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Current prospects and challenges for biomass energy conversion in Bangladesh: Attaining sustainable development goals

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ABSTRACT

Bangladesh has encountered several challenges, including issues like overpopulation, energy shortage, and global warming for the last few decades. Addressing the increasing energy demand has become a crucial concern because of rapid increase in population and lack of growth in the economic. The electricity production of a country heavily relies on fossil fuels, particularly natural gas, which makes up approximately 54% of the current installed capacity. Bangladesh is an agrarian nation and biomass stands out as a source of renewable energy having significant potential to mitigate the demand for heat and electricity. Biomass resources in the country mainly comprise animal dung, agricultural crop residuals, solid waste from municipalities and forest residues. The existing biomass resources contribute to producing a high amount of energy and content of around 1574.16 PJ of energy equivalent to 437.28 TWh of electricity in which agricultural residues, animal manure, municipal solid waste, and forest residues impart around 852.32 PJ, 399.04 PJ, 112.16 PJ, and 210.64 PJ of energy respectively. This paper explores the extent, possibilities, and technologies associated with biomass energy conversion. Additionally, the study delves into the several biomass projects that the government, as well as non-governmental groups, are working on for environmental sustainability along with plans, challenges, and methods that are being utilized to encourage biomass technologies across Bangladesh.

1. Introduction

Energy is turning into ever more essential because of population expansion, economic development, and technological innovation [1]. The need for energy and associated services is increasing to meet societal and economic development objectives, simultaneously enhancing human well-being and health. Meeting fundamental human needs and facilitating productive processes necessitate energy services for all societies. The worldwide reliance on fossil fuels such as coal, oil, and gas has surged, leading to a significant rise in carbon dioxide (CO_2) emissions. Emissions of Greenhouse Gases (GHG) from delivering energy services have played a substantial role in the historical upsurge in atmospheric GHG concentrations [2]. Biomass, which is comprised of animal waste, agricultural waste, and forest residue, can be used to cover a variety of energy requirements, including generating electricity, fueling automobiles, and supplying process heat for industrial facilities [3]. Biomass possesses a benefit over other forms of renewable energy due to its capacity for storage and easy year-round accessibility from diverse sources [4]. Among renewable energy sources, biomass has the important characteristics of being almost carbon neutral and abundantly available from a range of sources [5]. Fig. 1 shows the available biomass sources in Bangladesh.

Approximately 9.6% of global population lacks the availability of electricity today [6]. The fourth most prominent energy contributor globally, biomass meets the basic needs of rural households in developing nations for heating and cooking. Biomass includes all forms of organic material, including marine plants and fuel wood. By lowering the emission of common greenhouse gases, energy production utilizing biomass is a fantastic solution to environmental issues [7]. Various technologies are available for converting biomass into biogas, encompassing methods that generate both heat and electricity. Biogas, derived from animal dung, bird droppings, and other biomass wastes, constitutes a blend of greenhouse gases, primarily CH_4 (40–70%), CO_2 (30–60%), and other gases (1–5%). This combustible biogas serves as a valuable resource for power generation. It can be efficiently utilized for both cooking and electricity production [8,9]. Additionally, as a response to climate change, The United Nations has set forth the Sustainable

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Nomenclature

PJ	Petajoule
GHG	Greenhouse Gas
NGO	Non-governmental organization
Mt	Million ton
MSW	Municipal solid waste
BBS	Bangladesh Bureau of Statistics
FY	Fiscal Year
LPG	Liquefied Petroleum Gas
AD	Anaerobic Digestion
VFA	Volatility Fatty Acid
MJ	Megajoule
ICS	Improved Cook Stoves
BRAC	Bangladesh Rural Advancement Committee
NPV	Net Present Value
BRRI	Bangladesh Rice Research Institute
VAT	Value Added Tax
PSMP	Power System Master Plan
GDP	Gross Domestic Product
RE	Renewable Energy
GWh	Gigawatt hour
MW	Megawatt
M. ton	Metric ton
LCV	Lower Calorific Value
GP	Green Productivity
RET	Renewable Energy Technology
LHV	Lower Heating Value
COD	Chemical Oxygen Demand
IFRD	Institute of Fuel Research and Development
RSF	Rural Service Foundation
LGED	Local Government Engineering Department
NDBMP	National Domestic Biogas and Manure Program
GOB	Government of Bangladesh

Development Goals (SDGs) for 2030, emphasizing the critical imperative for accessible and clean energy, comprehensive and sustainable economic advancement, and technological innovation (SDGs 7, 8, 9, and 13).

Bangladesh is an agricultural nation with the ability to use biomass sources to produce electricity. For the production of biomass energy, Bangladesh has access to materials including rice husks, cattle manure, agricultural waste, chicken droppings, and water hyacinth. Rice husk, crop residue, wood, jute sticks, animal manure, municipal garbage, sugarcane biogases, and other materials are examples of common biomass resources. Currently, there are 65317 biogas plants operating nationwide, and more than 0.20 million improvement ovens have been erected to conserve biomass fuel [10]. Moreover, around 1000 briquetting machines have been in use on a commercial basis [11]. A rough estimate of the energy content of rice chaff is 16 MJ/kg 13648 btu/kWh is the heat rate of the biomass facility [12]. The emergence of new and renewable energy sources has become a focal point in the drive for industrial promotion and development. Globally, countries are actively seeking sustainable and clean alternatives to traditional fossil fuels. Biomass energy, a renewable resource, has garnered significant attention as it can be transformed into three distinct forms of fuel: gas, liquid, and solid [13,18–20]. Biomass stands out as a renewable energy source with widespread popularity and significant growth potential. Its appeal is attributed, in part, to its availability as a byproduct from various industrial and agricultural processes, making it globally accessible. The versatility of biomass is evident in its capacity to be directly burned in boilers for heat generation on both industrial and household scales. Additionally, it serves as a valuable resource in waste conversion plants where it can be utilized to generate electricity [14,15]. Various methods, such as direct combustion, pyrolysis, gasification, hydro gasification,

Fig. 1. Available biomass sources in Bangladesh (study area).

liquefaction, anaerobic digestion, alcoholic fermentation, and *trans*--esterification, are employed to derive energy from biomass. Each method comes with specific advantages, and the choice depends on factors like the biomass source and the desired type of energy [16,17].

