more than $1500, a significant investment (Morgan et al. 2018). The cost of treatment and transportation of feedstock can further reduce the economics of biogas power plants, especially over long distances (Mittal et al. 2018). Moreover, producing pure biogas from raw biogas requires expensive equipment such as H_2S scrubbers, CO_2 scrubbers, and gas conditioners (Satchwell et al. 2018), and mechanical pretreatment for optimal biogas generation is also costly (Rodriguez et al. 2017). Access to commercial capital to invest in biogas infrastructure is severely restricted in poor countries, mainly rural areas. As a result, subsidies, financial assistance programs, and low-interest loans are significant economic barriers that make biogas projects less attractive to investors (Chen and Liu 2017). Lack of long-term finance and high-interest rates also impair the economic viability of biogas plants (Schmidt and Dabur 2014).

Additionally, the lack of government incentives for adopting biogas technology and favoring fossil fuels over renewable fuels in many developing nations' financial structures delay or prevent the implementation of biogas initiatives (Christensen and Bach 2015; Roopnarain and Adeleke 2017). Corruption, lack of political will, and insufficient government policies further hinder the implementation of biogas systems (Bansal et al. 2013). The shortage of skilled researchers due to a lack of financing also poses a challenge (Shane et al. 2015a). More funds for research and development would enhance technology innovation (Cheng et al. 2017), and institutional networking for R&D and coordinated efforts in solving R&D obstacles should be established to improve biogas processes, reduce the cost of biogas technologies, make them available to more imperfect investors, and expand training and consulting opportunities.

Social barrier

The major sociocultural hurdle for biogas adoption is the lack of public participation and consumer interest. In India, households typically do not sort their organic waste, instead dumping it all in the same container due to a lack of knowledge and time. As a result, most people are unaware that biogas can be produced from home organic waste (Pradeep, Amit Pal, Samsher 2020; Herbes et al. 2018). In rural areas, several social and cultural barriers prevent the adoption of biogas. For example, there is a social taboo surrounding the use of human excrement in biogas plants, which contains plant owners and individuals from using this source. Although farm households are involved in developing these new technologies, it is not held accountable for their use, maintenance, or the environmental and economic benefits biogas consumption delivers (Chen et al. 2017). In addition, women in rural households are more likely to cook, which means it is more likely to be exposed to indoor air pollution caused by burning solid fuels. However, due to rural women's lack of decision-making authority, adopting clean energies is slow.

Furthermore, small-scale biogas installations are often ignored because people in these areas typically cook with dung, and local communities are unwilling to embrace the consumption of biogas due to cultural beliefs surrounding waste, excrement, or any other form of fecal material (Giwa et al. 2017). There are also problems with feedstock and slurry management, as many users hesitate to do the required daily dung mixing because it is an unpleasant burden (Khan et al. 2014). Similarly, using human excrement in biogas plants is socially undesirable due to filthy conditions within the home (Sharma et al. 2018). Some religions also have rigorous hygiene standards, particularly surrounding people and animal excrement (Gebreegziabher et al. 2014). Finally, the adoption and implementation of biogas plants may be affected by consumers' preference for existing brands over new ones, as it can be difficult for them to evaluate the quality of a new product (Dahlin et al. 2015). This knowledge affects the adoption and implementation of biogas plants.

Market barrier

The high cost of biogas compared to natural gas is a significant market barrier, making it difficult for new companies to enter the bioenergy technology market (Piwowar et al. 2016). Government regulations further complicate the market entry process, as licensing, raw material access, environmental requirements, and product testing are all subject to government oversight (D. Ravindranath 2011). To make biogas competitive in the public sector, its price must be lowered to match that of other available fuels (Martin 2015). Additionally, biogas faces competition from other, cheaper cooking alternatives, such as traditional solid biomass, firewood, and cow dung, all locally available (Rao and Ravindranath 2002). While biogas can potentially increase natural gas imports, customers are not interested in using 100% enhanced biogas due to its high cost. However, blending natural gas with biogas makes the fuel more acceptable to the general public (Sanches-Pereira et al. 2015). Biogas also faces competition from other fuel sources, such as bioethanol and electric cars. The success of electric vehicles has been linked to the increase in biogas use (Sanches-Pereira et al. 2015). The study's interviews indicate that municipalities prefer electric vehicles over biogas vehicles due to a lack of fueling infrastructure, internal mistrust, and a fear of accidents caused by a lack of knowledge (Ammenberg et al. 2018).

Additionally, established soil and organic fertilizer businesses compete with digestate-based product makers, as merchants and garden centers prefer providers with varied product offerings and the capacity to provide large volumes (Dahlin et al. 2015). Despite the excellent market potential for organic fertilizer, no substantial efforts have been made to develop and commercialize the non-energy products of the biogas process (Yousuf et al. 2016). These market barriers may hinder the participation of biogas plant developers (Kumaran et al. 2016).

Institutional barriers

The lack of government support and specific efforts is one of the primary impediments (Muradin and Foltynowicz 2014). Additionally, the energy sector has been ignored in emerging country policy discussions (Surendra et al. 2014). The National Biogas and Manure Management Program (NBMMP), launched by the Central Government, has too many formal requirements and administrative and legal processes, hindering biogas plant installation (Pazera et al. 2015). The program's capital subsidies require the possession of two to three cattle, making it difficult for most low-income rural families to secure a grant and impeding the application of biogas technology (Raha et al. 2014). As a result, low-income families resort to using locally available biomass for cooking. Several agencies implement the national biogas development effort. A lack of collaboration and competition for incentives has been identified as a reason for poor performance and limited dissemination of biogas technology in rural regions (Bansal et al. 2013). The policy environment's volatility and uncertainty are also tricky (Pazera et al. 2015), and cooperation between national and subnational governments is minimal. While standard pricing for electricity produced by biogas and waste-to-energy plants was established in 2016, state electrical regulatory commissions have not yet developed everyday prices for energy produced by anaerobic digestion power plants (SERCs), making it difficult to evaluate the project's feasibility during the pre-investment evaluation phase due to the uncertainty of pricing for the SERCs' power purchase agreement (MINISTRY OF POWER 2016). Private investment in large-scale biogas plants is discouraged without government initiatives such as specific guidance and stakeholder involvement, making risks associated with income sources, technology, and feed supplies essentially the responsibility of private parties (Martin 2015). According to several studies, the future of biogas taxes, incentives, and government support in India is mainly unpredictable (Martin 2015; Ammenberg and Feiz 2017). Regulatory restrictions, such as the need for permits from several government ministries, including the Petroleum Explosives Safety Organization (PESO) and the Ministry of Environment and Forest, inhibit the improved biogas industry (Mittal et al. 2018). The private sector is crucial for delivering biogas energy to the market and ensuring economic viability (Msibi and Kornelius 2017).

Information barrier

The lack of information and knowledge dissemination on biogas technology is a significant factor in its low adoption as a primary cooking fuel in rural areas (Blenkinsopp et al. 2013). The general public, including rural communities, financial institutions, and enterprises, lacks access to appropriate information and necessary tools, resulting in a lack of awareness and understanding of the numerous feedstock choices and how digesters might use them (Raha et al. 2014). This lack of information and technological, infrastructural, and user limitations have hindered biogas technology adoption in rural regions (Mittal et al. 2018). Despite decades of government efforts, adopting biogas technology in rural areas remains challenging. This is due to the poor performance of biogas technology, leading to its unsuitability and unreliability in meeting households' daily or seasonal cooking energy demands (Mittal et al. 2018). This results in rural families resorting to alternate, easily accessible fuels.

