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Biogas as A Renewable Energy Solution in Pakistan: Review of Sources, Technologies, And Implementation Barriers

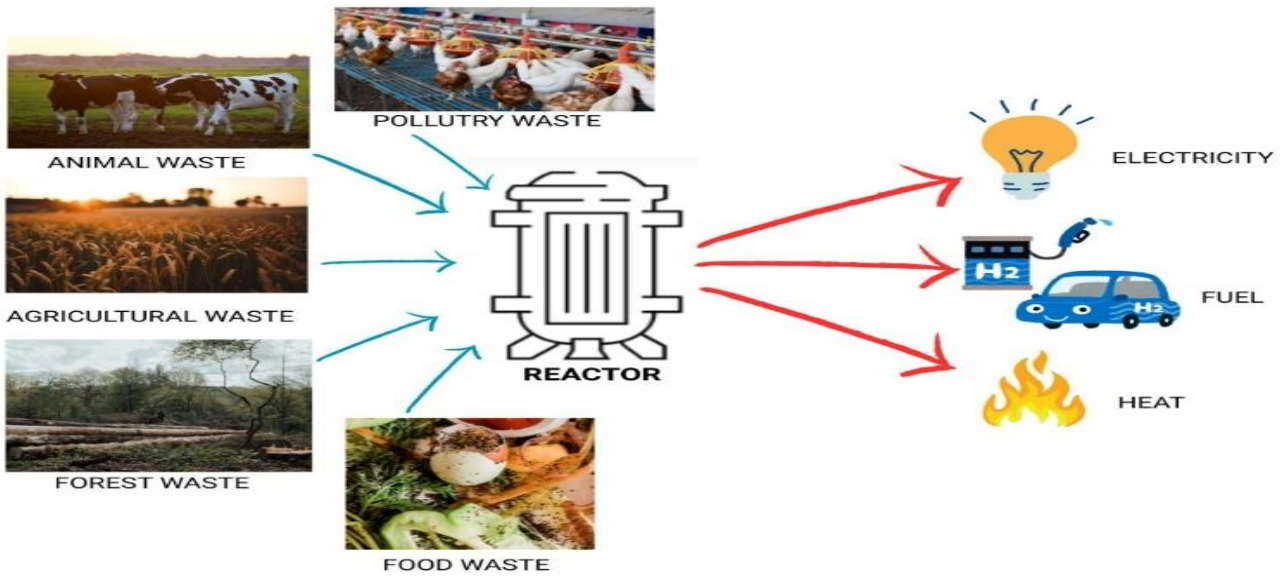
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Abstract

Energy is the main thread of any country's sustainability and development, especially for developing countries. Renewable energy sources are explored and utilized in the modern era to replace fossil fuels. In several developed and underdeveloped countries, biogas, as a renewable energy source, has drawn significant attention. Pakistan is an agriculture-based economy, and a significant portion of the population lives in rural areas. Pakistan could mainly meet its energy demand in rural areas and, to some extent, in urban areas by utilizing biogas as a renewable energy source, with the additional benefits of mitigating Greenhouse gas (GHG) emissions. This paper comprehensively reviews research achievements on biogas production, emphasizing the current status and economic potential of biogas in Pakistan. National assessments indicate a biogas potential of up to 226.8 million m³ per day from biomass waste. A comparative evaluation of digester technologies identifies fixed-dome digesters as the most cost-effective option for Pakistan's rural conditions. Furthermore, this review finds that financial and institutional barriers consistently outrank technical, environmental, and social barriers to biogas adoption in Pakistan, indicating that policy instruments such as feed-in tariffs and coordinated subsidy design should be prioritized.

Keywords: Biogas; Renewable Energy Source; Livestock; Biogas Technological Development



Graphical Abstract

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1. Introduction:

An essential component of a nation's socioeconomic development is energy. Approximately 85% of the world's primary energy consumption is met by fossil fuels [2]. The main causes of concern regarding the use of fossil fuels include the world's growing energy needs, the limited supply of fossil fuels, and environmental issues, including air pollution and global warming [3, 4]. As fossil fuels are used more often, the amount of CO_2 in the atmosphere rises, posing a serious threat to the modern world [5]. The primary causes of the growing energy consumption are economic growth, population growth, and improvements in living standards [6]. These factors also played a role in the increase in waste output, including agricultural, municipal solid waste, industrial, and animal waste. Due to improper disposal, these wastes are seriously harming the environment in emerging nations [7]. The aforementioned considerations all encourage the government to embrace renewable energy sources, such as solar, wind, biogas, and biofuels. [8, 9].

Among other things, biogas is thought to be a feasible energy source that can take the place of fossil fuels in the generation of power and energy [10, 11]. Compared to fossil fuels, biogas has the advantages of reduced carbon emissions and cost-effective replacements. Vegetable fruit, animal dung, poultry waste, and other feedstocks can all be used effectively by biogas plants [12]. Manure management facilities were made available by biogas plants, particularly for dairy & poultry farms. Methane produced by the microbial decomposition of solid waste makes up the majority of biogas [13, 14]. It can be used for several purposes, including power generation, industrial, household, and fertilizer, as well as synthetic natural gas (SNG) [15, 16]. The usage of coal in coal-based power plants produces massive emissions of the greenhouse gas CO_2. The use of biogas as an alternative to coal could address this issue. Previously regarded as a “poor man’s fuel,” biogas now plays a significant role in global energy planning [17, 18]. According to some studies, biogas can help with environmental problems and has great potential for use as a renewable energy source that is renewable [19-22]. The amount of power generated from biogas is predicted to increase globally from 331 TWh in 2010 to 1487 TWh by 2035 [23]. By the year 2035, 13 percent of the electrical energy produced by renewable energy sources will have increased from the current 8% [24, 25].

The technological advancement of the production of biogas for the generation of heat and electricity is the main emphasis of the European nations. Many biogas plants and biogas power generation systems are currently in operation throughout Europe [26, 27]. In order to meet the energy needs of rural areas, developing nations such as China and India also make investments in the technological development of biogas production processes and energy extraction [28]. Table 1 shows the energy generation using biogas technology for various nations worldwide.

Table 1: The installed capacity of biogas production country-wise [17]

Countries	Installed Biogas capacity (MW_{el})
Germany	6,000
USA	2300
UK	1800
Italy	1500
Thailand	300
China	290
France	250
Turkey	240

With a population of 241.5 million as of the 2023 national census [28], Pakistan is an emerging nation with a thriving agricultural base and a growing energy demand. Pakistan uses conventional fossil fuels (coal, gas, and oil) to supply its major energy needs, mostly for power generation. Pakistan's growing population and economy have contributed to the ongoing increase in energy demand, which is predicted to reach roughly 142 million tons of oil equivalent (MTOE) in 2030 [29, 30]. Because of fossil fuel imports, reliance on fossil fuels will grow to account for a sizable portion of energy output and create a circular debt trap in the economy. Between 2005 and 2015, CO_2 emissions rose from 38 to 177.43 million tons (Mt)/year due to a heavy reliance on fossil fuels [32].

Pakistan has several potential energy sources that are renewable, including wind, solar, biomass, hydro, and biogas, because of its geographic location [31]. Currently, power is generated by hydro, solar, and wind energy. Nevertheless, Pakistan's energy needs cannot be satisfied by these three resources alone. Adoption of additional renewable energy sources, such as biomass,

biogas, and biofuels, is necessary in this context. The creation of inexpensive, sustainable, and environmentally friendly power generation sources is another priority of Pakistan's 2019 alternative and renewable energy policy. Energy production from garbage, biomass, and biogas is encouraged by this policy [32, 33]. At an entire cost of 125.18 billion, the Pakistani government recently began phase 1 of the billion-tree tsunami initiative, which will last for four years from 2019 to 2023 [34]. This program's primary goals are to reduce climate change's adverse consequences, encourage ecotourism, and provide jobs for Pakistan's impoverished. In line with the objectives of the Paris Agreement, the Pakistani government is stepping up its efforts to use renewable energy sources [35].

Table 2: Livestock potential in Pakistan [36, 37]

Species	No. (Million)
Cattle	46.1
Buffalo	38.8
Sheep	30.5
Goat	74.1
Camels	1.1
Horses	0.4
Asses	5.3
Mules	0.2

Pakistan's natural gas balance has widened steadily into a structural deficit over the past decade. Domestic gas production fell from 35.0 billion cubic metres (bcm) in 2015 to 24.9 bcm in 2025, a decline of 29% over ten years and of 5.4% year-on-year in 2025 alone, driven by the depletion of mature fields [38]. Over the same period, national gas consumption has been comparatively stable, moving from 36.5 bcm in 2015 to a peak of 44.9 bcm in 2021 before easing to 34.1 bcm in 2025 as demand growth slowed [38]. The difference between the two was met almost entirely through imported liquefied natural gas (LNG), running at 9.1–12.2 bcm/year even as absolute demand fell, and reached 9.1 bcm in 2025 alone [38]. As shown in Figure 1, this structural reliance on LNG to bridge the gap between falling indigenous production and continuing demand underscores the urgency of developing domestic, non-imported alternatives such as biogas, which can supply gaseous fuel without exposure to the depletion of domestic reserves or to global LNG market volatility.

The price of natural gas supplied to Pakistani consumers has risen sharply and repeatedly since 2022, driven by the rising cost of imported LNG. The Oil and Gas Regulatory Authority (OGRA) approved a cumulative increase of roughly 193% in the prescribed gas price for Sui Northern Gas Pipelines Limited (SNGPL) between November 2023 and January 2024 alone, raising the average prescribed price from about Rs 1,238.68 to Rs 1,673.82 per mmBtu, and residential consumer prices were raised by up to 67% in February 2024 [39]. Pakistan's dependence on imported LNG also exposes the country to volatility in international gas markets and to the constraints of rigid, long-term supply contracts [39]. This episode illustrates concretely how exposure to international LNG pricing and contractual rigidity can leave Pakistan either overpaying for gas it does not need or under-supplied when domestic conditions shift quickly a volatility that a domestically produced, feedstock-based energy carrier such as biogas would not be exposed to in the same way.