The ongoing research investigates the viability of harnessing the complete biomass potential in Bangladesh, encompassing agricultural residue, forest residue, animal manure, and municipal solid waste. It also outlines the potential and feasible conversion technologies for electricity generation using recoverable biomass. However, not all recoverable biomass in Bangladesh is applicable for electricity generation, mainly due to its traditional usage in household activities across the nation. The document provides insights into the energy landscape of Bangladesh, the geographical support for biomass production, specifics of the available biomass resources, and evaluates the energy potential derived from biomass. Furthermore, it delves into various technologies for biomass-to-energy conversion and associated technologies present in Bangladesh, covering economic aspects and challenges encountered in the process of converting biomass into energy. The authors organize the works into various segments: **section 2** highlights the current energy scenario in Bangladesh. **Section 3** and **4** expatiate the biomass potentiality in developed countries and Bangladesh. **Section 5** discusses the energy potentiality from biogas in Bangladesh. The availability of conversion technology from biomass to energy is explained in **section 6**. **Section 7** discusses about the improved cooking stove. The factors affecting in the conversion processes are highlighted in **section 8** and the steps undertaken from the Bangladesh government and NGOs to encourage the utilization of biomass for the energy conversion are elucidated in **section 9**. **Sections 10** and **11** focus on the economical aspect, challenges, and benefits for the utilization of biomass in energy sector. Finally, **section 12** draws a conclusion.

2. Current renewable energy scenario of Bangladesh

2.1. Economic growth and energy consumption in Bangladesh

Bangladesh's economy is experiencing remarkable growth, ranking as the second-fastest in South Asia and the fifth-fastest globally. From 1972 to 2020, the country's Gross Domestic Product (GDP) surged nearly tenfold, soaring from 27 billion USD to 271 billion USD [21–23]. A crucial concern is whether Bangladesh's accelerating economic advancement aligns with the imperative of long-term environmental sustainability, particularly in terms of emission reduction and power generation. Now in Bangladesh the consumption of natural gas is reported at 3.012 ft^3/day bn [24]. Approximately 27% of the country's total energy consumption is derived from commercial energy sources, predominantly utilized in industrial and urban contexts.

2.2. Demand and scenario of energy

The total amount of available electrical power, which can be generated from several sources such as fossil fuels, renewable wind, biogas produced from organic waste, biomass produced from organic matter, radiant solar energy, and water-driven hydro sources, is referred to as energy. This applies to both the electricity produced for general use and the electricity produced for a single, specific use. The Power System Master Plan (PSMP) −2010 projected electricity demand depends on a 7% GDP growth rate. The rapid development of the electricity sector is crucial to expanding electricity access and fostering economic growth, targeting an annual economic growth rate of around 7%.

According to the findings which are presented in Fig. 2, the maximum requirement is estimated to reach approximately 10283 MW during the fiscal year of 2015, followed by 17304 MW in the fiscal year of 2020, further rising to 25199 MW by the year 2025 and predicted 33708 MW by the year of 2030.

During the fiscal year of 2010–11, the highest power production recorded was 4890 MW, which saw a significant surge to 15604 MW in the fiscal year of 2022–23. The installed capacity and maximum generation since FY 2010-23 are presented in Fig. 3.

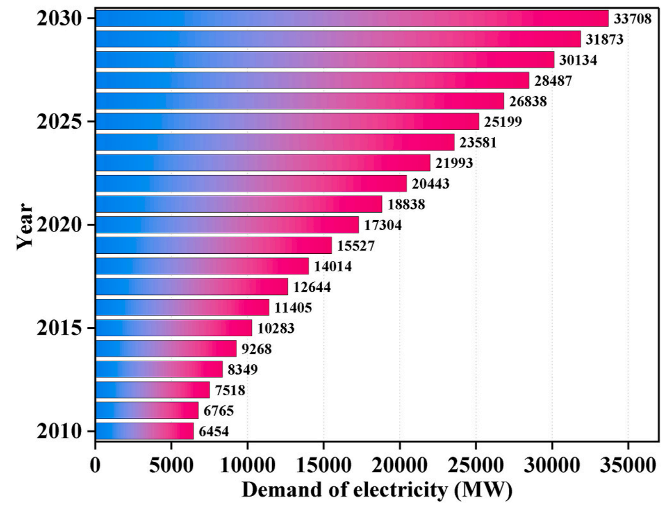

Fig. 2. Year-wise peak demand forecast [25].

Approximately 44.50% of the generated power is sourced from natural gas, with the remaining portion derived from liquid fuel, coal, and hydropower. The current contribution of renewable energy stands at an only 3.75%. The sources which are contributing to generate electricity in Bangladesh is illustrated in Fig. 4. The main source of power sector depends on fossil fuel which comes to end near future. Traditional power generation systems dependent on fossil fuels are anticipated to decline in the coming years due to the depletion of these resources. With the global population on the rise, the demand for energy is surging, prompting scientists, engineers, and communities to pivot toward renewable energy sources. The preparatory groundwork for the 2000 MW Rooppur Nuclear Power Plant (RNPP) project is set to commence in September this year [25].

The majority of power stations in the public sector are operating with outdated machinery that has been downgraded. Consequently, they are unable to function at their intended capacity, resulting in inadequate electricity production nationwide. The shortage of natural gas supply, which is the primary fuel source for these power stations, further exacerbates the issue, hampering power generation capacity. Apart from natural gas-powered plants, there are alternative power plants like the Kaptai Hydro Electric Plant, the Barapukuria coal-based plant, and various diesel and furnace oil-based plants throughout the country.

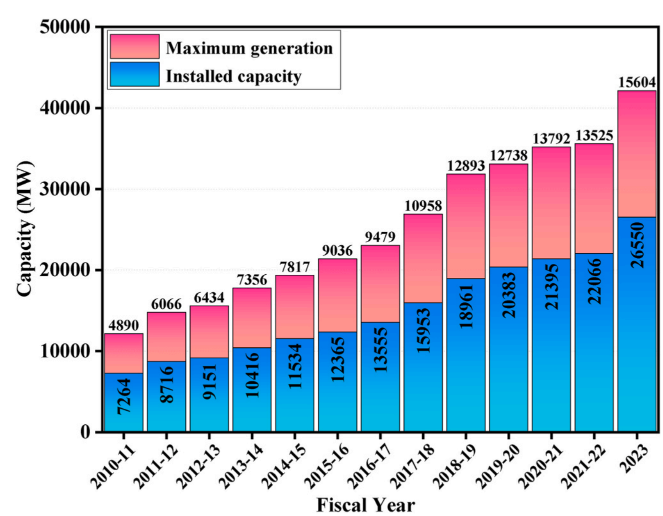

Fig. 3. Installed Capacity and Maximum Generation variation [26].