Additionally, NGOs, corporate groups, microfinance institutions, and governments are often unaware of the advantages of bioenergy, resulting in a stronger push for renewable energy alternatives such as wind and solar (Ghosh et al. 2006). Raising awareness is one of the three components of the integrated policy package necessary to combat climate change, alongside carbon pricing and innovation assistance (Stern 2007). However, agencies struggle to collect consistent information on biogas plant utilization and mitigation potential, hindering capacity-building efforts. Developing a sample plan for routine monitoring of biogas consumption in different regions can be a suitable solution. The long-term acceptability of biomass gasifiers and biogas facilities is hindered by a lack of information and awareness about proper operation and maintenance (D. Ravindranath

2011). Overall, the lack of available information and understanding regarding biogas technology has contributed to its low adoption in rural areas, emphasizing the need for better dissemination of information and capacity-building efforts.

Environmental barrier

Biogas production is not without its potential drawbacks and environmental concerns. One prominent challenge biogas plants face is the need for a significant amount of water, which is necessary for anaerobic digestion and maintaining the ideal water-to-manure ratio of 1:1 (Kelebe 2018). Biogas production can become challenging during dry seasons or in areas where water is scarce (Pazera et al. 2015). In addition, colder temperatures can negatively impact biogas production. For instance, temperatures below 15 °C can reduce biogas output, making it difficult for farmers in colder regions to use it as an energy source (Clemens et al. 2018). Furthermore, the potential for environmental harm exists in noise pollution, odor concerns, and gas leakage. In particular, broken digester lids and leaking gas valves can release a mixture of methane, carbon dioxide, and hydrogen sulfide, increasing greenhouse gas emissions and groundwater contamination (Cheng et al. 2017; Nevzorova and Kutcherov 2019). Certain African countries, such as Zambia, may face water shortages that could compound the challenge of operating biogas plants (Shane et al. 2015b). To mitigate these environmental risks, using leak-proof feedstock and digester storage areas and identifying hazardous locations are essential. Waste gas outlets should also be appropriately managed to protect groundwater and prevent unpleasant odors (Nevzorova and Kutcherov 2019).

Policy barrier

The renewable energy industry faces significant obstacles due to government policies, particularly energy price distortion, which favors fossil fuels over renewable energy sources (ESCAP 2004). In addition, low agricultural rates lead to excessive electricity and groundwater usage, and energy subsidies prevent progress in replacing inefficient agrarian pump sets (Phadke, A and Sathaye 2006). The lack of environmental policy and a defined policy on renewable energy utilization also hinders the spread of biofuel technologies (Jiang et al. 2011). Although the Electricity Act of 2003 mandates the establishment of a National Electricity Plan and a National Tariff Policy, tariff levels for renewable energy vary across different states, leading to developers' complaints about the system's fairness (CERC 2010; KERC 2005). The absence of a reliable waste collection and sorting infrastructure in most developing countries also impedes the growth of renewable energy. Waste management businesses often dispose of wastewater effluents in uncontrolled landfills or publicly burn them, causing environmental problems (The World Bank 2019). Land-tenure policies are another issue that limits the ability of farmers and municipalities to enter long-term contracts to acquire wood fuel for bioenergy (Rao and Ravindranath 2002). Corruption is also a significant barrier that decreases the rate of return on investment in implementing biogas investments and operating expenses (Taherzadeh and KR 2014).

Furthermore, the lack of government commitment and inadequate continuity of previous biogas program initiatives across successive governments also hinder the adoption of biogas technology (Akinbomi et al. 2014). In India, energy pricing regulations that favor existing technologies and heavily subsidize electricity use for farming further stifle the growth of biogas, as farmers lack incentives to invest in biogas technology (ESCAP 2004). These policies, combined with a lack of environmental policy and weak government commitment, impede the spread of biofuel technologies and hinder the renewable energy industry's development.

Government of India policies for setting up biogas plants

National Biogas and Manure Management Program

The National Biogas and Manure Management Program (NBMMP) is a scheme implemented by India's Ministry of New and Renewable Energy (MNRE). This program enables rural and semi-urban families to install Family Biogas Plants, which utilize organic resources such as cow manure, farm biomass, gardens, and kitchen waste to produce biogas. The NBMMP has been active since 1981–1982 and aims to provide rural households with cooking fuel and organic fertilizer through biogas systems (D. Ravindranath 2011). One of the primary objectives of the NBMMP is to improve sanitation in rural and semi-urban areas. By connecting latrines with cow dung biogas facilities, the program aims to alleviate the suffering of women, free up their time for other livelihood activities, reduce pressure on forests, and generate social benefits. The MNRE is responsible for implementing the NBMMP nationwide, and as of March 31, 2014, approximately 4.75 million biogas plants have been developed under this program (Saravanan et al. 2018). For the fiscal year 2014–2015, a target of 1.1 million biogas plants has been set (MNRE 2021b). Families with access to feedstock and a desire to become self-sufficient in cooking gas and organic biomanure are encouraged to install biogas facilities. This approach helps reduce the cost of refilling LPG cylinders while mitigating indoor air pollution. As part of the NBMMP, the Central Financial Assistance (CFA) provides subsidies for biogas plants. The subsidy ranges from Rs 7000 to Rs 15,000 for plants producing 1 m^3 of biogas per day and from Rs 9000 to Rs 17,000 for plants producing 2 to 6 m_3 per day.

An incentive of Rs 1200 is also awarded when a biogas plant fueled by cow manure is connected to hygienic toilets (MNRE 2021b). Under the NBMMP, purchasing a turnkey project includes 3 years of free maintenance and support for repairing non-functional or old plants. The program also focuses on promoting and expanding the benefits of biogas technology for users, masons, and entrepreneurs. At the state level, the Biogas Development and Training Center (BDTC) has developed financial assistance programs for institutions constructing cattle dung-based power plants (D. Ravindranath 2011).

New National Biogas and Organic Manure Program

In 2018, India's Ministry of New and Renewable Energy (MNRE) enhanced the National Biogas and Manure Management Program (NBMMP). It introduced the New National Biogas and Organic Manure Program (NNBOMP) across all states and union territories (MNRE 2020a). With a significant livestock population of 512.06 million animals in India, including 300 million bovines such as yak, cattle, and buffalo, there is ample capacity for biogas production (MNRE 2021c). The livestock industry plays a substantial role in India's gross domestic product and is expected to grow, making biogas technology a valuable asset for farmers. The primary objective of the NNBOMP is to provide clean cooking fuel for kitchens, lighting, and other thermal and small-scale power needs, specifically targeting farmers, dairy farmers, and individual households (Bharti 2019). Furthermore, the program aims to strengthen the use of a bioslurry-based organic manure system in rural and semi-urban areas by establishing small-scale biogas plants with capacities ranging from 1 to 25 m^3. By utilizing biogas slurry for activities such as vermicomposting and organic composting, the program seeks to reduce reliance on synthetic fertilizers like urea, thereby contributing to environmental sustainability and climate change mitigation by preventing the release of CO_2 and CH_4 into the atmosphere.