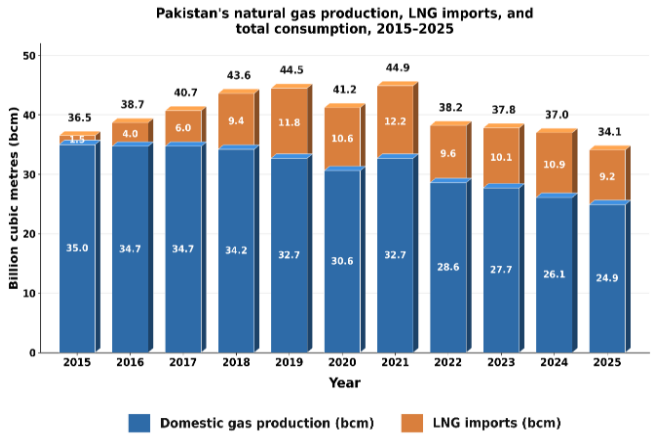


Figure 1. Pakistan's natural gas domestic production, LNG imports and consumption (billion cubic metres) [38].

The agriculture sector in Pakistan contributes significantly to economic growth, accounting for 60 percent of the nation's exports and 24.6% of its GDP [40]. 56% of Pakistan's agriculture sector, which generates 12% of the country's GDP, is devoted to the cattle industry [11, 41]. In Pakistan, the cattle industry plays a crucial part in the agricultural sector. It gives

small farmers, in particular, revenue, milk, and meat. Pakistan's livestock production is displayed in Table 2 [36]. This cattle produces almost 652 million kg of manure each day in Pakistan [42]. It is possible to generate 27.2 million m^3 of biogas per day from agricultural residue and manure, which is enough to generate 1900 MW of energy [36]. Currently, this animal dung is stored outdoors for cooking and heating, which leads to health issues, environmental issues, and disagreeable smells [43]. Therefore, Pakistan should concentrate on using biogas to generate electricity in order to meet its power requirements and address environmental concerns. Some research on Pakistan's biogas potential has been published. The majority of the studies concentrated on using solar, wind, and hydro energy as well as animal dung to generate biogas. All of the sources of biogas generation and technological advancement in Pakistan must currently be addressed [44-46].

Furthermore, why is it insufficiently utilized in Pakistan, a nation rich in cattle and agriculture? This review primarily focuses on four issues in this regard, which are: (1) Pakistani biogas production sources, such as chicken, kitchen waste, municipal solid waste, and forest residue; (2) Pakistani biogas technological advancements; (3) Pakistani biogas energy's economic effects; and (4) Pakistan's biogas use failures [47, 48].

2. Pakistan's Energy Scenario:

As shown in Figure 2(a), Pakistan is experiencing an electricity shortage as a result of the large disparity between supply and demand. Rural areas experience power outages for 12–16 hours throughout the summer, whereas urban areas experience power outages for 6–8 hours [15, 49, 50]. Pakistan's energy issue is mostly caused by a number of worrisome elements, including a lack of understanding, a lack of focus on using renewable energy sources, poor planning, small usage of renewable energy sources, and incorrect use of coal and hydro assets [51]. The requirements for power have increased more quickly than their supply over the past ten years.

The Pakistani government is working to boost installed capacity and electricity generation. Figure 2(b) compares the proportions of various energy sources used to produce electricity in the fiscal years 2019 and 2020. It has been demonstrated that a sizable portion of power generation comes from thermal energy resources such as coal, natural gas, and imported crude oil [52, 53]. Pakistan's share of thermal energy is still relatively high compared to other sources, even though it decreased last year. In 2020, the proportion of energy produced from renewable sources fell [10, 12, 54]. Since thermal energy generation is expensive and environmentally unfavorable, Pakistan must concentrate on renewable energy sources when calculating it energy needs. Pakistan consumes 19.68 million tons of petroleum products annually. Meanwhile, up to 11.5 million tons can be supplied annually by nearby refineries [55, 56].

The annual import of petroleum products is about 8.09 million tons. Crude oil imports are the main source of Pakistan's economic burden, costing the country over $14.5 billion in US dollars [54, 57]. The amount of imported oil and its price are contrasted in Figures 2(c) and (d). Some variables, such as the decline in global oil prices, the COVID-19 scenario, and the demand from the nation's market and industry, contributed to a significant drop in the cost and import of crude oil in 2020 [58, 59].

It is crucial to look for alternative sources of energy instead of relying on imported oil. A plan to raise Pakistan's energy capacity from renewable sources such as wind, solar, hydro, and biomass to 30% of the total was announced in April 2019. By 2030, this plan is expected to be completed. The government has begun construction on ten dams to generate power in this manner, but the process takes time and requires a significant amount of capital expenditure, which appears challenging to handle because it will be borrowed from foreign funding organizations [60, 61].

Biomass-based methods and sources were more appealing since they could be quickly gathered for energy production. One strategy to reduce the strain on expensive oil-based power generation is the production of biogas. It is an essential method of supplying Pakistan's energy needs. One m^3 of biogas can provide 2.5 kWh of electrical energy. The nation has the capacity to produce 27.2 million m^3/day of biogas [62, 63].

Since the livestock industry is growing at a pace of about 4% each year, biogas can be produced from its manure. By effectively utilizing biogas as an alternative energy source, the energy crisis can be reduced. A biogas plant can be installed at a very low cost. About 5375 biogas

plants have been established in Pakistan by the Pakistan Council of Renewable Energy Technologies, lowering reliance on LPG, wood, and kerosene oil while saving an average of USD 236,477 each month. Importing oil costs 20% of foreign reserves, which hurts Pakistan's economy. [64, 65].

3. The Potential of Biogas in Pakistan:

3.1. Biogas Production Prospectus in Pakistan:

In Pakistan, the installation of biogas plants began in 1959 in the province of Sindh [10]. In 1974, the Pakistani government established household biogas facilities after realizing the potential of biogas as an alternative energy source [66, 67]. Chinese fixed dome innovation served as the foundation for the development of 21 biogas facilities. Ten biogas plants were later created using Indian designs because Chinese technology was having trouble with gas leaks. Azad Jammu and Kashmir has these units installed, and they are operating efficiently [10, 68].

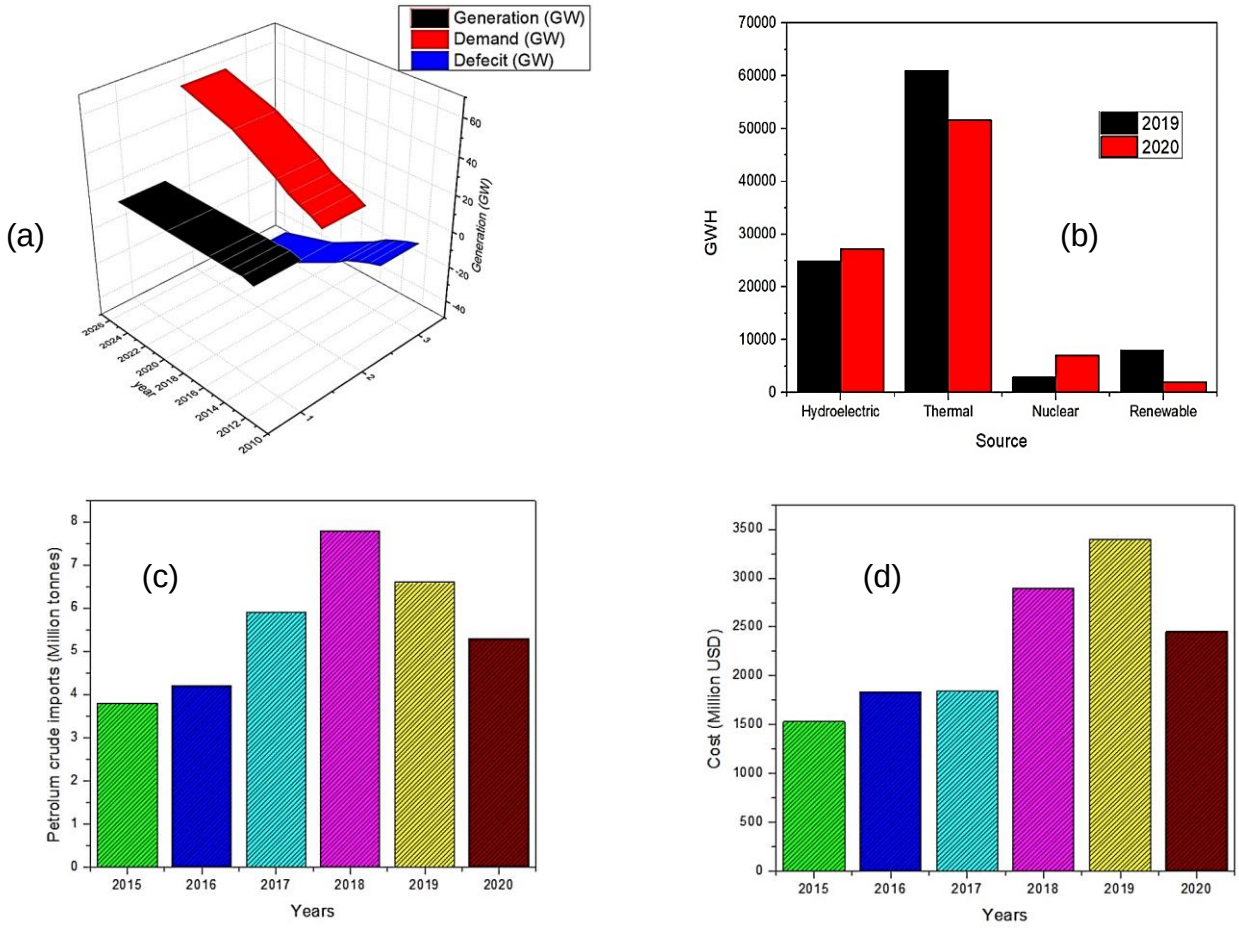


Figure 2. (a) Analysis of power supply, demand, and deficit during 2012-25 (b) Shares of different energy production sources for Pakistan (c) Petroleum crude import from 2015-20 & (d) Cost analysis of crude petroleum import during 2015-20.

With assistance from the Pakistani government, the Directorate General of New and Renewable Energy Resources (DNGRER) sought to establish nearly 4,137 biogas plants by 1986 [69]. This initiative was planned in three stages by the DNGRER. One hundred demonstration plants that were funded by the government were installed in the first phase. The third step offered technical services to those who were willing, while the second phase included a 50% subsidy for the installation of biogas plants [70, 71]. However, the cost of technology, members' inadequate training, the end of government subsidies, and an apparent absence of enthusiasm are the main reasons why this program fails. The Pakistani government launched the "Biogas Support Programme" (BSP) in 2000, and initially, 1200 biogas plants were installed under this initiative. Afterwards, BSP built around 10,000 biogas units until 2010 [10, 72].