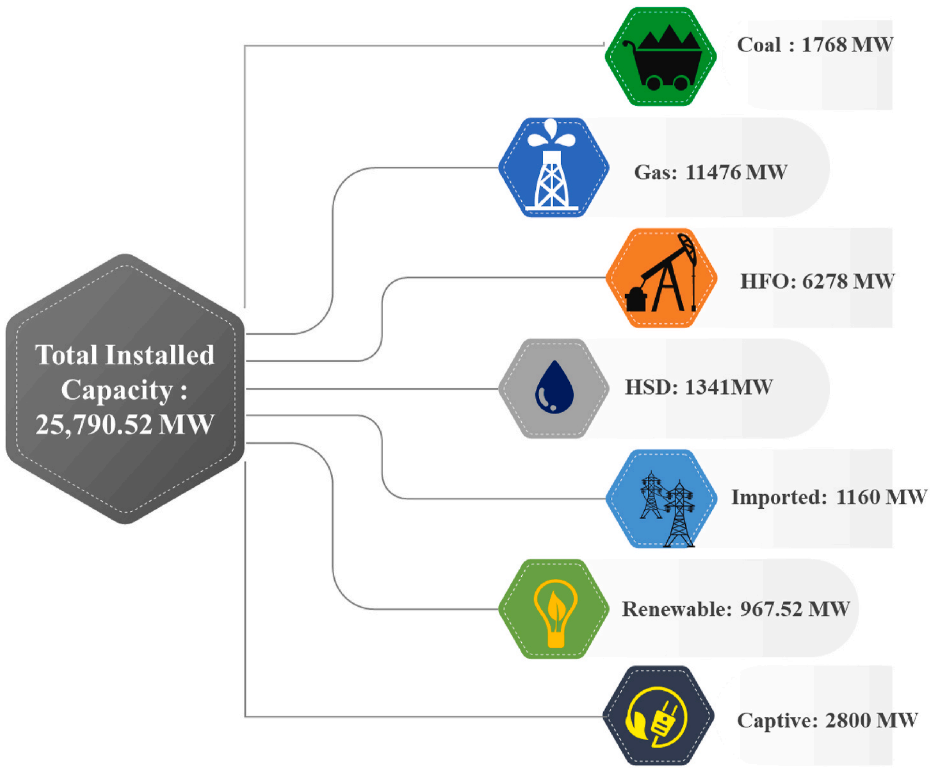

Fig. 4. Electricity generation from different resources (MW) [27].

Nevertheless, the insufficient gas supply has significantly diminished the overall power generation capability in the nation. Unfortunately, the country has not been able to fully utilize its domestic resources to achieve maximum power output [28].

2.3. Policy and legal framework for renewable energy development in Bangladesh

The GOB has extraordinarily reached the growth of gross domestic product (GDP) of more the 6% yearly over the last decade and has targeted to announce as a developed nation by 2041. The nation's development relies on the easy accessibility of power and the consumption rate of electricity. The electricity demand in Bangladesh is growing due to the higher population growth. The development of renewable energy sources is one of the most effective and efficient ways to satisfy future energy demand and ensure energy security, long-term sustainability, reliability, and affordability. As a result, GOB released a draft of a policy for renewable energy in 2002. This draft included the procedures, tariff regulations, and other incentives for the development of the RET and the establishment of the renewable energy authority named Renewable Energy Development Authority (REDA). The Power Division, Ministry of Power, Energy and Mineral Resources, Bangladesh revised the previous draft and finalized the draft named the 'Renewable Energy Policy' on 18 December 2018. The policy identified the global crisis of energy e.g. the gradual decline of fossil fuel, the importance of emission reduction (up to 80% by 2050), the price fluctuation due to the gap between demand and supply, and the demand for energy security. The major objectives of renewable energy policy are as follows [29]:

- To enhance the contribution of renewable sources for electricity production.
- To promote the related technologies in the field of renewable energy and dissemination of the RETs in rural and urban areas.
- To harness the potential of renewable energy sources like wind, solar, hydropower, biomass, etc.
- To establish a sustainable energy supply and replace the conventional energy supply.
- To encourage and enable public and private investors to invest in renewable energy technology for power production.
- To promote clean energy development through the clean development mechanism (CDM) and invite all industries and households to build up rooftop solar technology.

The Renewable Energy Policy, 2008 was constructed with some salient features to accomplish the objectives and they are as follows:

2.3.1. Programs for RETs and financial incentives

Salient features in Renewable Energy Policy, 2008 on the investment and financial incentives are given as follows:

- To exacerbate the production of renewable energy, all the raw materials and equipment involved in this technology will be exempted from the applying charge 15% VAT rate.
- The existence renewable energy financing facilities will be expanded to the public, private, donors so that they become capable of accessing and utilizing the resources properly. The investors who are involved in the development of renewable energy sources will be exempted for corporate income tax for a period of 5 years.
- A micro-credit support system will be established in the addition of commercial lending.
- The consideration of incentive tariffs for electricity generated from renewable sources was taken in this policy which is 10% higher than the purchase price of electricity generated by the utility from private generators.

2.3.2. Research and development on RETs

Intensive research is being carried out for the development of the various fields in RETs in Bangladesh by various organizations including state-owned organizations, institutes, universities, and a few NGOs. With the aid of locally accessible resources and facilities, a diverse range of technologies have been developed and tested [30]. The research is carried out for solar cookers, biogas plants, solar dryers, and improved stoves. Moreover, research and development are also conducted on wind turbines and current water turbines.

2.3.3. Awareness and dissemination programs

To develop and implement renewable energy sources and technology, people's awareness and the information to access this technology, especially in rural areas is mandatory. Considering this issue, various organizations like IDCOL, LGED, REB, and Grameen Shakti are executing RET awareness and dissemination programs. In rural regions, Grameen Shakti has initiated an awareness-building initiative that includes, among other things, village fairs, exhibitions, RET posters, and calendar distribution.

In Bangladesh, total power supply is increasing from 29247 GWh in 2010–80243 GWh in 2021 with the predicted requirement around 307000 GWh by 2041. The organization PSMP, 2016 estimated that the country will need to add 60000 MW of electricity by 2041. To meet this requirement, Bangladesh has to rely on the renewable energy sources to ensure the energy security and sustainability. The GOB has targeted to reach the RE-based power generation capacity around 30% by 2030, 40% by 2040, and 100% by 2050. However, Bangladesh is now sharing only 3.75% which is around 967.52 MW and the majority of electricity is coming from hydropower which contributes around 230 MW electricity. To reach the target, GOB comes up with new policy with the integration of "Renewable Energy Policy, 2008" since alone this policy failed to reach the targeted sharing 10% by 2021 and ended up only 1.24%. The new policy includes the strategies and integrated action plan, renewable purchase obligations, feed-in tariff (FIT), net metering, cost reduction policies, institutional arrangement and improved cooperation among stakeholders, and land acquisition guidelines etc. [31]. Under this policy, setting specific goals and strategy is crucial to attract the stakeholders for the development of RETs. Through the PSMP 2016, the GOB has set up a target for 2041 and released net-metering guidelines in 2018, a solar energy roadmap in 2021 for attaining the target. However, Sustainable and Renewable Energy Development Authority (SREDA), as a helping hand, established a five-year plan to develop the renewable energy based on the PSMP 2016 target. Renewable purchase obligations (RPO) need power generation companies both public and private and large electricity consumers to purchase or generate electricity to reach the target demand. The GOB is encouraging all commercial, industrial, and domestic consumers to utilize the rooftops space for developing the solar power system due to the scarcity of the land and introduced a rule in 2010 to mandatorily utilize the rooftops. According to this guideline, the domestic consumers need to have at least 3% solar power generation capacity against their demand and commercial and industrial consumers for 10% whose demands exceed 50 kW [32].