To benefit from the NNBOMP, individuals must own land or have an area of 50–60 m^2 to install a small biogas plant (MNRE 2021c). Beneficiaries must have access to cow manure and water and the ability to invest in biogas technology. Under the initiative, Central Financial Assistance (CFA) grants are provided, with subsidies ranging from \$106 to \$352, depending on the daily biogas generation capacity of the plants, which can produce 1 to 25 m^3 of biogas per day (Bharti 2019). In addition, an additional subsidy of Rs. 1600 is available for cow dung-based biogas plants connected to sanitary toilets, but this subsidy is limited to single-family homes (GRAMEEN 2021). Under the NNBOMP, the installation of 12 million biogas plants with capacities ranging from 1 to 25 m^3 per day has been planned. Thus far, 5 million biogas plants have been installed under the program (Bharti 2019). To facilitate the development and promotion of biogas technology, eight Biogas Development and Training Centers (BDTCs) collaborate with State Rural Development Departments and State Nodal Agencies. These centers provide technical support, training, field inspections, and information dissemination to ensure the effective implementation of the program. Monitoring biogas plants includes physical verification and village-by-village monitoring to ensure proper functioning (MNRE 2021d).

Biogas Power Generation (Off-Grid) and Thermal Energy Application Program (BPGTP)

The Ministry of New and Renewable Energy (MNRE) in India has introduced the Biogas Power Generation (Off-Grid) and Thermal Energy Application Program (BPGTP). This program aims to construct large-scale commercial biogas plants that generate and supply electricity to the power grid (Bhatia et al. 2020). The project will be undertaken by state agriculture and rural development departments and dairy cooperatives.

The primary objective of the BPGTP is to promote biogas as a decentralized renewable energy source for electricity generation (off-grid) in the range of 3 to 250 kW. It also encourages the utilization of biogas for thermal energy applications such as heating and cooling. Biogas plants with capacities ranging from 30 to 2500 m^3 will be established to facilitate these energy generation and utilization activities (Bharti 2019).

To support the development of large-scale biomethanation plants that generate power from municipal garbage, the Indian government provides financial assistance of up to 1 crore per megawatt. Additionally, 1.5 crores are allocated for constructing biogas bottling plants, 1 lakh for creating comprehensive project reports for bio methanation facilities, and a 5-year warranty on installation and maintenance (Kshirsagar et al. 2019). These initiatives aim to utilize organic and biomass waste as scientifically managed feedstock in biogas plants. The renewable energy sources used in these plants include cow dung/animal waste, food and kitchen waste, poultry waste, cattle dung, paddy straw, green grass, and waste from milk and food processing industries, agro-processing enterprises, gaushalas, food processing parks, agricultural farms, and dairies in rural areas.

The BPGTP focuses on biogas plant facilities for farmers, dairy farmers, and small businesses in rural regions. It is particularly beneficial for meeting these areas' electrical and thermal energy demands, especially for small dairy and poultry farms. The Central Financial Assistance (CFA) subsidy rates for biogas-based power generation (off-grid) and thermal application projects are categorized into three slabs based on the size of the biogas plants and their associated power generation and thermal power generation capacities. The subsidy rates range from Rs. 25,000 to Rs. 40,000 per kilowatt-hour (kWh) of electricity and Rs. 12,500 to Rs. 20,000 per kWh of thermal energy (MNRE 2021e). These goals and strategies demonstrate the government's commitment to enhancing the country's energy infrastructure and promoting environmental sustainability (Khanna et al. 2013). By encouraging the adoption of biogas technology and supporting its implementation in large-scale commercial plants, the BPGTP aims to harness the potential of organic waste to generate renewable energy and contribute to India's energy needs while mitigating the environmental impact.

GOBAR-Dhan waste-to-wealth program

The GOBAR-Dhan program, officially known as Galvanizing Organic Bio-Agricultural Resources Dhan, was launched by the Indian government in April 2018 as part of the Swachh Bharat Mission's Waste Management component. The program promotes rural cleanliness and creates economic value and energy from livestock and organic waste (Bharti 2019).

The key objectives of the GOBAR-Dhan program are to maintain clean villages, increase rural incomes, and generate electricity and organic fertilizer from cattle dung. It plays a significant role in helping communities achieve the Open Defecation Free (ODF) status, a crucial target of the Swachh Bharat Mission Phase 2.0 (GRAMEEN 2021).

The program's primary purpose is to effectively assist rural communities in managing their animal manure, agricultural waste/residues, and other organic waste. It focuses on converting organic waste, especially cow manure, into valuable resources such as fertilizer and electricity. This approach contributes to enhancing environmental sanitation, promoting livelihood development in rural regions, and raising the income of farmers and other residents (Affairs 2019).

The program's implementation involves the participation of various stakeholders, including self-help organizations, Gram Panchayats, bulk waste producers, and entrepreneurs. Biogas facilities are constructed by these entities, with state officials responsible for developing at least one biowaste management project in each district. Financial aid is available for the development of biogas projects, and the support provided by each Gram Panchayat depends on the total number of households. Biogas reduces the demand for liquefied petroleum gas (LPG), resulting in improved household income and savings (GRAMEEN 2021).

The GOBAR-Dhan program brings several benefits to agriculture and agricultural output by aiding in the creation of organic manure. It also provides employment and income generation opportunities for self-help groups (SHGs) and farmer groups. Moreover, the program conserves foreign currency by reducing the demand for natural gas imports.

In terms of implementation, the program aims to cover 700 districts during the 2018–2019 period. It was introduced on a trial basis in 350 districts, with the remaining districts being addressed in the second half of the fiscal year. The program has received 318 requests for the construction of biogas plants (Bharti 2019).

The GOBAR-Dhan program supports four models: the Individual Household model, the Cluster model, the Community model, and the Commercial model. Under the Individual Household model, Gram Panchayats identify suitable households and provide technical and financial assistance for constructing biogas plants. The government funds the construction of biogas plants for Gram Panchayats up to 100%. The cluster model involves selecting clusters of homes to install household-level biogas plants, with the government contributing 75% of the funding. The Community model allows for the construction biogas plants at the community level for five to ten dwellings, with up to a 50% government subsidy. Biogas plants are constructed in this model, and the produced biogas is used in homes, restaurants, and other enterprises. At the same time, the slurry is utilized in agriculture and converted into biofertilizers and organic manure (GRAMEEN 2021).

Under the Commercial model, entrepreneurs, cooperatives, gaushalas, dairies, and other entities can construct large-scale biogas or compressed biogas (CBG) facilities. The biogas is converted into CBG, which can be sold to industries or used directly as fuel. The state and districts actively encourage the construction of commercial units as part of the GOBAR-Dhan effort, aiming to promote biogas utilization for various purposes. The program focuses on creating policy regulations that facilitate entrepreneurs' and companies' establishment of business units. It encourages these entities to use different departments and institutions' loan and financial aid programs. Additionally, the program aims to promote the offtake of slurry by government agencies and other related entities by increasing awareness of the commercial viability of biogas facilities (GRAMEEN 2021).

Waste-to-energy program

The waste-to-energy program uses energy generated from various sources, including industrial, agricultural, and urban waste. This initiative involves biogas production through biomethanation, industrial waste, sewage treatment facilities, and urban and agricultural waste. Power plants are being constructed to generate energy from industrial effluents, sewage treatment facilities, and biogas plants that utilize urban and agricultural waste. Additionally, some plants produce bio-CNG or enriched biogas. The construction of waste-to-energy plants is eligible for subsidies and financial assistance, particularly for biogas facilities with a daily production capacity of over 2500 m^3 and a power generation capability of over 250 kW (Bharti 2019).

The waste-to-energy program includes the management of municipal solid waste (MSW) as part of its energy generation efforts. The program targets various industries, such as distilleries, paper mills, pulp mills, rice mills, textiles, and pharmaceuticals. Capital subsidies are provided to support the development of waste-to-energy plants. The Ministry of Road Transport and Highways has also made amendments to incorporate provisions for using biogas, particularly bio-CNG, in waste-to-energy vehicles (Hiloidhari et al. 2014).