In order to address energy needs at a reasonable cost, the Pakistan Dairy Development Company (PDDC) has

also taken the lead in developing biogas plants in rural regions [73]. Up till May 2009, PDDC had established 450 biogas plants [74, 75]. Following July 2009, there were 556 installed biogas plants as a result of the people's incredibly successful response. This program operated with 4-5 buffalo/cows dung at the residential level and was cost-effective, with an average installation cost of 35000-40000 PKR. Additionally, PDDC helped the farmers by giving them subsidies. To utilize the biogas around the nation, the Rural Support Program Network (RSPN) set up 70 biogas plants in that same year [76, 77]. In addition to offering their consumers a 7500 PKR subsidy, the RSPN initiative helped people by allowing them to select the size of biogas plants based on their ability to produce and accessibility.

In Pakistan, biogas research and development is carried out by the Pakistan Council for Renewable Energy Technologies (PCRET), the Pakistan Council for Appropriate Technology (PCAT), and the Pakistan Renewable Energy Society (PRES). Nearly 5357 biogas plants with capacities ranging from 3 to 15 m^3/day were installed by PCRET up until 2014 [78, 79]. Up until 2018, Pakistan planned to develop almost 14,500 biogas plants with a daily capacity of 3–15 m^3/day [80]. The Initial Environment Examination (IEE) for Pakistan's household biogas plants has been carried out by the Rural Support Network (RSN). During ten years, Pakistan needs to build about 300,000 residential biogas plants [70, 71].

Pakistan is the sixth most populous country in the world, home to over 220 million people [81, 82]. Sixty-two percent of Pakistanis live in rural areas [83]. These rural dwellers directly supply their domestic energy needs by using biofuels like wood and animal dung [84]. In Pakistan, energy is generated from organic matter, which includes agricultural waste, animal manure, animal waste, vegetable trash, and chicken waste [10, 29]. These resources generate 230 billion tons of biomass annually, which can be converted into biogas [87,88]. In Pakistani cities, 60000 tons of solid trash are generated. In Pakistani cities, 60000 tons of solid trash are generated [85, 86]. Different Pakistani provinces, 22% Sindh, 68% Punjab, 3.5% Baluchistan, and 6.5% KPK, will produce 15 million layer chickens and 528 broiler chickens. These biogas generation sources are covered in detail in the next section [87, 88]

4. Sources of Biogas Generation:

The production of biogas has historically been the main application for animal manure. The ability to generate energy is closely correlated with the amount of animal excrement produced [89]. Furthermore, many variables, including the type of animal, body weight, and feed quantity, affect the formation of manure [31, 90]. According to Avcioğlu et al. [90], camels create 15–17 kg of dung per day, while cattle produce 10–20 kg. In contrast, horses, mules, and asses have a daily dung production capability of roughly 10 to 15 kg. Using the excrement of the water buffalo, the anaerobic fermentation process creates a mixture of hydrogen and methane gas [10]. Manure production is influenced by a number of parameters, including its availability, volume, and total solids content [90]. The following formula can be used to determine the theoretical potential for biogas from animal waste.

$$\boldsymbol{TPB = M * AC * TS * \frac{BY}{kg} * TS} \quad ----------(1)$$

Whereas:

TPB = Theoretical Potential of Biogas (million m^3/year)

M quantity of manure /year (million kg /year)

AC = availability of the coefficient of animal manure for selected species

TS = Total solid contents

BY = Biogas yield of animal manure (m^3 /kg × TS)

In 1959, a biogas facility utilizing farmyard waste was developed in Pakistan's Sindh area. Phosphorus levels in cow farm dung ranged from 4100 to 18,300 mg/kg of dry matter, according to He et al. [91, 92] However, after accounting for all types of losses, only fifty-seven percent of the total amount of manure produced could be collected (19% fresh manure nitrogen, 37% phosphorus, and 29% potassium to plant) [10]. Many other sources can be used for biogas production that are extensively available in Pakistan; the potential of some sources is given below. The potential of a few of the numerous other sources that are widely accessible in Pakistan and can be utilized for the production of biogas is listed below.

4.1. Biogas Generation from Poultry Waste:

Pakistan's increasing demand for meat has led to a highly developed poultry sector [93]. With an annual production of 1,163 million broilers (chicken), Pakistan ranks 11th in the world in terms of poultry production [47, 94]. As Pakistan's population grows, the number of

poultry farms keeps growing, producing enormous amounts of waste [95, 96].

Feathers, blood, dung, and other chicken waste produced during operations can be used to create biogas. Poultry waste can be converted into biogas using the anaerobic digestion process, which has been proven to be an effective method for producing biogas from animal manure [97, 98]. Bio-digestate, a by-product of anaerobic digestion processes, is enriched with nutrients and can be utilized as an organic crop fertilizer [99]. Every year, one million tons of poultry manure are produced in Pakistan. Each chicken produces about 2 kg of manure per year [100, 101]. Manure is composed of 18% lipids, 24% protein, and 35% dry matter.

Approximately 20% of a chicken's weight is wasted during the slaughtering process. Every year, four million tons of feathers are gathered as trash from slaughter [102, 103]. The components of individual bird excrement are displayed in Figure 3 below. Slaughtering waste contains valuable organic stuff and feedstock [104]. Even a small amount of butchering waste contains crude proteins and lipids. Feathers include around 90% of the protein; heads and legs are made of lipids and protein, while bones contain mineral elements [105, 106]. Another type of animal waste that contains proteins and lipids is blood. Proteases include disulfide bones, and feathers contain beta-keratin, which is difficult to digest. [107, 108]. Digestion is solely the responsibility of the anaerobic process [97].

Poultry waste contains biodegradable substances such as proteins, lipids, and carbohydrates. Figure 4 displays the products of biogas and biodegradation. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four main phases of biogas formation [109, 110]. The breakdown of biomaterials into glucose, fatty acids, and amino acids is known as hydrolysis [111, 112]. Methanogens are a type of biogas through the anaerobic breakdown of organic materials [113]. Following hydrolysis, which produces hydrogen, carbon dioxide, acetates, and volatile fatty acids, biogas is produced.

The breakdown of volatile fatty acids results in the formation of hydrogen and acetate. In the final phase, methane is produced with the aid of methanogenic bacteria [12, 114]. In essence, it is an anaerobic digestion method. Poultry waste (manure, blood, feathers, fat, etc.) exists in large quantities. The biogas of about 97.5 $\times 10^6$ m^3 can be obtained after proper management of waste with the help of an anaerobic digestion method. About 300 MWh/day of energy can be created by 97.5×10^6 m^3 biogas [100, 115-119].

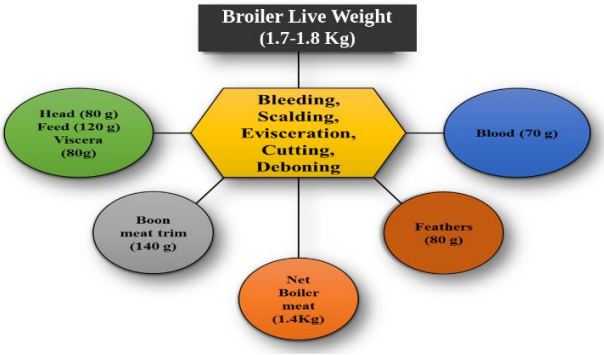


Figure 3: Single bird waste components

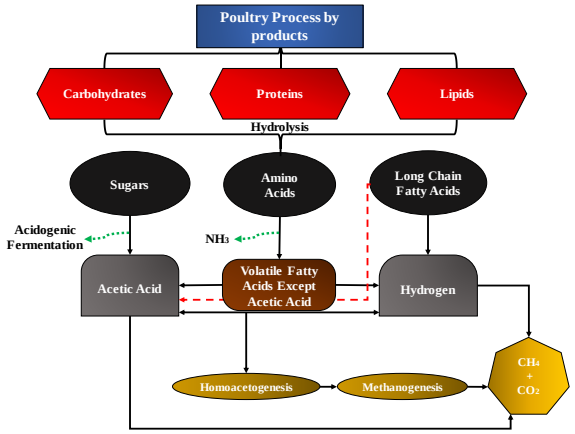


Figure 4: Biogas production from poultry products

4.2. Biogas Generation from Municipal Solid Waste:

Managing the organic and inorganic garbage generated by human activity, known as municipal solid waste, is a significant problem [120]. Numerous solid waste sources, including cities, municipalities, and domestic activities, are included in municipal solid waste [121]. Municipal solid waste usually consists of organics, glass, paper, plastic, metal, and all recyclables. Organic matter makes up the majority of municipal solid trash. Figure 5(a) displays the makeup of municipal solid trash. Table 3 provides an analysis of the generation of municipal solid trash in several Pakistani cities.

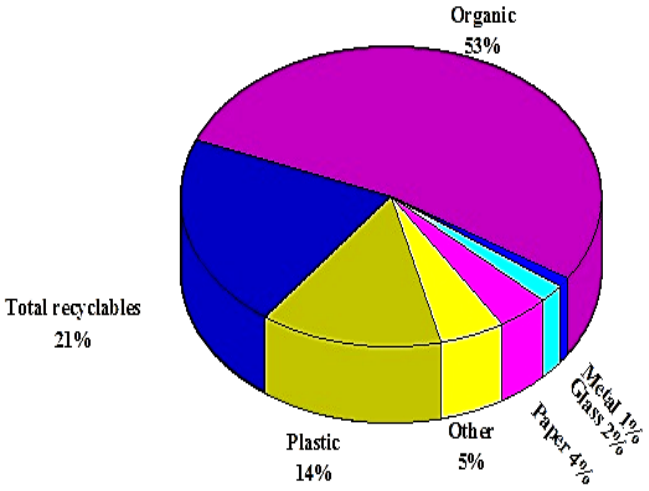
Table 3: Municipal solid waste generation in Pakistan [122, 123].