2.4. Present scenario of renewable energy

Renewable energy presents a viable solution to ameliorate the challenges posed by the power crisis and foster economic and environmental progress. Nearly all renewable energy sources are characterized by their cleanliness. In the context of Bangladesh, renewable energy pertains to the utilization of sources like biogas, biomass, hydro power, solar, and wind to generate electricity. Table 1 shows the present situation of renewable energy sources for generating electricity in Bangladesh and are illustrated in Fig. 5.

Despite the significant expenses associated with renewable energy, it is imperative to establish its viability as an alternative solution. Bangladesh's government has introduced a goal to produce 15% of the total electricity from renewable sources by 2041. Nevertheless, the present utilization of renewable energy in the country remains minimal and falls short of meeting the power sector's vision for 2041. Biomass/biogas technology holds promise as a feasible option, but further advancements are necessary. However, this will necessitate the implementation of appropriate policies, programs, and technological breakthroughs.

Table 1
Present situation of RE sources for generation electricity in Bangladesh [33].

RE Source	Technology	Volume	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	Solar Drinking Water System	82	0.09	0	0.09
	Rooftop Solar Except NEM	201	18.47	40.90	59.37
	Solar Park	9	0	261	261
	Net Metering Rooftop Solar	1819	0	66.58	66.58
	Solar Irrigation	2801	49.34	1.99	51.33
	Solar Home System	6037689	263.79	0	263.79
	Solar Minigrid	28	5.81	0	5.81
	Solar Microgrid	0	0	0	0
	Solar nanogrid	2	0.001	0	0.001
	Solar Charging Station	14	0.27	0.02	0.28
	Solar street light	296861	17.07	0	17.07
	Solar Powered Telecom BTS	1933	8.06	0	8.06
	Total Solar Projects	**6341439**	**362.89**	**370.49**	**733.38**
Wind	All Wind Projects	3	2	0.90	2.90
Hydro	All Hydro Projects	1	0	230	230
Biogas	Biogas to electricity	7	0.69	0	0.69
	Biogas plant	87536	0	0	0
Biomass	Biomass to electricity	1	0.40	0	0.40
Total		**6428987**	**365.98**	**601.39**	**967.37**

3. Biomass energy practice in developed countries

The ability to produce renewable bioenergy from biomass varies across different countries due to factors such as geography, resource availability, biodiversity, technology, and economic conditions. Projections suggest that by 2050, biomass has the potential to generate around 3000 TWh of electricity and save approximately 1.3 billion M. ton of CO_2 equivalent emissions annually. It is important to note that for every TWh of energy produced, approximately 472.89 thousand M.ton of CO_2 are emitted. In the last ten years, a significant global transformation in the utilization of renewable energy has taken place. China has experienced a twenty-fold surge in renewable energy consumption since 2008. Moreover, although to a lesser extent, substantial increases have also been observed in the United States, Germany, Canada, and India. Similarly, the growing need for biofuels as a substitute for traditional fuels has resulted in higher production of biofuel globally. Among these nations, the United States stands as the largest contributor to biofuel production, followed by Brazil and Germany [34]. In the report on 2022, the contribution of biomass for electricity production in USA is by about 53000 GWh with the production of biomass approximately 702 Mt per year [35]. Canada possesses abundant natural resources and boasts a diverse range of geography and landforms. In nations that are progressing towards bio economies, agriculture and the forest industry hold significant importance. Canadian companies are utilizing biomass derived from agricultural and forest residues to manufacture bio products and sustainable renewable energy. From the market and mandates scenario in Canada, the total production of biomass and electricity was estimated by around 37.30 Mt and 33.40 TWh [36]. Renewable resources play a significant role in Brazil's energy mix. In 2015, renewables accounted for 41.20% of the country's total energy composition. The largest share, contributing 16.90%, came from sugarcane biomass, while the remainder consisted of forest residue, charcoal, and other renewable sources. Brazil is actively working to decrease its dependency on fossil fuels by prioritizing the generation of biofuels from renewable

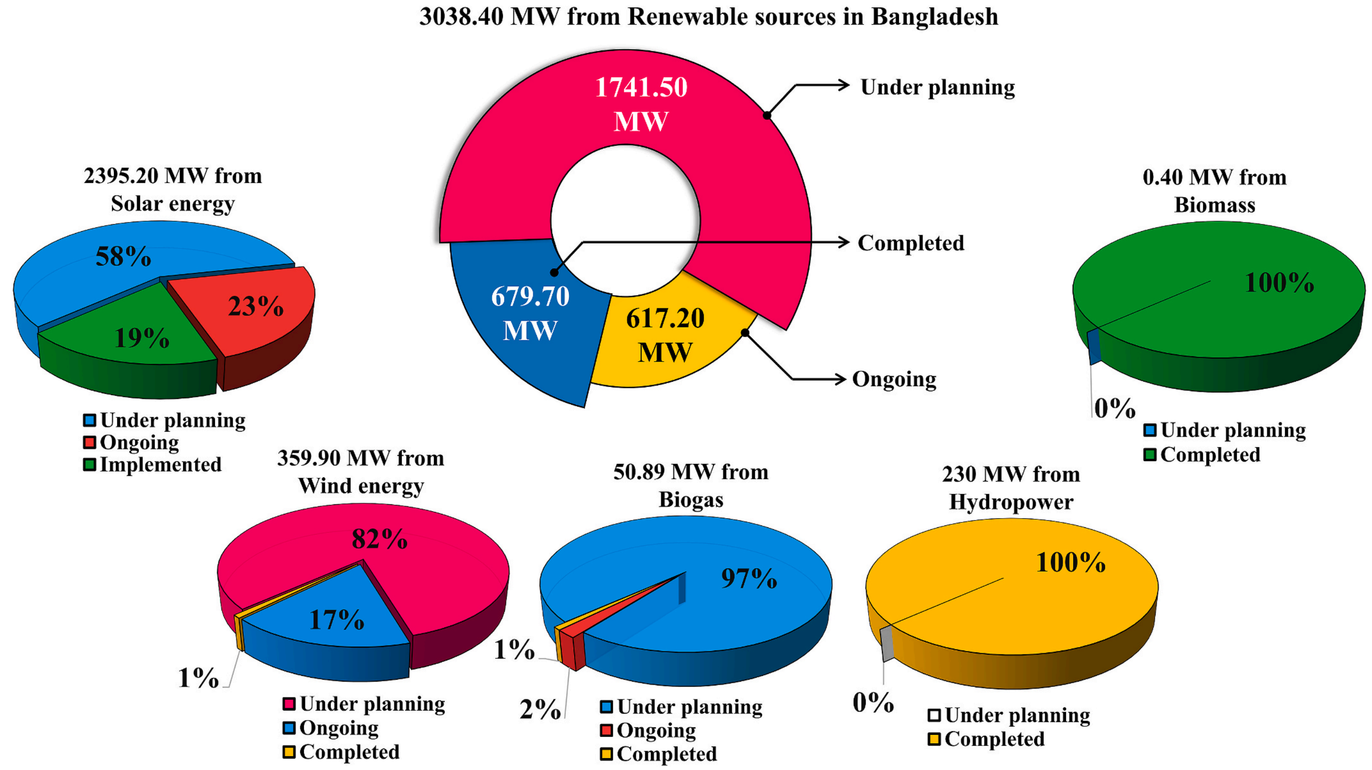

Fig. 5. Current status of renewable energy in Bangladesh [33].