The initiative holds significant potential, with the ability to generate 5690 MW of power from urban garbage and industrial organic waste. Currently, 330 MW of power has already been achieved through this program (Bharti 2019).

To ensure the timely completion of projects, state nodal authorities will monitor their development and provide necessary recommendations. Developers are required to provide quarterly progress updates to the Ministry of New and Renewable Energy (MNRE). MNRE may establish a monitoring committee comprising financial institutions/banks, technical institutions, and state nodal agencies to track project execution and performance (MNRE 2020b).

Sustainable Alternative Towards Affordable Transportation

The Sustainable Alternative Towards Affordable Transportation (SATAT) program was established by the Ministry of Petroleum and Natural Gas and the Ministry of Skill Development and Entrepreneurship in October 2018. The primary objective of SATAT is to establish CBG manufacturing plants and make CBG available as fuel for vehicles. The program was launched during the Swachhta Hi Seva fortnight, a state-wide campaign to achieve Mahatma Gandhi's vision of a Clean India. SATAT aims to increase the availability of affordable transportation fuels, utilize agricultural waste, cow dung, and municipal solid waste, and provide farmers with a new source of income. It can also improve municipal solid waste management and address air pollution caused by farm stubble burning and carbon emissions (MOP&NG 2021).

SATAT was developed in collaboration with government agencies and oil marketing corporations, with IOCL, BPCL, and HPCL among the early adopters. Oil and gas marketing firms have partnered with approximately 344 small-scale biogas companies to supply compressed biogas sustainably to the automotive industry, utilizing biogas generated from municipal solid waste in cities (Gas 2018). The establishment of compressed biogas plants will primarily be undertaken by individual entrepreneurs (BYJU'S 2021). India's network of 1500 CNG stations currently serves around 3.2 million gas-powered vehicles. Entrepreneurs can generate additional revenue by selling other by-products from these plants, such as biomanure and carbon dioxide. The plan is to establish 5000 compressed biogas facilities across India in phases, with 250 plants completed by 2020, 1000 plants completed by 2022, and 5000 plants completed by 2025 (Vikaspedia 2021). These plants are expected to produce 15 million tons of CBG annually, accounting for nearly 40% of the country's current CNG consumption of 44 million tons annually. The estimated cost of this project is over Rs. 1.7 lakh crore, providing direct employment to 75,000 people and producing 50 million tons of biomanure for agricultural use (Bharti 2019). Due to the abundance of biomass in the country, compressed biogas can potentially replace CNG in future automotive, industrial, and commercial applications.

The future directions and latest policies added by the Indian government

The Government of India has set forth a series of forward-looking policies and initiatives on implementing biogas plants. These measures reflect a concerted effort to promote sustainable energy solutions and address environmental concerns.

Promotion of compressed biogas

The government is actively promoting the production of compressed biogas from biomass, organic waste, and sewage. This is intended to serve as an alternative and cleaner fuel source for transportation, reducing dependence on fossil fuels (Ministry of Petroleum & Natural Gas 2018).

National Policy on Biofuels (2018)

The National Policy on Biofuels outlines the strategic roadmap for expanding the production and use of various biofuels, including biogas. It provides measures for creating an enabling environment for biofuels and sets targets for their integration into the energy mix (Ministry of New and Renewable Energy 2018).

Biogas Development Fund

The government has established a Biogas Development Fund to support installing biogas plants. This fund helps subsidize the initial costs of setting up biogas units (Ministry of New and Renewable Energy 2021a, b).

Integration with waste management

There is a growing emphasis on integrating biogas generation with waste management practices. This approach helps in efficient waste disposal while generating renewable energy (Ministry of New and Renewable Energy 2021a, b).

Research and development initiatives

The government is investing in research and development to enhance biogas technology. This includes efforts to develop advanced digester designs, explore new feedstock options, and improve the overall efficiency of biogas production (Ministry of New and Renewable Energy 2021a, b).

Financial incentives and subsides

Various financial incentives and subsidies are available to support the establishment and maintenance of biogas plants. These incentives aim to make biogas technology more affordable and accessible for rural and urban communities (Ministry of New and Renewable Energy 2021a, b).

Collaborations and partnerships

The government actively engages with international organizations, research institutions, and industry partners to exchange knowledge and best practices in biogas technology and policy development. These collaborations leverage global expertise to benefit India's biogas sector (Ministry of External Affairs 2021).

Comparative analysis with neighboring countries

Nepal Nepal has a well-established track record in community-based biogas programs facilitated by the National Biodigester Program. This program has significantly contributed to rural energy access and sustainable waste management. The success of this program lies in its community-driven approach and extensive technical support. Nepal's biogas initiatives emphasize decentralized systems and community participation, making them highly effective in rural areas (Ministry of Population and Environment 2021).

Bangladesh Bangladesh has made remarkable strides in promoting biogas for rural electrification through the Infrastructure Development Company Limited (IDCOL) Biogas Program. This program focuses on providing clean energy solutions to off-grid areas, thereby improving rural livelihoods and reducing dependence on traditional biomass sources. Bangladesh's emphasis on rural electrification sets it apart and addresses the energy needs of underserved populations (Infrastructure Development Company Limited 2021).

Sri Lanka Sri Lanka actively promotes biogas technology to address energy security and environmental sustainability. The government has implemented policies to incentivize biogas plant installations, particularly in the agricultural sector. This approach reduces greenhouse gas emissions while providing a renewable energy source for rural communities. Sri Lanka's focus on agriculture and emission reduction aligns with its environmental challenges (Ministry of Mahaweli Development 2021).

Pakistan Pakistan has been making strides in promoting biogas as a renewable energy source. The Pakistan Biogas Development Company (PBDC) plays a crucial role in facilitating the adoption of biogas technology. The focus is on rural electrification and providing clean cooking energy to households. Additionally, there are initiatives to explore the potential of biogas in the agricultural sector for enhanced productivity and sustainability. Pakistan's focus on rural electrification and agrarian productivity highlights its unique approach to biogas implementation (Rabia Liaquat et al. 2021).

Conclusion

This comprehensive review offers a detailed assessment of India's biogas landscape, divided into five key segments. It commences with an in-depth analysis of biogas production growth since 1990, revealing divergent trajectories across different geographical zones. Noteworthy highlights include Madhya Pradesh's remarkable 446.71% surge in the West Zone and Uttarakhand's exceptional 1831.9% growth in the North Zone. The subsequent section evaluates biogas plant installations, categorizing zones based on target achievements, with Uttarakhand surpassing its capacity by over 100%. The third section scrutinizes waste-to-energy facilities and biogas production, spotlighting substantial advancements in the West Zone. The fourth section identifies an array of technical, financial, and policy-related hurdles. Lastly, the review outlines key government initiatives such as NBMMP, NNBOMP, and SATAT, underscoring their pivotal role in driving forward green energy generation. This review provides a comprehensive overview of achievements and areas for enhancement in India's biogas development endeavors.