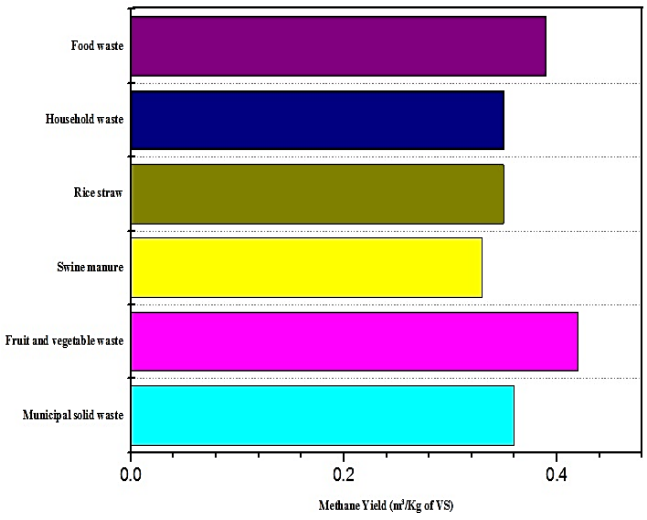
City	Population (million)	MSW generation (Tons)
Quetta	600,000	326
Sargodha	4,500,000	2930
Multan	5,200,000	3385
Rawalpindi	5,900,000	3841
Lahore	10,000,000	6510
Karachi	20,500,000	9440
Faisalabad	7,500,000	4883
Hyderabad	5,500,000	3581
Gujranwala	4,800,000	3125
Peshawar	2,900,000	1888

The two major cities, Karachi and Lahore, are the biggest producers of municipal solid garbage. Since organics make up the majority of municipal solid waste, they can be broken down by a variety of procedures. When there is no air present, organic stuff decomposes [124, 125]. Organic matter breaks down in the presence of air during the aerobic process. Ammonia, carbon dioxide, and humus are typically included in the final aerobic product. Without air, biological stuff breaks down during the anaerobic process. Anaerobic processes can occur naturally or under regulated conditions, such as pressure, temperature, etc. [126, 127]. The breakdown process produces some byproducts. While biogas is the primary output and manure and peat are byproducts, if the decay process takes place underwater or in animal intestines [128, 129], biogas is produced with sludge as a result of the decay process taking place in an airtight digester, as shown in Figure 6.

Anaerobic digestion (AD) was employed to produce biogas utilizing a variety of organic waste as input material. Methane (CH_4) gas is the main component of biogas. CH_4, 20–50% CO_2, and trace amounts of N_2, H_2, H_2S, and O_2 make up roughly 50–70% of biogas [124]. Figure 6(b) shows the CH_4 yield analysis for various waste materials. Anaerobic digestion of municipal solid waste can produce biogas. An anaerobic digester with a 10 m^3 capacity and regulated pH and temperature was employed by Biswas et al. [130, 131].

The concentration of the influent slurry ranged from 20 to 56 kg/m^3. For fifteen days, the digester was in operation. The digester produces bio-methane gas with a concentration of 80% (V/V). It was also discovered





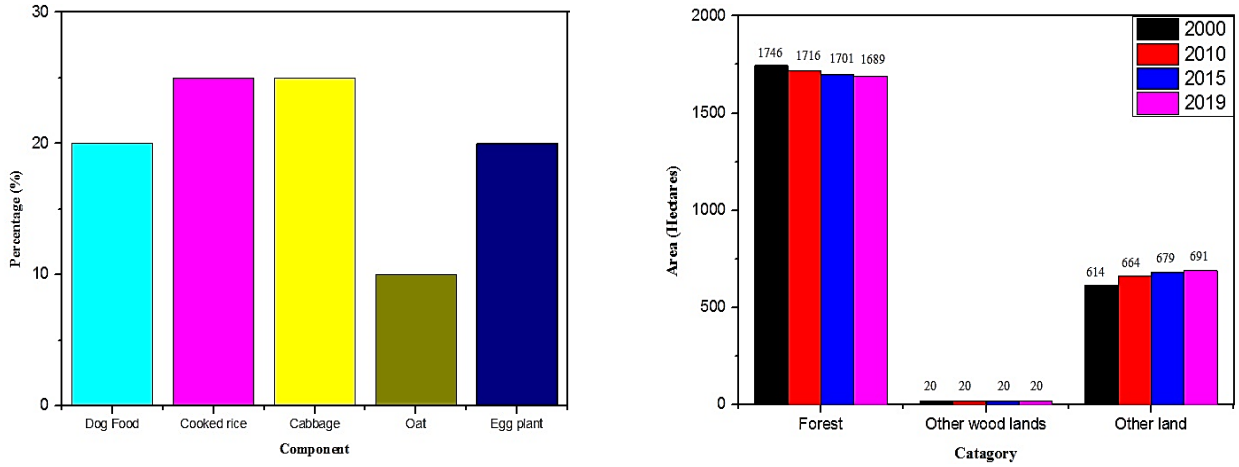


Figure 5. (a) Composition of municipal solid waste (b) Biogas generation from different organic solid waste by using anaerobic digestion (c) Composition of kitchen waste & (d) Comparison of forest and woody land area in Pakistan.

that the digester's biogas has a calorific value between 27.98 and 31.46 MJ/Nm^3. The initial concentration of the slurry, protein, fat, and carbohydrates in relation to the feed of municipal wastes determines the digester's performance [31, 132]. Elango et al. [133] looked into how adding household and municipal solid waste affected the production of biogas. By setting a hydraulic retention duration of 25 days, the reactor was run at temperatures ranging from 26 to 36 °C. Different rates of 0.5, 1.0, 2.3, 2.9, 3.5, and 4.3 kg of volatile solids (VS) per m^3 of digester slurry per day were fed into the digester. Adding household waste to municipal solid waste increases the production of biogas [134-136].

At a feeding rate of 2.9 kg of VS/m^3, the maximum biogas generation value of roughly 0.36 m3/kg of VS per day was observed. It was discovered that the biogas produced via anaerobic digestion has a quality of 68–72%. Co-digesting household and municipal solid waste can boost the production of biogas. The addition of household trash inhibits anaerobic digestion. While household sewage raises the quantity of soluble substrate that the microorganisms need, the addition of municipal solid waste increases the number of microorganisms [131, 137, 138].

Consequently, the effluent's nitrogen, phosphorus, and potassium levels are 60%, 73%, and 70% of the sludge, respectively, and the production of CH_4 is at its highest when compared to MSW alone. In agriculture, the nutrients produced by this process can be applied as fertilizer. Over the past few years, the production of biogas or bio-methane via anaerobic digestion has increased steadily [139, 140].

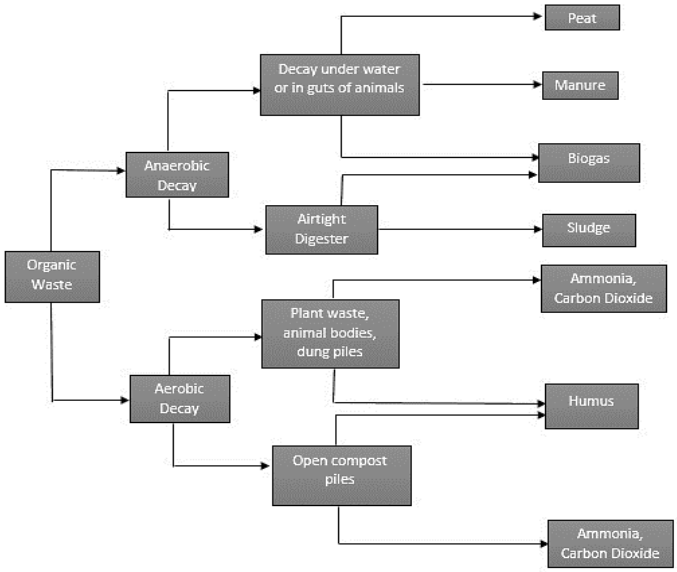


Figure 6. Organic decomposition using aerobic and anaerobic processes [124] Copyright Elsevier 2021.

CH_4 has a heating value of 55.5 MJ/kg, which is the same as 3.7 kg of wood or 1.2 kg of diesel [141]. By adding digestible co-substrates to the organic fraction, CH_4 generation and anaerobic digester performance can be enhanced. Fountoulakis et al. [142, 143] evaluated the effectiveness of a single-stage anaerobic reactor in processing organic waste by adding crude glycerol. Following the addition of crude glycerol in the organic fraction to municipal solid waste, the reactor's daily CH_4 production increased from 1400 mL to 2094 mL. The reactor generated 1400 mL CH_4/day, but after the addition of crude glycerol in organic fraction to municipal solid waste, the production increased from 1400 mL/day CH_4 to 2094 mL/day [144, 145]. The

addition of wastewater from slaughterhouses and olive mills, combined with crude glycerol in a 1:4 ratio, greatly enhanced CH_4 generation. AD can produce biogas, but the process's effectiveness is dependent on the substrate's makeup [146, 147].

4.3. Biogas Generation from Kitchen Waste:

Kitchen garbage makes up a significant portion of municipal solid waste. 20–65% of kitchen garbage is found in municipal solid waste [148]. Figure 5(c) shows the model kitchen waste's composition in accordance with Canadian food rules. Biodegradation of kitchen garbage is uncomplicated. It has a higher moisture content, protein, fats, and carbs [144, 149]. Due to the fact that it provides sufficient nutrients for bacteria, kitchen waste is a significant source of biogas production [150]. The formation of volatile fatty acids, which lowers pH and prevents bacteria from methanizing waste, is one of the major drawbacks of the anaerobic digestion of kitchen waste [151, 152].

Various strategies have been tried to reduce the formation of volatile fatty acids. Combining kitchen waste with other organic resources, such as dairy manure, can help reduce it [153]. The C/N ratio was adjusted using activated sludge [154]. It is possible to boost methanogen development and CH_4 generation by adding trace elements [155, 156]. Trace elements are crucial for methanogenesis and for enzymes [157]. The impact on CH_4 production was determined using eight trace elements: iron, nickel, cobalt, molybdenum, zinc, manganese, boron, and copper. Low doses of excess trace elements have less impact on methane generation [158, 159]. Up to 37% more CH_4 was produced as a result of trace element optimization [158]. The demand has significantly increased due to the growing energy use; thus, finding alternative resources is crucial to overcoming this shortfall [160-162]. Among the resources are wind, sun, and biomass. Biogas, which primarily consists of methane, can be produced from biomass. Biomass resources that can be turned into biogas are abundant in Pakistan. One form of biomass, kitchen trash, can generate 60% CH_4 gas, 30% CO_2, 8% N_2, and the remaining hydrogen sulfide [163, 164]. Table 4 lists the physiochemical makeup of kitchen garbage.