sources. A significant portion of available biomass is used for electricity production through thermoelectric plants. Sugarcane, corn, soybean, and cassava are the primary biomass contributors in the country, with an estimated total production of around 657.10 million M.ton annually. Among these crops, sugarcane dominates both in terms of production and bioenergy generation. The average annual sugarcane production from 2008 to 2012 was approximately 751.10 million M.ton, resulting in an average biomass output of 405.60 million M.ton per year and an energy potential of 1802755 GWh [37,38]. In 2022, the electricity generation from the biomass reached around 25500 GWh in Brazil [39]. China aims to decrease coal consumption by 50 million M.ton in rural areas and generate 30 billion m^3 of biogas from crop residues and manure by 2030. Achieving these targets would require an investment of CDN 7–10 billion USD to establish 3000–4000 facilities. China possesses a significant potential for generating renewable energy from crop biomass and producing electricity around 13260 GWh [40]. Presently, by harnessing its renewable energy resources, China stands as the world's third-largest bioethanol producer. Since 2012, an annual production of 1.5 million M.ton of bioethanol has been achieved, with the United States and Brazil leading in bioethanol production [41,42].

India, as one of the largest consumers of fossil-based energy and a significant producer of greenhouse gases (GHGs), has implemented various incentive programs nationwide to decrease its reliance on fossil fuels. The aim is to generate bioenergy by utilizing untapped non-fossil natural resources, specifically biomass. At present, biomass accounts for 32% of the country's total energy consumption [43]. Approximately 500 million M.ton of surplus biomass derived from agricultural and forest residues are estimated to be available each year for electricity generation and the electricity generation reaches around 17500 MW [44]. In Pakistan, the yearly production of feedstock, comprising around 121 Mt of agricultural residues, 427 Mt of animal manure, and 7.50 Mt of municipal solid waste (MSW), holds the potential to generate approximately 20790 MW of electricity [45]. Malaysia, a nation in South Asia, holds substantial prospects for biomass generation. Forests encompass roughly 62% of the land area, and agricultural activities occupy around 4.90 million hectares. Malaysia generates about 168 million M.ton of biomass from these sources, with key contributors being oil palm (85.50%), municipal solid waste (9.50%), the wood industry (3.70%), rice (0.70%), and sugarcane (0.50%) [46,47]. Fig. 6 shows the amount of biomass produced per year and electricity generation from biomass in the globe.

4. Biomass potentials of Bangladesh

Bangladesh possesses a variety of biomass resources, including agricultural waste, forest residues, animal manure, and MSW, among others. These resources hold the potential for widespread utilization in electricity generation on a larger scale.

4.1. Agricultural residue

The current study examined the availability of biomass residues in different types of lands within the country. These lands include forest which spans 6363 thousand acres, and Net Cropped Area, covering 20081 thousand acres. Together, these lands constitute 72% of the total area of the country. Unfortunately, due to a lack of data on biomass production, we were unable to assess the supply of biomass residues from Cultivable Waste (671 thousand acres), Current Fallow (1066 thousand acres), and Not Available for Cultivation (8284 thousand acres) lands, shown in Fig. 7. These categories account for 28% of the total area. It is worth noting that some of these lands are used for grazing livestock, growing fodder, and cultivating trees. From the perspective of biomass supply, these lands can be broadly classified as "non-cropped land" for fodder production and "non-forest land" for tree cultivation. Within the total area of Not Available for Cultivation is covered by various water bodies which are not suitable for growing biomass for fuel purposes, village forest, spanning, government forest land.

In Bangladesh, major agricultural crops such as rice, maize, wheat, coconut, groundnut, vegetables, jute, and sugarcane play a vital role in the country's economy. The residues generated from these crops offer

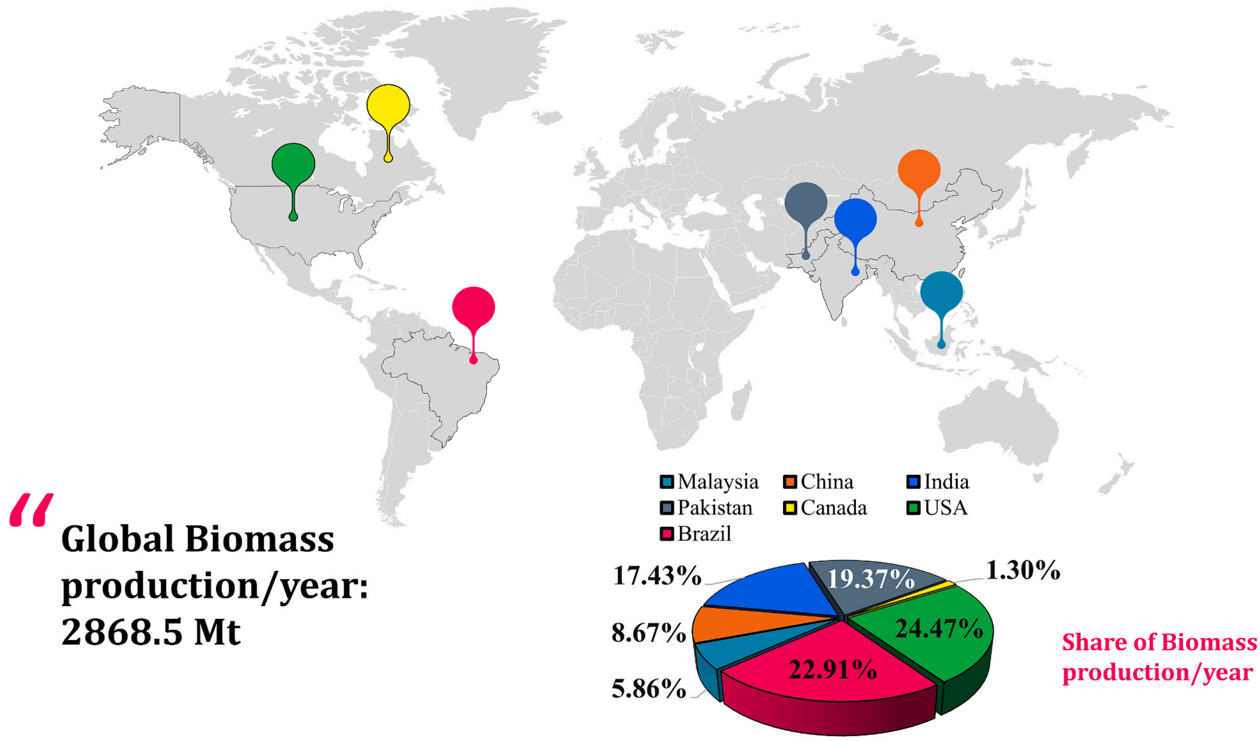

Fig. 6. Bioenergy potential in the world.