Acknowledgements The authors would like to thank Dr. Amit Pal for his support in editing this research and the Delhi Technical University Administration for their valuable support.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Pradeep Kumar Meena, Amit Pal, and Samsher Gautam. The first draft of the manuscript was written by Pradeep Kumar Meena, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Affairs CC on E (2019) Financial support to Integrated Bioethanol Projects using lignocellulosic biomass and other renewable feed stock. https://pib.gov.in/PressReleasePage.aspx?PRID=1566711. Accessed 28 Aug 2021

Akinbami JFK, Ilori MO, Oyebisi TO, Akinwumi IO, Adeoti O (2001) Biogas energy use in Nigeria: current status, future prospects and policy implications. RSER 5:97–112. https://doi.org/10.1016/S1364-0321(00)00005-8

Akinbomi J, Brandberg T, Sanni SA, Taherzadeh MJ (2014) Development and dissemination strategies for accelerating biogas production in Nigeria. Bioresources 9:5707–5737. https://doi.org/10.15376/biores.9.3

Amigun B, Von Blottnitz H (2010) Capacity-cost and location-cost analyses for biogas plants in Africa. Resour Conserv Recycl 55:63–73. https://doi.org/10.1016/j.resconrec.2010.07.004

Ammenberg J, Feiz R (2017) Assessment of feedstocks for biogas production, part II—results for strategic decision making. Resour Conserv Recycl 122:388–404. https://doi.org/10.1016/j.resconrec.2017.01.020

Ammenberg J, Anderberg S, Lönnqvist T, Grönkvist S (2018) Biogas in the transport sector—actor and policy analysis focusing on the demand side in the Stockholm region. Resour Conserv Recycl 129:70–80. https://doi.org/10.1016/j.resconrec.2017.10.010

Amuzu-Sefordzi B, Martinus K, Tschakert P, Wills R (2018) Disruptive innovations and decentralized renewable energy systems in Africa: a socio-technical review. ERSS 46:140–154. https://doi.org/10.1016/j.erss.2018.06.014

Angelidaki I, Treu L, Tsapekos P, Luo G, Campanaro S, Wenzel H, Kougias PG (2018) Biogas upgrading and utilization: current status and perspectives. Biotechnol Adv 36:452–466. https://doi.org/10.1016/j.biotechadv.2018.01.011

Auburger S, Petig E, Bahrs E (2017) Assessment of grassland as biogas feedstock in terms of production costs and greenhouse gas emissions in exemplary federal states of Germany. Biomass Bioenergy 101:44–52. https://doi.org/10.1016/j.biombioe.2017.03.008

Avery L, Joanne S, Tumwesige V (2019) Small-scale biogas digester for sustainable energy production in Sub-Saharan Africa. 587. https://doi.org/10.3390/wsf-00587

Bag S, Mondal N, Dubey R (2016) Modeling barriers of solid waste to energy practices: an Indian perspective. GJESM 2:39–48. https://doi.org/10.7508/gjesm.2016.01.005

Bajić BZ, Dodić SN, Vučurović DG, Dodić JM, Grahovacet JA (2015) Waste-to-energy status in Serbia. RSER 50:1437–1444. https://doi.org/10.1016/j.rser.2015.05.079

Bansal M, Saini RP, Khatod DK (2013) Development of cooking sector in rural areas in India—a review. RSER 17:44–53. https://doi.org/10.1016/j.rser.2012.09.014

Bedi AS, Pellegrini L, Tasciotti L (2015) The effects of rwanda's biogas program on energy expenditure and fuel use. World Dev 67:461–474. https://doi.org/10.1016/j.worlddev.2014.11.008

Bharti V (2019) India's programmes and incentives being implemented to support biogas systems

Bhatia RK, Ramadoss G, Jain AK, Dhiman RK, Bhatia SK, Bhatt AK (2020) Conversion of waste biomass into gaseous fuel: present status and challenges in India. Bioenergy Res 13:1046–1068. https://doi.org/10.1007/s12155-020-10137-4

Ministry of New and Renewable Energy. (2021) Biogas Development Fund. In: 2021. mnre.gov.in. Accessed 9 Oct 2023a

Infrastructure Development Company Limited (IDCOL). (2021) Biogas. In: 2021. idcol.org. Accessed 9 Oct 2023

Blenkinsopp T, Coles SR, Kirwan K (2013) Renewable energy for rural communities in Maharashtra, India. Energy Policy 60:192–199. https://doi.org/10.1016/j.enpol.2013.04.077

Bond T, Templeton MR (2011) History and future of domestic biogas plants in the developing world. Energy Sustain Dev 15:347–354. https://doi.org/10.1016/j.esd.2011.09.003

BYJU'S (2021) SATAT Initiative - Sustainable Alternative Towards Affordable Transportation. https://byjus.com/current-affairs/satat-initiative/. Accessed 25 Aug 2021

Casson Moreno V, Papasidero S, Scarponi GE et al (2016) Analysis of accidents in biogas production and upgrading. Renew Energy 96:1127–1134. https://doi.org/10.1016/j.renene.2015.10.017

Census of India (2008) "Area of India/state/district". Government of India (2001). https://www.censusindia.gov.in/Census_Data_2001/Census_Data_online/Administrative_Divisions/Area_of_India.aspx. Accessed 30 Aug 2021

Census of India (2011) Populations, Size and Decadal Change by residence

CERC I (2010) Central Electricity Regulatory Commission (CERC) India. 2010

Chen Q, Liu T (2017) Biogas system in rural China: upgrading from decentralized to centralized? RSER 78:933–944. https://doi.org/10.1016/j.rser.2017.04.113

Chen Y, Yang G, Sweeney S, Feng Y (2010) Household biogas use in rural China: a study of opportunities and constraints. RSER 14:545–549. https://doi.org/10.1016/j.rser.2009.07.019

Chen Y, Hu W, Chen P, Ruan R (2017) Household biogas CDM project development in rural China. RSER 67:184–191. https://doi.org/10.1016/j.rser.2016.09.052

Cheng S, Zhao M, Mang HP, Zhou X, Li Z (2017) Development and application of biogas project for domestic sewage treatment in rural China: opportunities and challenges. J Water Sanitation Hyg Dev 7:576–588. https://doi.org/10.2166/washdev.2017.011

Christensen D, Bach LT (2015) A Danish-Vietnamese partnership for business and technology development in solid waste management. Resour Conserv Recycl 105:123–133. https://doi.org/10.1016/j.resconrec.2015.10.019

Clemens H, Bailis R, Nyambane A, Ndung'u V (2018) Africa Biogas Partnership Program: a review of clean cooking implementation through market development in East Africa. Energy for Sustainable Development 46:23–31. https://doi.org/10.1016/j.esd.2018.05.012

D. Ravindranath SR (2011) Bioenergy in India: barriers and policy options. In: Diffusion of renewable energy technologies: Case studies of enabling frameworks in developing countries. 139

Dahlin J, Herbes C, Nelles M (2015) Biogas digestate marketing: qualitative insights into the supply side. Resour Conserv Recycl 104:152–161. https://doi.org/10.1016/j.resconrec.2015.08.013

De Clercq D, Wen Z, Gottfried O, Schmidt F, Fei F (2017) A review of global strategies promoting the conversion of food waste to bioenergy via anaerobic digestion. Renew Sustain Energ Rev 79:204–221. https://doi.org/10.1016/j.rser.2017.05.047

Di Maria F, Barratta M, Bianconi F, Placidi P, Passeri D (2017) Solid anaerobic digestion batch with liquid digestate recirculation and wet anaerobic digestion of organic waste: comparison of system performances and identification of microbial guilds. Waste Management 59:172–180. https://doi.org/10.1016/j.wasman.2016.10.039

Dieter Deublein AS (2011) Biogas from Waste and Renewable Resources: An Introduction, 2nd, Revised and, Expanded. Wiley-VCH Verlag, Germany

Diouf B, Miezan E (2019) The biogas initiative in developing countries, from technical potential to failure: the case study of Senegal. RSER 101:248–254. https://doi.org/10.1016/j.rser.2018.11.011

ESCAP UN (2004) End-use energy efficiency and promotion of a sustainable energy future. New York

Gabriel CA (2016) What is challenging renewable energy entrepreneurs in developing countries? RSER 64:362–371. https://doi.org/10.1016/j.rser.2016.06.025