Table 4: Physiochemical composition of kitchen waste [165]

Parameter	Value
Total solids (%)	20
Volatile solids (%)	19.5
Total carbohydrate (%)	42.6
Crude protein (%)	22.1
Lipids (%)	17.1
Total Carbon (%)	49.8
Total Nitrogen (%)	3.6

Using an integrated biological reactor (IBR) and anaerobic fermentation, Guo et al. [166] produced biogas. An up-flow anaerobic sludge bed reactor and a continuously stirred tank reactor are combined to create an integrative biological reactor. The production rate of CH_4 was reported to be 1.5-2.4 L/day, and the optimal volume load rate (VLR) for CH_4 production using kitchen trash as substrate was determined to be 6-8 Kg COD/(m^3.day). Ye et al. [167, 168] investigated how various feed ratios affected biogas production. Pig dung, rice straw, and kitchen trash were all co-digested anaerobically. Based on volatile solids, a single-stage batch anaerobic digestion was carried out with a substrate concentration of 54 g/L. The ideal proportion of kitchen garbage, pig dung, and rice straw was 1:1.6:0.4. Compared to digesting pig dung or rice straw alone, more biogas was produced. [169, 170]. The impact of co-digesting kitchen trash with cow dung on the production of biogas was investigated by Li et al. [171]. When compared to the digestion of kitchen garbage alone, the formation of CH_4 rose by 40%.

The production of biogas can be increased by using several pretreatment techniques. Acid pretreatment, heat, pressure-depressure, thermo-acid, and freeze-thaw pretreatment are among the techniques [172]. Using HCl to acidify kitchen trash is part of the acid pretreatment process. Kitchen garbage is thermally pretreated by autoclaving it at 120 °C. Acidification and autoclaving are two steps in the thermo-acid pretreatment process [173, 174]. Using carbon dioxide as a pressurizing gas, waste from the kitchen is pressurized and depressurized as part of the pressure-depressurization treatment process. Kitchen garbage is frozen to 80 °C and then thawed in a thermal oven set to 50 °C for two hours as part of the freeze-thaw process [175, 176]. The pressure-depressure pretreatment approach produced the best biogas productivity.

4.4. Forest Residue as a Source of Biogas Production:

An essential resource for the production of energy is forest remains. Households use forest leftovers for heating and cooking [177]. As illustrated in Figure 6(d), Pakistan's total land mass area is 79,610,000 hectares, of which 1,686,000 hectares comprise forest area [178]. It demonstrates how the rising utilization of forests in Pakistan's northern regions is causing their area to shrink over time. Forest residue comes in two varieties. Logging residue is the first, followed by wood processing residue [179, 180]. Harvesting operations generate logging leftovers. It consists of sawdust, branches, roots, and stumps. The primary sources of wood processing residue are sawmill operations and plywood processing. Barks, sawdust, leftover logs, and offcuts make up this material [181, 182]. Up to 80% of Pakistan's total use of energy from biomass resources can be met by forest residue, making it a significant biomass source [72, 183]. The main components of several waste streams, including forestry and agricultural waste, are lignocelluloses. An estimated 200 billion tons of lignocellulose are generated each year [184]. Table 5 provides information about pine's chemical makeup.

Table 5: Chemical properties of pine [185]

Parameter	Stem wood	Needles	Bark
Extractives	3	12.6	4.5
Lignin	28.1	28.4	29.2
Carbohydrates	67.9	54	62.4
Cellulose	40.8	29.1	36.2
Glucomannan	15.4	11.8	5.2
Galactose	1.1	3,7	4.2
Arabinose	0.8	3.4	9.2
Xylene	7.7	3.9	5.5
Uronic acid	2.1	2.1	2.1
Unknown	1	5	4

Biogas can be generated from these carbon-rich substrates (lignocellulose), but pretreatment is needed before anaerobic digestion. Different methods available for the pretreatment of cellulosic biomass have more advantages than thermal pretreatments for removing the crystallinity of cellulose. Due to the low growth rate of methanogenic bacteria, they are sensitive to the product that inhibits their growth during the methanogenic process [186]. The development of such compounds that can function as inhibitors during the pretreatment phase is a potential. The formation of phenolic compounds and furans by various application techniques, such as steam explosion, ammonia fiber explosion, and diluted acid pretreatment, might influence the anaerobic digestion process and boost the production of biogas. This means that the pretreatment method should be chosen without producing inhibitor compounds, as the presence of these molecules slows down the pace at which bacteria grow.

Analysis of CH_4 generation was done by Kabir et al. [187] both before and after the application of particular organic solvents. Pretreatment solvents included methanol, ethanol, and acetic acid. Methane production ranged from 0.05 m^3 CH_4/kg VS without pretreatment to 0.23–0.34 m^3 CH_4/kg VS with pretreatment. The production of CH_4 increased by 50%. The biogas produced by Teghammar et al. [188] from the organic fraction of municipal solid waste and the residue that had been processed with N-methyl morpholine oxide (NMMO) was assessed economically. Co-digesting prepared forest residue with municipal solid trash produces biogas. Milling forest debris, pretreatment, washing, and filtering were the phases in the process.

The methane-yield values summarized in Table 6 were obtained from independent studies. Several factors explain the variation of CH_4 yeild observed across the three feed sources. First, feedstock biodegradability differs substantially: kitchen waste, being rich in readily degradable carbohydrates and lipids, achieves the highest reported yields (0.68–0.725 m^3 CH_4/kg VS) even without pretreatment [189], whereas forest residue, being lignocellulosic and structurally recalcitrant, achieves the lowest yields (0.10–0.34 m^3 CH_4/kg VS) and requires pretreatment to approach even these levels [187, 190]. Second, municipal solid waste yields (0.20–0.43 m^3 CH_4/kg VS) vary widely depending on the degree of mechanical pre-processing applied before digestion, which affects particle size, contaminant removal, and substrate accessibility to microorganisms [191, 192]. Third, differences in reactor configuration, for example, standard anaerobic digestion versus rotary drum reactors, affect mixing, retention time, and organic loading rate, all of which influence methane output independently of feedstock type.

Table 6: CH_4 yield analysis of three feed sources using different pretreatment methods

Source	Method	Pretreatment	CH_4 yield (m^3/Kg of VS)	References
Municipal Solid Waste	Anaerobic digestion	-	0.36	[133]
		-	0.20	[193]
		-	0.40-0.43	[194]
		Rotary drum reactor	0.28-0.29	[191]
		Shredder + magnet	0.42	[192]
		Screw press	0.40	
		Disc screen	0.37	
Kitchen waste	Anaerobic digestion	-	0.683-0.725	[189]
		Microwave irradiation	0.21-0.34	[195]
		-	0.28	[196]
Forest residue	Anaerobic digestion	Acetic acid, ethanol, and methanol	0.23-0.34	[187]
		N-methyl morpholine oxide (NMMO)	0.1-0.109	[197]

Ultimately, the biogas and co-digestion process were improved and dewatered. Evaporation of the washing water and chemical preparation with NMMO were the expensive steps. Economic evaluations were conducted on various processes, including plant capacity, treatment costs, and the digestion of between 25,000 and 400,000 dried-weight tons of forest residue annually. According to the economic evaluation, plants that can produce 50,000 dried-weight forest waste residues are profitable. It was discovered that co-digestion was more feasible than just digesting the residue from forest trash. Table 6 provides an analysis of the methane yield, pretreatment techniques, processing methods, and all three feed sources.

Table 7: Comparative Overview of Biogas Substrate Pretreatment Methods

Pretreatment technique	Mechanism	Reported effect on CH_4 yield	Principal limitation
Acid pretreatment	Acidification of substrate (e.g., HCl) to break down complex organics before digestion	Improves hydrolysis rate; contributes to the ~50% yield increase reported for chemically pretreated forest-residue substrates [187]	Chemical cost; risk of inhibitory by-product (e.g., furan) formation if not controlled [186]
Thermal / thermo-acid pretreatment	Autoclaving (e.g., 120°C) combined with acidification	Increases substrate solubilisation ahead of anaerobic digestion [173, 174]	Energy input required for heating;limited independent yield data for Pakistan-relevant feedstocks
Freeze–thaw pretreatment	Freezing (e.g., to −80°C) followed by controlled thawing (e.g., 50°C oven, 2 h) [175, 176]	Disrupts cell structure to aid subsequent digestion	High energy demand for freezing step; impractical at field scale in most rural Pakistani settings
Solvent-based pretreatment (methanol, ethanol, acetic acid, NMMO)	Organic solvents used to delignify or solubilise lignocellulosic material	NMMO Pretreatment of forest-residue blends assessed economically [188, 197]	Solvent cost and recovery are the main economic barriers; profitable only above an estimated ~50,000 dried-weight-ton/year plant capacity

Comparing these techniques directly, chemical and solvent-based pretreatments deliver the largest and best-quantified yield improvements for lignocellulosic feedstocks such as forest residue, but carry the highest chemical-cost and recovery burden; thermal and freeze–thaw methods are comparatively easy to implement conceptually but are energy-intensive and, in the case of freeze–thaw, impractical to scale in most rural Pakistani contexts.

5. Biogas Technological Development in Pakistan:

5.1. Biogas Digesters Used in Pakistan:

Affordability, current model performance, climate, and usage are some of the variables that influence the choice of biogas reactors [198]. Low-rate digesters are general designs utilized for the digestion of cow dung in the majority of poor nations. Biogas digesters are often balloon or tube types, floating drums, or fixed domes in developing nations like China and India [199]. It is simple to design and build these permanent home plants. Fixed dome-type biogas digesters, which come in the forms of Chinese fixed dome and Indian Deebandhu, are appropriate for the environmental conditions in Pakistan and India [200].