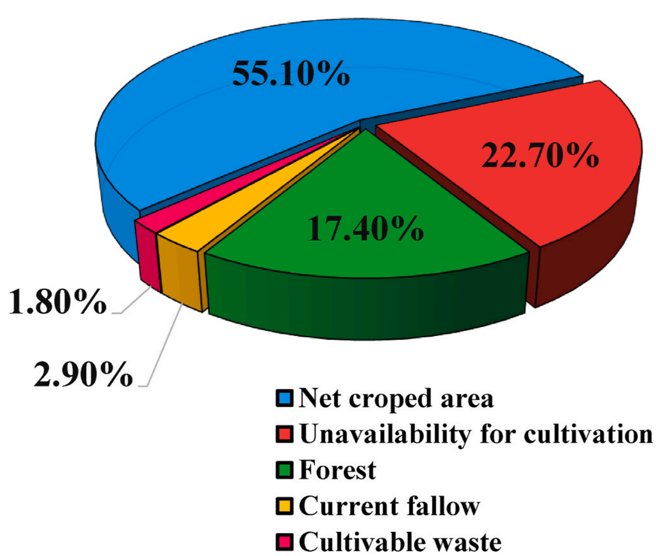

Fig. 7. Land utilization statistics of Bangladesh (2019–2020) [48].

potential for energy production. These residuals are picked up either simultaneously with the main crop harvest or afterward. There are two categories of crop residues based on the collection period: field residue and processing residue. Field residues, gathered post-harvest, are commonly used as fertilizers. On the other hand, processing residues are collected from mills where additional processing of the crops occurs. Rice straw, rice husk, sugarcane bagasse, and jute stick collectively contribute to about 46% of the total biomass energy [19]. These agricultural residues serve as renewable energy sources and can also be used for cooking and raw material manufacturing. In rural areas of Bangladesh, where commercial gas supply is absent, agricultural crop residues such as straw and husk are widely used as the primary cooking fuel. Dry cow manure, wood, and kitchen by-products are also utilized to some extent. The calculation of total crop residue generation is derived from observed generation and recovery ratios in nearby developing countries in South Asia. Field crop residues have an assumed recovery rate of 35%, while process crop residues are assumed to have a 100% recovery rate [49,50].

Rice holds the position of the primary agricultural crop in Bangladesh, encompassing the majority of the total agricultural area and meeting the nation's predominant calorie requirements. The production data for agricultural crops from fiscal year (FY) 2020-21 to FY 2021-22 is provided in Table 2.

As per the Bangladesh Bureau of Statistics, the amount of rice production in FY 2020-21 was 37607756 M.ton. In FY 2021–22, the total rice production was 38145192 M.ton. During this time, the field area dedicated to rice ploughing decreased from 28913022 acres to 28891835 acres. Fig. 8 Approximations of agricultural crop (a) cultivation and (b) production in Bangladesh during the period of 2020-21 and 2021–22 [51].Rice straw and rice husk stand out as the primary residues resulting from rice cultivation. Rice straw denotes the dried stalks of cereal plants that remain in the fields after harvesting. Conversely, rice husk constitutes the outer layer of the rice grain and rice straw, categorized as residues from the processing phase. In Bangladesh, rice straw is commonly utilized as livestock, poultry, and fish feed. Notably, there has been a growing trend in the small-scale utilization of rice husk for electricity production. The rice milling sector is the primary consumer of energy derived from rice husk. In the fiscal year 2021–22, the total recoverable rice residues in Bangladesh amounted to 34.29 Mt, with an estimated overall energy potential of 488.19 PJ. Other energy sources from various agricultural crops, such as sugarcane, coconut husks, maize stalks, maize husks, cotton stalks, groundnut straws, and husks, contributed to generating almost 165.35 PJ of energy in the same fiscal year, as detailed in Table 3.

4.2. Animal manure

Animal manure represents a blend comprising organic matter, moisture, and ash. Its decomposition can occur under both aerobic and

Table 2
Crop residue characteristic factors [52–56].

Crop	Residue	Residue to crop yield mass ratio (RYR);	Residue recovery factor kg/kg of residue (RRF)	Surplus availability factor kg/kg of residue (SAF)	Total production (Million tons)	Total residue (Million tons)
Rice	Rice straws	1.76	0.60	0.80	38.15	32.22
Rice	Rice husks	0.08	1	0.21	38.15	2.08
Sugarcane	Sugarcane tops	0.30	0.70	1	30.87	6.48
Wheat	Wheat straws	1.75	0.35	0.20	1.09	0.13
jute	Jute stalks	3.00	0.35	0.50	1.84	0.96
Coconut	Coconut husks	1.03	0.90	0.57	0.41	0.22
Cotton	Cotton stalks	2.75	0.35	0.68	0.02	0.01
Maize	Maize stalks	2.00	0.60	1	4.26	5.12
Maize	Maize husks	0.20	1	0.50	4.26	0.43
Ground Nut	Ground nut straws	2.30	0.35	0.64	0.33	0.17
Vegetables	Vegetables	0.40	0.35	0.50	4.61	0.32
Sugarcane	sugarcane bagasse	0.25	1	0.21	30.87	1.62

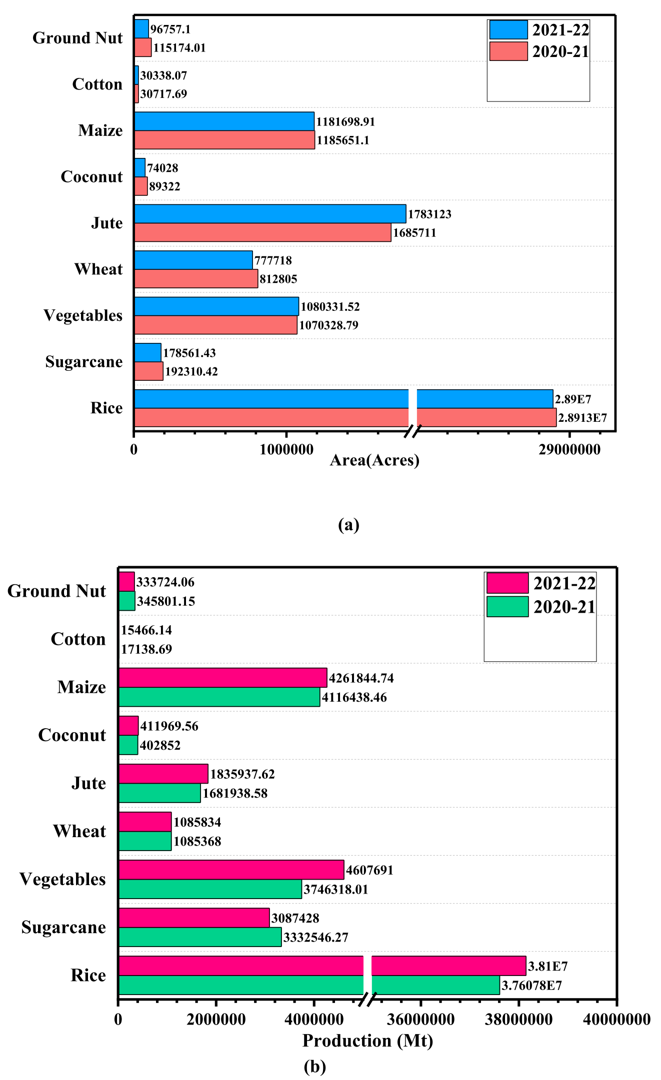

Fig. 8. Approximations of agricultural crop (a) cultivation and (b) production in Bangladesh during the period of 2020-21 and 2021–22 [51].