Gas M of P & N (2018) Promoting Use of Compressed Bio Gas as Alternative Green Transport Fuel. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1557898. Accessed 26 Aug 2021

Gebreegziabher Z, Naik L, Melamu R, Balana BB (2014) Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa. Biomass Bioenergy 70:130–140. https://doi.org/10.1016/j.biombioe.2014.02.036

Ghafoor A, Rehman TU, Munir A, Ahmad M, Iqbalet M (2016) Current status and overview of renewable energy potential in Pakistan for continuous energy sustainability. RSER 60:1332–1342. https://doi.org/10.1016/j.rser.2016.03.020

Ghimire PC (2013) SNV supported domestic biogas programmes in Asia and Africa. Renew Energy 49:90–94. https://doi.org/10.1016/j.renene.2012.01.058

Ghosh D, Sagar AD, Kishore VVN (2006) Scaling up biomass gasifier use: an application-specific approach. Energy Policy 34:1566–1582. https://doi.org/10.1016/j.enpol.2004.11.014

Giwa A, Alabi A, Yusuf A, Olukan T (2017) A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. RSER 69:620–641. https://doi.org/10.1016/j.rser.2016.11.160

GRAMEEN SBM (2021) GOBAR-DHAN – WASTE TO WEALTH

Gu L, Zhang YX, Wang JZ, Gina Chen G, Battyeet H (2016) Where is the future of China's biogas? Review, forecast, and policy implications. Pet Sci 13:604–624. https://doi.org/10.1007/s12182-016-0105-6

Gülzow (2010) Guide to Biogas: From Production to Use

Herbes C, Chouvellon S, Lacombe J (2018) Towards marketing biomethane in France-French consumers' perception of biomethane. Energy Sustain Soc 8:. https://doi.org/10.1186/s13705-018-0179-7

Hiloidhari M, Das D, Baruah DC (2014) Bioenergy potential from crop residue biomass in India. RSER 32:504–512. https://doi.org/10.1016/j.rser.2014.01.025

Hirmer S, Cruickshank H (2014) The user-value of rural electrification: an analysis and adoption of existing models and theories. RSER 34:145–154. https://doi.org/10.1016/j.rser.2014.03.005

Ministry of New and Renewable Energy. (2021) Financial Incentives. In: 2021. https://mnre.gov.in/. Accessed 9 Oct 2023b

International Institute of Health and Hygiene (2020) ENVIS Centre on Hygiene, Sanitation, Sewage Treatment Systems and Technology. http://www.sulabhenvis.nic.in/Database/TabularData_9639.aspx. Accessed 5 Jun 2021

Jiang Z, Zhongbao L, Yinghua L, Xuemin T (2011) Cultivation of the microalga, chlorella pyrenoidosa, in biogas wastewater. Afr J Biotechnol 10:13115–13120. https://doi.org/10.5897/AJB11.358

Kabera T, Nishimwe H, Imanantirenganya I, Mbonyi MK (2016) Impact and effectiveness of Rwanda's National Domestic Biogas programme. Int J Environ Studies 73:402–421. https://doi.org/10.1080/00207233.2016.1165480

Kabir H, Yegbemey RN, Bauer S (2013) Factors determinant of biogas adoption in Bangladesh. RSER 28:881–889. https://doi.org/10.1016/j.rser.2013.08.046

Karagiannidis A (2012) Anaerobic digestion of waste. In: Karagiannidis Avraam (ed) Waste to Energy. Springer, pp 107–35

Kelebe HE (2018) Returns, setbacks, and future prospects of bio-energy promotion in northern Ethiopia: the case of family-sized biogas energy. Energy Sustain Soc 8. https://doi.org/10.1186/s13705-018-0171-2

KERC (2005) Karnataka Electricity Regulatory Commission (KERC). 2005

Khan EU, Martin AR (2016) Review of biogas digester technology in rural Bangladesh. RSER 62:247–259. https://doi.org/10.1016/j.rser.2016.04.044

Khan EU, Mainali B, Martin A, Silveira S (2014) Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study. Sustain Energy Technol Assessments 7:68–78. https://doi.org/10.1016/j.seta.2014.03.004

Khanna M, Önal H, Crago CL, Mino K (2013) Can India meet biofuel policy targets? Implications for food and fuel prices. Am J Agric Econ 95:296–302. https://doi.org/10.1093/ajae/aas040

Kothari R, Tyagi VV, Pathak A (2010) Waste-to-energy: a way from renewable energy sources to sustainable development. RSER 14:3164–3170. https://doi.org/10.1016/j.rser.2010.05.005

Kshirsagar VS, Pawar PM, Mehetre ST (2019) Holistic approach for biogas technology implementation to improve sustainability. Curr Sci 116:249–255. https://doi.org/10.18520/cs/v116/i2/249-255

Kumar A, Kumar N, Baredar P, Shukla A (2015) A review on biomass energy resources, potential, conversion and policy in India. RSER 45:530–539. https://doi.org/10.1016/j.rser.2015.02.007

Kumaran P, Hephzibah D, Sivasankari R, Saifuddin N, Shamsuddin AH (2016) A review on industrial scale anaerobic digestion systems deployment in Malaysia: opportunities and challenges. RSER 56:929–940. https://doi.org/10.1016/j.rser.2015.11.069

Landi M, Sovacool BK, Eidsness J (2013) Cooking with gas: policy lessons from Rwanda's National Domestic Biogas Program (NDBP). Energy Sustaina Dev 17:347–356. https://doi.org/10.1016/j.esd.2013.03.007

Lewis JJ, Hollingsworth JW, Chartier RT, Cooper EM, Foster WM, Gomes GL, Kussin PS, MacInnis JJ, Padhi BK, Panigrahi P, Rodes CE, Ryde IT, Singha AK, Stapleton HM, Thornburg J, Young CJ, Meyer JN, Pattanayak SK (2017) Biogas stoves reduce firewood use, household air pollution, and hospital visits in Odisha, India. Environ Sci Technol 51:560–569. https://doi.org/10.1021/acs.est.6b02466

Rabia Liaquat, Muhammad Ali Qureshi, Mavra Bari (2021) BIOGAS: an overlooked piece in the renewables puzzle in Pakistan. Pakistan

Lohan SK, Dixit J, Kumar R, Pandey Y, Khan J, Ishaq M, Modasir S, Kumar D (2015) Biogas: a boon for sustainable energy development in India's cold climate. RSER 43:95–101. https://doi.org/10.1016/j.rser.2014.11.028

Lora Grando R, de Souza Antune AM, da Fonseca FV, Sánchez A, Barrena R, Font X (2017) Technology overview of biogas production in anaerobic digestion plants: a European evaluation of research and development. RSER 80:44–53. https://doi.org/10.1016/j.rser.2017.05.079

Lüker-Jans N, Simmering D, Otte A (2017) The impact of biogas plants on regional dynamics of permanent grassland and maize area—the example of Hesse, Germany (2005–2010). Agric Ecosyst Environ 241:24–38. https://doi.org/10.1016/j.agee.2017.02.023

Martin M (2015) Potential of biogas expansion in Sweden: identifying the gap between potential studies and producer perspectives. Biofuels 6:233–240. https://doi.org/10.1080/17597269.2015.1090769

Masera OR, Bailis R, Drigo R, Adrian Ghilardi A, Mercado IR (2015) Environmental burden of traditional bioenergy use.