Bricks are among the materials used in the construction of fixed dome-type methane digesters. Types of floating drums are made of concrete or steel. Biogas digesters of the floating drum type consist of an underground digester and a mobile gas storage or drum. A guiding frame is also used to keep the gas digester from tilting [57, 201, 202]. The inlets and exits of balloon-type biogas digesters are porcelain pipes. They are composed of polyethylene foils that have been folded. These biogas digesters operate on a nearly identical premise. Feedstocks enter each digester through a feeding pipe at the intake, either straight from the source or after being mixed in a pit. The mesophilic (20–40 °C) or thermophilic (over 40 °C) temperature ranges are normally where anaerobic digesters function. The substrate can be retained in mesophilic digesters for 20–100 days [199]. Before exiting through the pipe, biogas is gathered at the outlet pipe above the slurry. Another option for producing biogas is to use a pit in the ground as a biogas reactor. Figure 7 depicts the layout of these biogas digesters.

PCRET has constructed a 5 m^3 biogas anaerobic digester to meet the energy needs of Pakistani single-householders [198]. It's a typical subterranean digester. The primary digester body is 6 by 2 feet. Trash collection takes place close to the 3.5 x 2 ft^2 pond. The pipe feeds the waste into the digester. The gas is collected in a 5.5-foot-diameter iron cylinder. Gas can be used for power generation or cooking after it has been collected. Figure 8 shows the dimensions of this digester.

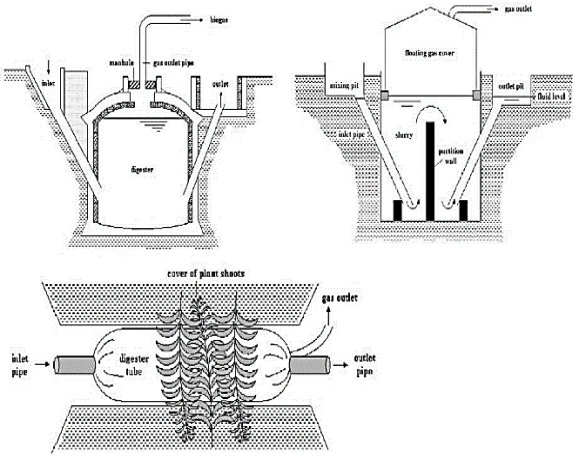


Figure 7. Top left: fixed dome digester (Chinese type). Top right: floating cover digester (Indian type). Below: balloon or tube digester [203] Copyright Elsevier 2021.

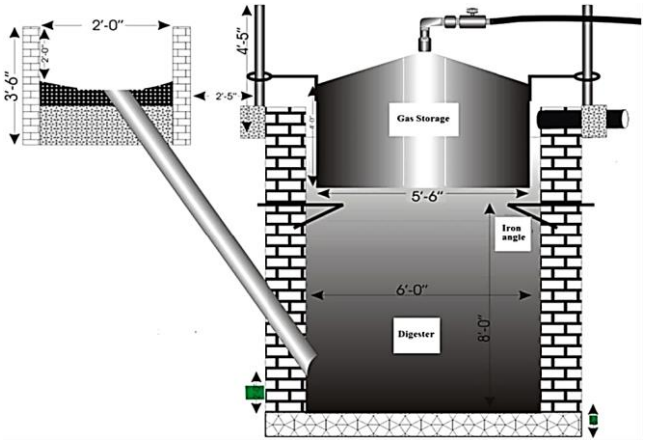


Figure 8. Design of Anaerobic digester for 5m^3 biogas output [204]. Copyright Elsevier 2021.

Table 8: Biogas availability concerning the number of persons and corresponding cattle requirements [11]

Availability of gas for several persons	Dung required (Kg/day)	No. of cattle required	Gas capacity (m^3)
4-5	50	3-4	2
6-7	75	4-5	3
9-10	100	6-7	4
11-12	125	8-9	5

The accessibility of the dung and the number of people to be served determine the size and capacity of the biogas plant that will be erected. One kilogram of dung is thought to produce 0.04 m^3 of biogas. A single person's cooking needs require 0.425 m^3 of biogas, while a single cattle typically generates 15-20 kg of dung each day; 25 kg of dung is needed to produce 1 m^3 of biogas. Table 8 displays the biogas's availability in relation to the number of people to be fed and the livestock's needs.

Table 9: Overview of Conventional and Advanced Digester Technologies for Biogas Production

Digester type	Typical HRT / temperature regime	Reported performance	Advantages	Limitations
Fixed-dome (Chinese / Deenbandhu)	Mesophilic, 20–100 days [199]	Most widely deployed household design in Pakistan; simple brick-and-mortar construction	Low capital cost; durable; low maintenance [200]	Fixed gas-storage volume; gas pressure fluctuates with slurry level [199, 200]
Floating-drum	Mesophilic, 20–100 days [199]	Moving steel or concrete drum provides visual, near-constant-pressure gas storage	Constant gas pressure; stored gas volume easy to gauge [57, 201, 202]	Higher capital and maintenance cost than fixed-dome; steel drums corrode over time [57, 201, 202]
Balloon / tubular	Mesophilic, 20–100 days [199]	Polyethylene-foil balloon or tube digester; lowest-cost of the three traditional designs	Cheapest to install; portable; simple installation	Shortest material lifespan; vulnerable to puncture and UV degradation
Plug-flow	Mesophilic or thermophilic; HRT 15–20 days; loaded at 11–14% total solids [205]	Long, narrow (~5:1 length:width) tank with no internal agitation	Handles thick, fibrous, high-solids manure (e.g., dairy) without agitation energy input; suited to scrape-manure systems with little bedding [205]	Not suited to dilute or sandy manure; no deployment yet reported in the Pakistan-specific literature
Continuous stirred-tank reactor (CSTR)	Mesophilic 30–35°C (HRT 15–30 days) or thermophilic 55°C (HRT 12–14 days); mechanically, pump-, or biogas-mixed [205]	A single thermophilic CSTR digesting cattle manure for 15 days achieved lower yield [206]. A two-stage thermophilic CSTR digesting cattle manure for 15 days achieved higher yield [206].	Continuous, controllable process; the serial configuration is a low-cost retrofit that recovers otherwise-lost methane potential without phase separation [206]	Requires continuous power for mixing and heating; a single-stage CSTR alone under-uses the feedstock's methane potential unless modified [206]
Advanced high-rate digesters (e.g., anaerobic packed-bed (APBR) / Up flow Anaerobic Sludge Blanket (UASB)	HRT reduced from 30–40 days to a few hours days by retaining biomass as a fixed biofilm on an inert packing medium [205]	In a controlled comparison treating potato-waste. UASB gave a higher methane yield than APBR [205]	Tolerates high organic loading rates; better resistance to, and recovery from, shock and toxic loading than conventional digesters [205]	Requires specialized packing/support media and more complex construction; not yet piloted for Pakistan's own feedstocks (poultry waste, MSW, forest residue)

This comparison supports the manuscript's existing conclusion, discussed later in the barriers section, that fixed-dome digesters are more cost-effective and durable than floating-drum types and are consequently the most appropriate choice for widespread household-scale deployment in Pakistan, while CSTR and advanced high-rate systems, though offering higher throughput, are better suited to institutional or industrial applications where capital cost is less constraining.

6. Economic Impact of Biogas Plants in Pakistan:

Numerous electricity-generating plants have been set up in Pakistani cities. Capacity exceeds 5 m^3, typically falling between 10 m^3, 15 m^3, and 20 m^3. They are situated in Punjab province's cities of Narowal, Sialkot, Jhang, and others. 92 plants with 5 KW to 100 KW of electricity-generating capacity have been installed by PCERT. According to PCRET research, 5 m^3 of biogas can save around 800 kg of wood, 64 kg of liquefied petroleum gas, and 93 liters of kerosene oil. Between 2002 and 2007, 1596 biogas plants were installed, while between 2007 and 2012, 2513 units were installed. Figure 9 (a-b) show the distribution of area-wise plants. Table 10 lists the generation and savings of electricity by various technologies. According to this, PCRET erected 5000 biogas plants with a 5 m^3 plant capacity up till 2015. These plants generated 43.8 MWh of energy, and the amount of biogas produced was 9.125 million m^3 [207]. PCRET added 4,016 additional biogas plants between 2015 and 2019 [208]. 14395 m^3 of gas, or 8924.9 liters of kerosene oil, are produced daily on average by 3500 biogas plants with a 5 m_3 capacity. An estimated USD 1.51 million is saved annually in oil imports as a result of this gas generation. Utilizing a 10 m^3 biogas plant to purchase other fuels results in a yearly savings of USD 569 [10].

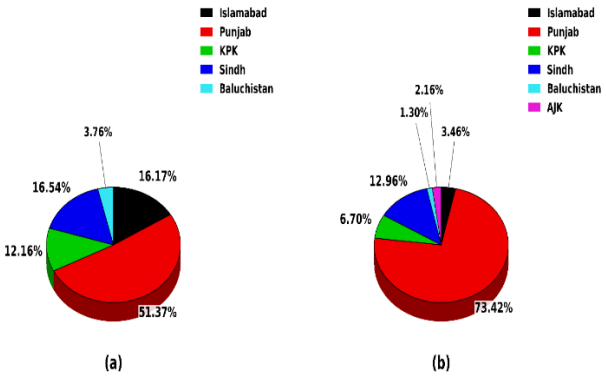


Figure 9. (a) Shows plants installed in Pakistan during 2002-07 (b) Shows plants installed during 2007-12.

Table 10: Power generation and savings by PCRET 2014-15 [207, 209]

Technology	No. of Plants	Capacity	Generation	Savings (USD)
Micro Hydel	562	9 MW	52560MWh	-
Biomass	5000	$5m^3$	43.8MWh	-
Solar Energy	-	200KW	438 MWh	-
Kerosene	-	-	-	270000
Wood	-	-	-	360000
LPG	-	-	-	260000

Table 11 presents a cost-saving analysis of the generation of biogas, wood equivalent, kerosene oil equivalent, and biofertilizer. Therefore, these 3500 biogas plants saved a total of USD 1.75 million each month in terms of fertilizer and kerosene oil imports alone. Diesel tube wells have an operational cost of approximately USD 1731 million. Switching to biogas from diesel tube wells might save an estimated USD 1236 million.