anaerobic conditions. Aerobic decomposition yields CO_2 and stabilized organic materials. In contrast, anaerobic decomposition produces methane, CO_2 gas, and stabilized organic materials [60,61]. Cattle, goats, buffaloes, and sheep serve as the primary contributors of animal manure in the region, commonly employed as fertilizer. Leveraging animal manure for biomass energy production and electricity generation presents a practical solution to address energy needs in rural and distant areas of Bangladesh. This strategy not only mitigates the unpleasant odor from manure but also reduces emissions, enhancing convenience. The biogas derived from manure finds application in fulfilling cooking fuel requirements. Furthermore, there exists potential for generating small-scale electricity by utilizing gas produced from waste at slaughterhouses. The volume of manure produced by animals is contingent on factors like age, breed, and dietary habits. Additionally, dung yield fluctuates with seasons, with higher production observed during the rainy season due to increased grass growth [62]. Fig. 9 displays the livestock and poultry numbers in Bangladesh from FY 2020-21 to FY 2021–22. The data in Fig. 9 indicates an increase in the number of livestock and poultry, consequently leading to a rise in manure production. In FY 2020–21, the statistics show approximately 24.55 million cattle, 1.50 million buffaloes, 26.60 million goats, 3.68 million sheep, 304.11 million chickens, and 61.75 million ducks. The total population of livestock and poultry in FY 2020-21 amounted to 56.33 million and 365.85 million, respectively.

To estimate the daily waste production by livestock and poultry, the generation ratio used is derived from neighboring Asian countries, with values of 7.50 kg wet matter/animal/day for cattle, 10 kg wet matter/animal/day for buffaloes, 0.38 kg wet matter/animal/day for goats, 0.38 kg wet matter/animal/day for sheep, and 0.10 kg wet matter/poultry/day. The total annual waste production is calculated by multiplying the yearly waste production by the number of livestock or poultry. Hence, in FY 2021–22, approximately 56.73 million livestock produced 77298696.25 ton of waste, while 375.65 million poultry generated 13711042.50 ton of waste. Based on the factor, the estimated recoverable amounts of animal waste and poultry droppings in Bangladesh for FY 2021-22 were 37967765.38 ton and 12339938.25 ton, respectively. Considering the moisture content and lower calorific value of biogas the energy content was calculated for FY 2021-22 which was 315.74 PJ for livestock and 83.29 PJ for poultry, presented in Table 4.

4.3. *Municipal solid waste*

Municipal solid waste (MSW) constitutes a varied assortment of waste materials generated from human activities in urban areas. This includes a mixture of biodegradable and non-biodegradable components, incorporating detrimental and harmless items [37]. The quantity of waste generated per person depends on factors such as economic status, dietary habits, age, gender, and seasonal variations within households. The increase rate of solid waste in Asian cities is a result of population expansion, industrial development, and improved qualities of life. Governments recognize the importance of implementing Green Productivity (GP) measures, such as waste reduction, recycling, reuse,

Table 3
Energy potential of agricultural residue for 2021–22 [57–59].

Crop	Residue	Total residue (Million tons)	Moisture (%)	Dry Content (ton)	LCV (Gj/t)	Energy Content (PJ)	Electricity generation (TWh)
Rice	Rice straws	32.22	0.13	28132334.20	16.30	458.56	127.38
Rice	Rice husks	2.08	0.12	1817777.08	16.30	29.63	8.23
Sugarcane	Sugarcane tops	6.48	0.50	3241770	15.81	51.25	14.24
Wheat	Wheat straws	0.13	0.08	123038.57	15.76	1.94	0.54
jute	Jute stalks	0.96	0.01	872281.99	16.91	14.75	4.10
Coconut	Coconut husks	0.21	0.11	193735.47	18.53	3.59	0.99
Cotton	Cotton stalks	0.01	0.12	8907.79	16.40	0.15	0.04
Maize	Maize stalks	5.11	0.12	4500460.80	14.70	66.16	18.38
Maize	Maize husks	0.43	0.11	378874.02	17.27	6.54	1.82
Ground Nut	Groundnut straws	0.17	0.12	151130.52	17.58	2.66	0.74
Vegetables	Vegetables	0.32	0.20	258025.60	13	3.36	0.93
Sugarcane	sugarcane bagasse	1.62	0.49	826651.35	18.10	14.96	4.16
Others	Straws, husks and stalks	15.06	0.25	1204772.73	16.50	198.78	55.22
					Total	**852.32**	**236.77**

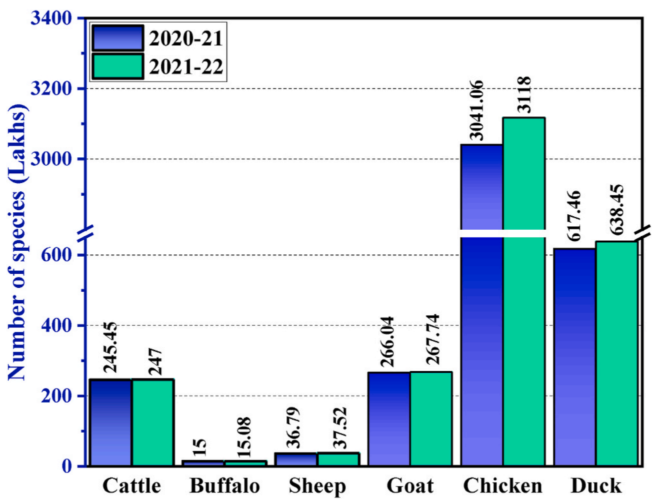

Fig. 9. Livestock population of Bangladesh (in lakh number) [63].

and recovery, to manage the rapid waste accumulation in urban areas. National campaigns promoting GP measures and recycling initiatives are regularly conducted. Bangladesh, like many developing nations, faces significant environmental challenges due to the substantial generation and mismanagement of MSW [38]. Domestic area, commercial zones, industries and hospital are main contributors to MSW. MSW components consist of food, plastics, forest residues, vegetables, paper, plastics, leather, rubber, textiles and other flammable materials. The waste heat recovery burner strategies are utilized to transform MSW into energy, using untreated MSW like a fuel [69].