Annu Rev Environ Resour 40:121–150. https://doi.org/10.1146/annurev-environ-102014-021318
Mengistu MG, Simane B, Eshete G, Workneh TS (2016) Factors affecting households' decisions in biogas technology adoption, the case of Ofla and Mecha Districts, northern Ethiopia. Renew Energy 93:215–227. https://doi.org/10.1016/j.renene.2016.02.066
Ministry of External Affairs G of India (2021) India's Multilateral Engagements. In: 2021. https://mea.gov.in/. Accessed 8 Oct 2023
Ministry of Home Affairs (2021) Office of the Registrar General & Census Commissioner, India. https://www.censusindia.gov.in/Census_Data_2001/India_at_Glance/area.aspx. Accessed 30 Aug 2021
Ministry of Mahaweli Development A and TG of SLanka (2021). Biogas. In: 2021. https://mahaweli.gov.lk/. Accessed 9 Oct 2023
Ministry of New and Renewable Energy. (2018) National Policy on Biofuels. https://mnre.gov.in/. Accessed 8 Oct 2023
Ministry of New and Renewable Energy. (2021). Waste to Energy. In: 2021. https://mnre.gov.in/. Accessed 9 Oct 2023a
Ministry of New and Renewable Energy. (2021). Research & Development. In: 2021. https://mnre.gov.in/. Accessed 9 Oct 2023b
Ministry of Petroleum & Natural Gas (2018) Press Information Bureau, Government of India. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1532265. Accessed 7 Oct 2023
Ministry of Population and Environment G of Nepal (2021). National Biodigester Programme. In: 2021. http://nbp.org.kh/. Accessed 9 Oct 2023
Ministry of Power (2016) tariff policy. Delhi
Mittal S, Ahlgren EO, Shukla PR (2018) Barriers to biogas dissemination in India: a review. Energy Policy 112:361–370. https://doi.org/10.1016/j.enpol.2017.10.027
MNRE (2019) Ministry of New and Renewable Energy, Government of India (2019) Annual report 2018-2019 in India.
MNRE (2020b) Programme on Energy from Urban, Industrial, Agricultural Wastes/ Residues and Municipal Solid Waste
MNRE (2021b) National Biogas and Manure Management Programme (NBMMP). http://164.100.94.214/biogas. Accessed 26 Aug 2021
MNRE (2021c) New National Biogas and Organic Manure Programme (NNBOMP). https://biogas.mnre.gov.in/about-the-programmes. Accessed 20 Aug 2021
MNRE (2021d) New National biogas and organic manure programme (NNBOMP). https://mnre.gov.in/bio-energy/schemes. Accessed 26 Aug 2021
MNRE (2021e) Biogas power generation (off grid) and thermal energy application programe (BPGTP). https://mnre.gov.in/bio-energy/schemes. Accessed 26 Aug 2021
MNRE (2020a) New National Biogas Organic Manure Programme (NNBOMP) upto 2020. https://www.eqmagpro.com/new-national-biogas-organic-manure-programmennbomp-upto-2020-1/. Accessed 29 Aug 2021
MNRE (2021a) BIO ENERGY. https://mnre.gov.in/bio-energy/current-status. Accessed 20 Mar 2021
MOP&NG (2021) Sustainable Alternative Towards Affordable Transportation. https://iocl.com/pages/satat-overview. Accessed 26 Aug 2021
Morgan HM, Xie W, Liang J, Mao H, Leib H, Ruan R, Bu Q (2018) A techno-economic evaluation of anaerobic biogas producing systems in developing countries. Bioresour Technol 250:910–921. https://doi.org/10.1016/j.biortech.2017.12.013
Msibi SS, Kornelius G (2017) Potential for domestic biogas as household energy supply in South Africa. Journal of Energy in Southern Africa 28:1–13. https://doi.org/10.17159/2413-3051/2017/v28i2a1754
MSME (2021) List of State/UTs by Zones, Number of Districts & Registered Manufacturing MSME (Estimated)
Mukeshimana MC, Zhao ZY, Ahmad M, Irfan M (2021) Analysis on barriers to biogas dissemination in Rwanda: AHP approach. Renew Energy 163:1127–1137. https://doi.org/10.1016/j.renene.2020.09.051
Mulinda C, Hu Q, Pan K (2013) Dissemination and Problems of African Biogas Technology. Energy Power Eng 05:506–512. https://doi.org/10.4236/epe.2013.58055
Muradin M, Foltynowicz Z (2014) Potential for producing biogas from agricultural waste in rural plants in Poland. Sustainability (Switzerland) 6:5065–5074. https://doi.org/10.3390/su6085065
Mwirigi J, Balana B, Mugisha J, Walekhwa P, Melamu R, Nakami S, Makenzi P (2014) ScienceDirect socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa : a review. Biomass Bioenergy 1–9. https://doi.org/10.1016/j.biombioe.2014.02.018
Nevzorova T, Kutcherov V (2019) Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review. Energy Strategy Reviews 26:100414. https://doi.org/10.1016/j.esr.2019.100414
Njoroge DK (2007) Evolution of biogas technology in South Sudan ; current and future challenges. Appropriate Technology 1–5
Pandyaswargo AH, Gamaralalage PJD, Liu C, Knaus M, Onoda H, Mahichi F, Guo Y (2019) Challenges and an implementation framework for sustainable municipal organic waste management using biogas technology in emerging Asian countries. Sustainability (Switzerland) 11:. https://doi.org/10.3390/su11226331
Parawira W (2009) Biogas technology in sub-Saharan Africa: status, prospects and constraints. Rev Environ Sci Biotechnol 8:187–200. https://doi.org/10.1007/s11157-009-9148-0
Pathak H, Jain N, Bhatia A, Mohanty S, Gupta N (2009) Global warming mitigation potential of biogas plants in India. Environ Monit Assess 157:407–418. https://doi.org/10.1007/s10661-008-0545-6
Patinvoh RJ, Taherzadeh MJ (2019) Challenges of biogas implementation in developing countries. Curr Opin Environ Sci Health 12:30–37. https://doi.org/10.1016/j.coesh.2019.09.006
Pazera A, Slezak R, Krzystek L, Ledakowicz S, Bochmann G, Gabauer W, Helm S, Reitmeier S, Marley L, Gorga F, Farrant L, Suchan V, Kara J (2015) Biogas in Europe: Food and Beverage (FAB) Waste Potential for Biogas Production. Energy and Fuels 29:4011–4021. https://doi.org/10.1021/ef502812s
Phadke, A and Sathaye J (2006) Cost of electric power sector carbon mitigation in India: international implications. Energy Policy 34:
Piwowar A, Dzikuć M, Adamczyk J (2016) Agricultural biogas plants in Poland—selected technological, market and environmental aspects. RSER 58:69–74. https://doi.org/10.1016/j.rser.2015.12.153
Planning Commission (2014a) Report of the Task Force on Waste to Energy (Volume I)
Planning Commission (2014) Report of the Task Force on Waste to Energy: Volume I prepared by Planning Commission (PC). Task Force on Waste to Energy I:1–178
Planning Commission of India (2019) Demographic details, Literate Population (Total, Rural & Urban) (PDF). https://niti.gov.in/planningcommission.gov.in/docs/data/datatable/index.php?data=datatab. Accessed 10 Aug 2021
Prabakar D, Suvetha KS, Manimudi VT, Mathimani T, Kumar G, Rene ER, Pugazhendhi A (2018) Pretreatment technologies for industrial effluents: critical review on bioenergy production and environmental concerns. J Environ Manage 218:165–180. https://doi.org/10.1016/j.jenvman.2018.03.136
Pradeep, Amit Pal, Samsher (2020) Experimental analysis of four-stroke single-cylinder diesel engine using biogas as a dual fuel. In: Recent Advances in Mechanical Engineering. Springer, 395–406
Putra RARS, Liu Z, Lund M (2017) The impact of biogas technology adoption for farm households—empirical evidence from