Table 11: Financial impact on the economy [210]

No. of Biogas plants	Energy Equivalent Production	Savings per year ($\times 10^6$) USD /Month
3500	33.50million kg/year (wood equivalent)	-
	3.75 million liters/year (kerosene oil equivalent)	1.48
	Biofertilizer	0.27
		Total= 1.75

7. Latest Developments in Pakistan's Biogas Industry:

The debut of one of Pakistan's biggest biogas facilities in Lahore marked a significant turning point in the country's biogas landscape. The government of Pakistan launched the development of this 6,000 cubic meter facility, which cost Rs350 million (€1.2 million) to build. An estimated Rs. 80 million (€273,000) in revenue is anticipated from the plant each year, guaranteeing a prompt return on investment and allocating earnings to regional development initiatives. The Gujjarpura Biogas Plant, another important project, can process 1,600 kg of dung every day, generating 16,000 kg of organic fertilizer and 600 cubic meters of gas. By producing organic fertilizer, this project helps the Parks and Horticulture Authority (PHA) and nearby farmers in addition to offering a sustainable energy alternative [211]. Commercial-scale biogas facilities have also been erected by some sizable dairy farms. The sustainability of biogas as a renewable energy source in the agricultural sector is demonstrated by the 4.97 GWh of electricity that these facilities together export to the national grid annually [212]

The development of Pakistan's biogas industry has been greatly aided by private sector involvement. Nestlé's biogas initiative, which turns cow waste into on-farm electricity, is a noteworthy example. By installing five biogas plants, the project seeks to cut fuel usage by 25–35%, promoting sustainability and cost-effectiveness [212]. Alongside business endeavors, cooperative research projects have also become more popular. Biogas technology research is being carried out by Pak Suzuki Motor Company and the University of Agriculture, Faisalabad (UAF). Greener fuel technology may result from this partnership's exploration of alternative energy sources in the automotive industry [213]. Recently, there have been a few large-scale biogas projects in recent years, mostly due to research collaborations, industrial uses, and private sector activities. For example, Nestlé Pakistan's dairy processing plant in Sheikhupura now incorporates a biogas plant based on anaerobic digestion. The plant greatly lessens its need for fossil fuels by producing sustainable energy from organic residue and effluent from milk processing. This program supports Nestlé's worldwide goal of having zero net carbon emissions by 2050 [214]. Likewise, a biogas feasibility study has been started by the Lahore Waste Management Company (LWMC) in order to turn municipal solid waste into compressed natural gas (CNG) and biogas. In order to produce biogas for generating power and transportation fuel, the project intends to process 500–1,000 tons of organic waste every day. This initiative is being supported by the Punjab Energy Department, which aims to include biogas in Lahore's urban energy supply [215].

Moreover, bagasse and molasses have been used by Pakistan's sugar industry to produce biogas. Businesses such as JDW Sugar Mills and Almoiz Industries have reduced their reliance on fossil fuels by implementing biogas-to-electricity systems that turn by-products of sugar processing into bioenergy. Up to 5 MW of electricity is produced by some of these plants; the excess power is fed into the national grid and utilized for internal purposes [216]. Pilot-scale biogas facilities have been started by a number of academic institutions and research centers, including UET Lahore (University of Engineering and Technology Lahore) and NUST (National University of Sciences and Technology). The goals of these initiatives are to increase the efficiency of anaerobic digestion, co-digest various feedstocks, and convert biogas into biomethane for grid injection [7].

8. Bottlenecks/Reasons for Failure Biogas Implementation in Pakistan:

8.1. Institutional and Policy Implementation Challenges:

The difficulties and prospects for the use of biogas are summed up in Figures 10(a) and (b). The government lacks all-encompassing plans for deploying biogas plants and other renewable energy sources. Several government agencies and other recipients do not adequately coordinate their efforts in accordance with technical, financial, informational, and physical cooperation. The primary causes of installed biogas plants' lack of societal acceptance thus far are their low efficiency, high capital costs, and small capacity [138].

8.2. Social & Cultural Challenges:

The lack of developing capacity for biogas operators and installers via suitable training and workshops to improve their technical understanding regarding biogas plant maintenance and operation services is the primary obstacle to biogas implementations. One major obstacle is the low level of public and buyer involvement, as well

as unfamiliarity (since there aren't many Biogas demonstration units nationwide) [217].

8.3. Environmental Challenges:

Given the current circumstances, biogas appears to be the most viable alternative to offset the depletion of traditional fossil fuels. Additionally, the use of wood as fuel will decline. The ability to recycle manure and other agro-industrial waste into bio-fertilizers is an extra benefit. Biogas has the potential to support biodiversity conservation, a sustainable ecosystem, and a pleasant environment. Despite these advantages, there is a chance that it will cause odors and noise pollution. During the dry season, producing biogas can be difficult, especially in remote water supply locations [218]. A large quantity of water is required for the bio-digestion process.

8.4. Financial Challenges:

The use of biogas in Pakistan is hampered by financial issues. The primary factors influencing customer decisions for the installation of biogas plants are high capital investment, technology introduction, management, and maintenance costs [219]. The bulk of people live in poverty in rural areas, and the nation's pervasive poverty has left little money for plant growth. In contrast to large capital expenditures, a biogas plant does not generate cash [216]. Selections on the setting up of biogas plants and consumers are significantly influenced by the high capital cost [220].

8.5. Technical Challenges:

One of the biggest obstacles still facing Pakistan is the advancement and application of biogas technology. Pakistan has abundant resources for biomass, but because of a lack of adequate technical infrastructure, these resources have not been fully utilized. Because biogas technology operators were not sufficiently trained by institutions, biogas production was low and less profitable than traditional energy sources. Additionally, the plant owners do not adhere to the suggested ratio of water to feed. As a result, the technical design processes were not practical. There isn't a technical institution that can deal with technical issues, their fixes, or the appropriate training of plant employees [221].

8.6. Related Challenges:

The primary commercial obstacle to the widespread use of biogas is its higher cost compared to traditional fossil fuels. To make biogas a contender in the market, subsidies for the installation of biogas plants must be eliminated, while subsidies for traditional fossil fuels must be eliminated [218]. The absence of research and development efforts led to a misalignment.

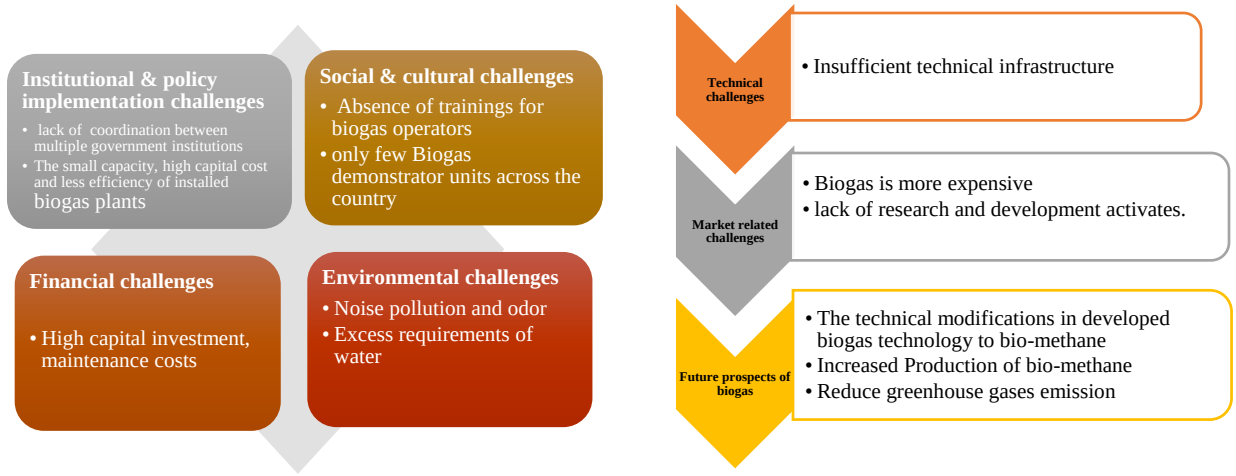


Figure 10. (a) Challenges for the biogas implementations (b) stakeholder and future perspectives with market demands [1]for biogas in Pakistan.

9. Policy Framework, Regulatory Challenges, and Government Initiatives for the Biogas Industry in Pakistan:

Pakistan's legislative structure and regulatory environment have a big impact on how the biogas sector develops there. Commercialization and large-scale investments have been restricted by the absence of a specific biogas policy in the nation. Aiming for 30% renewable energy by 2030, the Alternative and Renewable Energy Policy 2019 (ARE-2019) primarily prioritizes solar and wind energy, with minimal consideration paid to biogas [222]. Similarly, the National Climate Change Policy 2021 recognizes biogas as a viable solution for lowering greenhouse gas

emissions but does not offer a specific implementation strategy [223]. The Pakistan Energy Security Plan 2022 emphasizes the importance of indigenous energy resources, including biogas, but does not include specific investment methods or policy incentives [224]

The absence of clarified feed-in tariffs (FiTs) for electricity produced by biogas is a significant regulatory obstacle in the biogas industry. Since biogas electricity lacks a defined pricing system, private investors find it challenging to project possible profits, in contrast to solar and wind power, which experience set tariff rates. Several organizations, including the Pakistan Environmental Protection Agency (Pak-EPA), provincial energy departments, NEPRA (for grid integration), and OGRA (for Bio-CNG production and distribution), are involved in the extensive regulatory approval process for biogas projects. Long project approval periods, typically 12 to 18 months, caused by these administrative roadblocks, deter both domestic and foreign investment. Additionally, import taxes on biogas-related equipment, which vary from 10% to 20%, raise capital expenses even more and render biogas projects unprofitable. Pakistan lacks a specialized regulatory authority for biogas, which results in dispersed efforts and an unsteady pace of development in contrast to solar and wind energy, which have specialized government agencies like the Alternative Energy Development Board (AEDB) [225]

The government has launched many initiatives to support biogas despite these legislative obstacles, although they haven't been very successful. Launched in partnership with SNV Netherlands Development Organization, the Pakistan Domestic Biogas Program (PDBP) (2009–2018) sought to install 10,000 household biogas plants; however, due to financial limitations, only 7,500 plants were successfully installed before the program was terminated [226]. More recently, PKR 2 billion ($7 million) was set aside for renewable energy projects, like as biogas, under the Punjab Green Development Program [227]. Although bio-CNG production pilot projects have been started in dairy farms, widespread adoption is still scarce.

The Small and Medium Enterprises Development Authority (SMEDA) also provides technical help and commercial financing of up to PKR 10 million to biogas entrepreneurs [228]. However, high interest rates (12-14%) and complicated loan approval processes continue to discourage small-scale enterprises from entering the biogas sector.

To address these policy and regulatory problems, many actions must be implemented. First, Pakistan should set up a National Biogas Development Authority (NBDA) to monitor policy execution, investment facilitation, and subsidy allocation. Second, in order to guarantee returns for investors and encourage grid integration, NEPRA ought to implement feed-in tariffs for biogas electricity. Third, in order to attract investment, the government ought to lower import taxes on biogas equipment from 20% to at least 5% and provide tax breaks (for a period of 5 to 10 years) on biogas projects. Large-scale biogas facilities should also be financed through public-private partnerships (PPPs), especially in industrial and agricultural areas [229]. Furthermore, ARE-2019 ought to be updated to incorporate particular biogas goals, including reaching a minimum of 5% of Pakistan's energy mix from biogas by 2030 [222]. By providing incentives, including duty-free imports of biogas technology and discounted loans for large-scale projects, the government could also encourage foreign direct investment (FDI) in biogas infrastructure [230]

Pakistan's biogas industry has the potential to make a substantial contribution to the nation's energy security if these legislative changes are effectively implemented. By 2035, biogas is predicted to replace 10–15% of the demand for natural gas, lowering reliance on imported LNG and potentially saving up to $500 million yearly [230]. Furthermore, by reducing CO_2 emissions, the sector might help Pakistan meet its COP28 climate obligations [231] [229]. However, the biogas industry will continue to be underdeveloped in the absence of significant regulatory changes, losing a significant chance to improve environmental sustainability and energy diversification. To draw in investment and increase output, Pakistan must incorporate biogas into its national energy policy and offer a clear regulatory framework.

Table 12: Relative significance of biogas implementation barriers in Pakistan and mitigation strategies supported by recent literature and case studies

Barrier category	Relative significance	Practical mitigation strategy	Supporting case study / evidence
Financial (high upfront capital cost relative to household income)	Ranked the most consistently reported constraint at the household adoption scale, ahead of technical and environmental barriers [232-234]	Microfinance and targeted capital subsidy schemes that reduce upfront household cost [232-234]	Germany's biogas subsidy framework made household- and farm-scale biogas a profitable business and is credited with driving the country to 28.1% of world installed biogas capacity and over 9,000 operating plants [235]
Institutional and policy (absence of feed-in tariffs, fragmented regulatory authority, weak central–local coordination)	Ranked more significant than financial cost alone at the utility and industrial scale ; “lack of coordination across central and local governments” is independently identified as a leading global barrier [232-234]	A single coordinating regulatory authority (e.g., the National Biogas Development Authority proposed above), feed-in tariffs, and joint central–local–international planning [232-235]	China's Sino-German Resource Recovery of Bio-organic Municipal Waste platform coordinated central government, municipal authorities, and an international partner to forecast and scale municipal-waste-to-biogas capacity to an estimated 25 GW by 2050 [235]
Technical skills and public awareness (untrained operators, low community familiarity with biogas)	Consistently identified but ranks below financial and institutional barriers in AHP and G-TOPSIS prioritization studies [234]; described as the leading barrier in global assessments (“lack of consciousness of biogas benefits”) [235]	Extension and hands-on training programs delivered through farmer networks, NGOs, and universities [235]	NGOs and universities in Latin America have played a “fundamental role” in sustaining biogas uptake; Bolivia's Andean region alone has more than 700 fully functioning household digesters maintained through this community-support model [236]
Environmental and social (competing manure uses, water requirement, odor/social acceptance)	Consistently identified but generally ranks lowest among the four categories in Pakistan-specific prioritization studies [234]	Extension messaging that frames digestate as a co-product (biofertilizer) rather than a trade-off against direct manure use, offsetting the perceived opportunity cost [235]	Targeted program incentives (rather than blanket subsidies) have driven more than 60,000 biodigesters into operation across Africa despite comparable resource constraints to Pakistan [236]
Market immaturity for non-energy by-products (undeveloped domestic market for biogas	Identified in the global literature as a distinct barrier separate from financial and institutional constraints, since it limits revenue diversification	Deliberate development of a domestic biofertilizer market alongside the energy market, and monitoring/data	A documented benefit–cost analysis of a comparable developing-country biogas project reported annual benefits of USD 65,232 against USD 26,460 in annual operating cost on a USD 120,000 investment, illustrating

digestate/biofertilizer)	even where a digester is successfully installed [235]	collection on digestate sales to demonstrate a second revenue stream to investors [235]	how quantified, multi-revenue-stream project economics can be used to support financing decisions [235]

Two conclusions follow from this comparison. First, financial and institutional barriers consistently outrank technical, environmental, and social barriers in the Pakistan, which indicates that policy instruments such as feed-in tariffs and coordinated subsidy design should be prioritized over awareness campaigns alone if the goal is to accelerate near-term adoption. Second, successful international cases show that mitigation strategies are most effective when matched to the specific barrier they target rather than applied uniformly. A market-immaturity barrier for biogas by-products, not previously discussed in this manuscript, is also surfaced by this comparison and is addressed above.

10. The prospect of biogas in Pakistan:

Recent Pakistan-specific assessments reinforce this potential: national biomass-waste resources have been estimated to support around 226.8 million m^3 of biogas production per day, corresponding to an electricity-generation potential equivalent to roughly half of the country's total power output [24], while a separate assessment estimates a biogas potential of 12,615 million m3 per year from Pakistan's biomass resource base [187] .

An essential component of Pakistan's agriculture-based economy is the cattle industry [237]. In Pakistan, animals create almost 652 million kg of manure each day. Pakistan may generate 1900 MW of power by using animal dung and crop leftovers. However, because biogas has not yet reached its full potential, Pakistan is currently experiencing a serious energy crisis. For cooking and heating purposes, the vast majority of Pakistanis rely on firewood and animal manure [238]. Pakistan is lacking in the use of waste materials for the manufacture of biogas.

Both Karachi and Lahore generate large amounts of municipal garbage (6510 and 9440 tons, respectively) that can be turned into biogas.

Pakistan must concentrate on using the right technologies to produce energy from biogas. Economics plays a key role in the development of technology connected to biogas. Due to its status as a developing nation, public-private collaborations are necessary to develop and make biogas technologies available to the impoverished in rural areas. Private companies should be encouraged to expand biogas technologies nationwide by offering tax-free business opportunities. By purchasing electricity from biogas plants, the government must show its support for the biogas industry. Pakistani researchers ought to be supported in their efforts to create locally produced, reasonably priced technology. Research and development is required to model and construct sustainable, affordable, and efficient plants. To improve the technical understanding of biogas plant operations and maintenance services in Pakistan, suitable training and workshops are needed. The UN and other international environmental organizations must also play a part in helping poor nations like Pakistan by giving them the money and appropriate technologies they need to fully utilize biogas [222, 227]. Nonetheless, there are some issues the industry is facing, such as competition from conventional energy sources. Because of Pakistan's well-established fossil fuel infrastructure and government subsidies for petroleum and natural gas, renewable energy sources find it challenging to compete. Long-term investment planning is hampered by political and economic unpredictability, endangering investor confidence and policy continuity.

The economic viability of biogas plants depends on factors like initial investment, operational costs, and potential savings. Fixed dome digesters are more cost-effective and durable than floating drum types, making them suitable for Pakistan. Installation costs range from $300–$500 in Asian countries. Biogas can replace LPG, offering significant savings, enhancing energy security, and reducing reliance on imported fuels [239]. It also produces a nutrient-rich slurry usable as organic fertilizer, benefiting agriculture and providing extra income. However, challenges such as a lack of awareness, technical skills, and limited financial support hinder adoption. Collaborative efforts from government,

NGOs, and the private sector are needed to promote biogas use [240].

11. Research Needs and Future Directions:

Despite its promising potential, widespread adoption of biogas in Pakistan faces several challenges. Key issues include the lack of comprehensive resource assessments, limited understanding of seasonal feedstock variations, and the need to optimize anaerobic digestion for local climatic conditions. Most existing estimations of biogas potential are theoretical and do not account for geographic factors such as feedstock availability, livestock density, and energy demand proximity. Moreover, low methane yields from common feedstocks like livestock manure and municipal solid waste highlight the need for advanced co-digestion techniques and pretreatment methods, such as thermochemical and enzymatic processes. These could significantly improve gas output but remain under-researched. Additionally, the absence of regulatory support, such as feed-in tariffs and mandatory waste segregation laws, discourages private investment and limits the quality of biogas production [10].

To bridge these gaps, future research should focus on microbial consortia, development of high-solids anaerobic digestion, advanced biogas upgrading technologies suited for Pakistan's temperature fluctuations, the development of self-heating and hybrid anaerobic digesters, and advanced upgrading methods to enhance biogas quality. Investigating biogas-to-hydrogen conversion and integration with other waste-to-energy systems can further strengthen its role in Pakistan's energy mix. Life-cycle assessments comparing biogas with other fuels and exploring its role in carbon credit markets could also boost investor confidence. Policymakers should consider implementing feed-in tariffs, promoting public-private partnerships, and establishing a clear regulatory framework to support the biogas sector’s expansion. A multidisciplinary approach involving engineers, economists, and environmental scientists is essential to unlock the full potential of biogas as a sustainable energy source [241].

12. Conclusion:

Pakistan's economic growth is affected badly due to the challenges of the energy crisis. Pakistan spends approximately 14-15 billion US dollars on crude oil imports to meet the energy demand. Pakistan should rely on renewable energy sources to meet its energy needs. Biogas is a significant renewable energy source in many countries of the World. Pakistan has the potential to exploit biogas energy to overcome its energy demand and adverse effects on the economy. Pakistan has a significant share of biomass (forest residue), municipal waste, animal manure, and waste generated from the kitchen, which can be used as raw materials for biogas production. In comparison with imported crude oil, biogas installation requires less investment and produces energy at a low cost. Pakistan is not utilizing biogas sources efficiently. Lack of awareness, low investment by the government, improper planning, and technological barriers are the main hurdles behind the low utilization of biogas in Pakistan. The government should focus on the technological development and commercialization of the biogas plants in Pakistan. It is necessary to be aware of the business communities and the people to invest in biogas resources.

Authors Contribution

Ali Ahmad: Conceptualization, Data Curation, Writing-Original Draft. Naeem Akram: Conceptualization, Supervision, Writing-Review and Editing. Muhammad Ammar Nadeem: Visualization, Data Curation, Writing-Review and Editing.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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