mixed crop and livestock farming systems in Indonesia. RSER 74:1371–1378. https://doi.org/10.1016/j.rser.2016.11.164
Qureshi VPK and MA (1985) Biogas Development in India and the PRC
Rabezandrina R (1990) Biogas: evolution of actions and prospects for the rural environment in Africa. Ambio 19:424–426. https://doi.org/10.2307/4313757
Raha D, Mahanta P, Clarke ML (2014) The implementation of decentralised biogas plants in Assam, NE India: the impact and effectiveness of the National Biogas and Manure Management Programme. Energy Policy 68:80–91. https://doi.org/10.1016/j.enpol.2013.12.048
Rao KU, Ravindranath NH (2002) Policies to overcome barriers to the spread of bioenergy technologies in India. Energy Sustain Dev 6:59–73. https://doi.org/10.1016/S0973-0826(08)60326-9
Ravindranath NH, Balachandra P (2009) Sustainable bioenergy for India: technical, economic and policy analysis. Energy 34:1003–1013. https://doi.org/10.1016/j.energy.2008.12.012
Rodriguez C, Alaswad A, El-Hassan Z, Olabi AG (2017) Mechanical pretreatment of waste paper for biogas production. Waste Management 68:157–164. https://doi.org/10.1016/j.wasman.2017.06.040
Roopnarain A, Adeleke R (2017) Current status, hurdles and future prospects of biogas digestion technology in Africa. RSER 67:1162–1179. https://doi.org/10.1016/j.rser.2016.09.087
Rupf GV, Bahri PA, De Boer K, McHenry MP (2015) Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. RSER 52:468–476. https://doi.org/10.1016/j.rser.2015.07.107
Saidmamatov O, Rudenko I, Baier U, Khodjaniyazov E (2021) Challenges and solutions for biogas production from agriculture waste in the aral sea basin. Processes 9:1–16. https://doi.org/10.3390/pr9020199
Sanches-Pereira A, Lönnqvist T, Gómez MF, Coelho ST, Tudeschini LG (2015) Is natural gas a backup fuel against shortages of biogas or a threat to the Swedish vision of pursuing a vehicle fleet independent of fossil fuels? Renew Energy 83:1187–1199. https://doi.org/10.1016/j.renene.2015.06.006
Saravanan AP, Mathimani T, Deviram G, Rajendran K, Pugazhendhi A (2018) Biofuel policy in India: a review of policy barriers in sustainable marketing of biofuel. J Clean Prod 193:734–747. https://doi.org/10.1016/j.jclepro.2018.05.033
Satchwell AJ, Scown CD, Smith SJ, Amirebrahimi J, Jin L, Kirchstetter TW, Brown NJ, Preble CV (2018) Accelerating the deployment of anaerobic digestion to meet zero waste goals. Environ Sci Technol 52:13663–13669. https://doi.org/10.1021/acs.est.8b04481
Schmidt TS, Dabur S (2014) Explaining the diffusion of biogas in India: a new functional approach considering national borders and technology transfer. Environmental Economics and Policy Studies 16:171–199. https://doi.org/10.1007/s10018-013-0058-6
Shafiee S, Topal E (2009) When will fossil fuel reserves be diminished? Energy Policy 37:181–189. https://doi.org/10.1016/j.enpol.2008.08.016
Shane A, Gheewala SH, Kasali G (2015) Potential, Barriers and Prospects of Biogas Production in Zambia. JSEE 6:21–27
Sharma N, Dubey SK, Singh L (2018) Utilizing cow dung and slurry for energy sufficiency of farms and households : experiences of field studies across three Indian states utilizing cow dung and slurry for energy sufficiency of farms and households : Experiences of field studies across three
The World Bank (2019) Solid Waste Management, Understanding poverty. 2019. https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management. Accessed 30 Aug 2021
Statista (2021) Number of biogas plants across India as of March 2020, by state. https://www.statista.com/statistics/941298/india-number-of-biogas-plants-by-state/. Accessed 26 Aug 2021
Stern N (2007) The Economics of Climate Change: The Stern Review. London
Subramanyam Dr V. (2015) Statistical year book 2015, Directorate of Economics and Statistics Government of Telangana Hyderabad
Surendra KC, Takara D, Hashimoto AG, Khanal SK (2014) Biogas as a sustainable energy source for developing countries: opportunities and challenges. RSER 31:846–859. https://doi.org/10.1016/j.rser.2013.12.015
Taherzadeh MJ and KR (2014) Factors affecting development of waste management. In: Karin M. Ekström (ed) Waste Management and Sustainable Consumption. Routledge
Tanto D, Wiratni BM (2018) Menembus Pagar Baja: Dimensi Sosial dalam Proses Difusi Teknologi Biogas. UGM Press, Jogjakarta
Terrapon-Pfaff J, Dienst C, König J, Ortiz W (2014) A cross-sectional review: impacts and sustainability of small-scale renewable energy projects in developing countries. RSER 40:1–10. https://doi.org/10.1016/j.rser.2014.07.161
Teymoori Hamzehkolaei F, Amjady N (2018) A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units. Renew Energy 118:602–614. https://doi.org/10.1016/j.renene.2017.11.054
Tigabu AD, Berkhout F, van Beukering P (2015) Technology innovation systems and technology diffusion: adoption of bio-digestion in an emerging innovation system in Rwanda. Technol Forecast Soc Change 90:318–330. https://doi.org/10.1016/j.techfore.2013.10.011
Tomar SS (1995) Status of biogas plants in India—an overview. Energy Sustain Dev 1:53–56. https://doi.org/10.1016/S0973-0826(08)60088-5
Tyagi VK, Fdez-Güelfo LA, Zhou Y, Álvarez-Gallego C, Garcia LR, Ng WJ (2018) Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): progress and challenges. RSER 93:380–399. https://doi.org/10.1016/j.rser.2018.05.051
Uddin W, Khan B, Shaukat N, Majid M, Mujtaba G, Mehmood A, Ali S, Younas U, Anwar M, Almeshal AM (2016) Biogas potential for electric power generation in Pakistan: a survey. RSER 54:25–33. https://doi.org/10.1016/j.rser.2015.09.083
Vikaspedia (2021) Sustainable Alternative Towards Affordable Transportation. https://vikaspedia.in/energy/policy-support/renewable-energy-1/biofuels/sustainable-alternative-towards-affordable-transportation. Accessed 25 Aug 2021
Walekhwa PN, Mugisha J, Drake L (2009) Biogas energy from family-sized digesters in Uganda: critical factors and policy implications. Energy Policy 37:2754–2762. https://doi.org/10.1016/j.enpol.2009.03.018
WHO (2009) The energy access situation in developing countries: a review focusing on the least developed countries and Sub-Saharan Africa
Yasar A, Nazir S, Rasheed R, Tabinda AB, Nazar M (2017) Economic review of different designs of biogas plants at household level in Pakistan. Renew Sustain Energy Rev 74:221–229. https://doi.org/10.1016/j.rser.2017.01.128
Yousuf A, Khan MR, Pirozzi D, Ab Wahid Z (2016) Financial sustainability of biogas technology: barriers, opportunities, and solutions. Energy Sources, Part B: Econ Plan Policy 11:841–848. https://doi.org/10.1080/15567249.2016.1148084
Zhang L, Loh KC, Zhang J (2019) Enhanced biogas production from anaerobic digestion of solid organic wastes: current status and prospects. Elsevier Ltd