The daily per capita waste generation ratio in urban and rural areas of Bangladesh is reported to be 0.41 kg and 0.15 kg, respectively. In 2022, the urban and rural population of Bangladesh was recorded as 68.80 million and 103.20 million, respectively. By multiplying the respective population figures with their corresponding waste generation rates, the total MSW generation in the country for that year was estimated to be 43002.73 tons, as presented in Table 5.

Fig. 10 provides an overview of the waste composition in six city corporations of Bangladesh. The estimated percentages indicate that approximately 68–81% of the generated waste consists of organic matter, while 7–11% comes from paper, 3–4% from plastic, and 9–16% from textile, forest residues, leather, rubber, metal, glass, and other materials. Glass, leather, and rubber constitute the least percentage, while food and vegetables contribute the most in all towns. The biodegradable component, mainly consisting of organic matter, is higher than other waste sources, given the consumption of fresh vegetables and food, coupled with the absence of food processing industries. Table 6 shows the main chemical components of MSW generated in different cities in Bangladesh.

Based on estimates, the recovery rate of MSW is reported as 70%. Taking into account the 70% recovery rate, the estimated amount of MSW that can be recovered in 2022 was approximately 10987.19 tons. The total energy potential in 2022 was calculated to be around 112.16 PJ, considering a moisture content of 45% and a lower calorific value of 18.56 GJ/ton. Table 7 shows the energy potential of MSW residues [65].

4.4. Forest residues

Forest residues refer to the remnants typically remaining on the forest floor following wood harvesting activities. Wood wastes, on the other hand, are acquired from wood cutting activities like sawmilling, plywood manufacturing, and particle board production. In many cases, a significant portion of the wood is collected as firewood for household use. However, the recovery rates of wood residues can vary depending on local practices and the specific tree species involved. Wood processing residues and recycled wood play a vital role as energy sources, with plywood mills and sawmills generating comparable amounts of residues. Total forest area of Bangladesh is shown in Fig. 11.

The classification of residues as dry or tree residues is not applicable to all types of residues. Wood fuel and wood processing residues typically contain a wet content of around 20%. Taking this into account, the estimated total amount of recoverable dry residues was approximately 14.32 Mt. Considering the lower calorific value of each residue, the total recoverable energy potential was estimated to be about 210.64 PJ, as shown in Table 8.

5. Energy potential from biogas in Bangladesh

Biomass energy holds significant importance as an energy source across numerous Asian countries. Households and industries heavily rely on forest residues, agricultural residues, animal manure, and leaves for various purposes. Cooking and heating are the primary household applications, while industrial applications encompass various activities including food processing, mineral extraction, textile production, metal processing, and miscellaneous uses like road tarring and tire re-treading. Apart from these heating applications, biomass fuels like bagasse and oil palm residues are extensively utilized for electricity generation or the simultaneous production of electricity and steam in industrial settings. Fig. 12 shows the potential energy content of biogas product.

Based on the estimation, the total available biomass energy amounts to 1574.15 PJ, equivalent to 4.372 625 $\times$ 10^8 MWh. The energy contributions from different sources are as follows: agricultural residues account for 54.15%, animal wastes and poultry droppings contribute 25.35%, municipal solid waste contributes 7.13%, and forest residues contribute 13.38% of the total energy potential.

Table 4
Residue generation from livestock residues and Energy potential of livestock residues [19,57,64–68].

Name of Species	Number of animals	Dung Yield (kg/animal/day)	Residues generation (ton/year)	Residue recover factor	Residues recover amount (ton)	Moisture (%)	Dry Content (ton)	LCV (Gj/ton)	Energy content (PJ)	Electricity generation (TWh)
Cattle	24700000	7.50	67616250	0.50	33808125	0.40	20284875	13.86	281.15	78.09
Buffalo	1508000	10	5504200	0.50	2752100		1651260		22.89	6.36
Sheep	3752000	0.38	513555	0.60	308133		184879.80		2.56	0.71
Goat	26774000	0.38	3664691.25	0.30	1099407.38		659644.43		9.14	2.54
Total Ruminant	**56734000**		**77298696.25**	**1.90**	**37967765.38**		**22780659.20**		**315.74**	**87.70**
Chicken	311800000	0.10	11380700	0.90	10242630	0.50	5121315	13.50	69.14	19.21
Duck	63845000	0.10	2330342.50	0.90	2097308.25		1048654.13		14.14	3.93
Total Poultry	**375645000**		**13711042.50**	**1.80**	**12339938.25**		**6169969.13**		**83.29**	**23.14**
Total Livestock	**432379000**		**91009738.75**	**3.70**	**50307703.63**		**28950628**		**399.04**	**110.84**

Table 5
MSW generation of Bangladesh in 2022 [70,71].

MSW Residue	Waste Generation (kg/capita/day)	Population (Million)	Waste generation (kg/day)
Urban	0.40	68.80	27521747.20
Rural	0.15	103.20	15480982.80
	Total	**172010920**	**43002730**

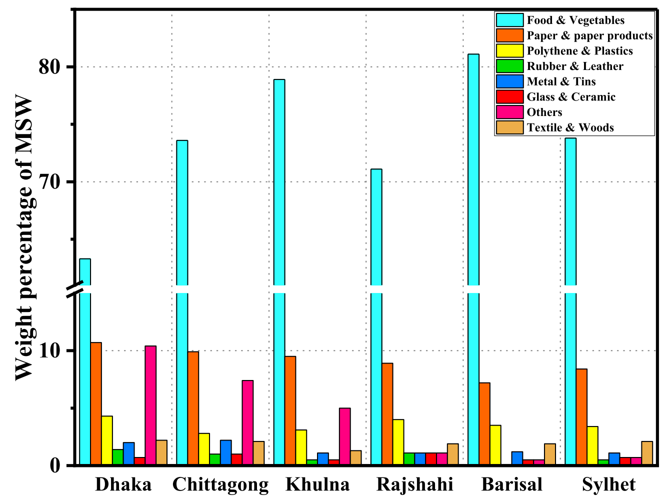

Fig. 10. Average Physical Components in weight percentage of MSW in different cities of Bangladesh [72].

6. Available biomass conversion technologies

The conventional practice of using biomass for cooking purposes in rural regions of Bangladesh has detrimental effects on the environment. Biomass burning contributes significantly to the release of greenhouse gases and solid particles into the troposphere. Comparatively, kerosene and LPG (liquefied petroleum gas) generate less greenhouse gas per unit of energy production when compared to traditional biomass fuels [76]. Consequently, there is a renewed focus on Renewable Energy Technologies (RETs) to foster environmentally friendly effective growth in remote area. Biomass possesses the potential to be directly or indirectly used for the generation of energy products, such as biofuels, although the process of conversion involves intricate phenomena. There are various technologies available for transforming the potential energy content of biomass into useable forms of energy. These technologies differ in terms of efficiency, level of development, investment requirements, operational and maintenance costs, as well as labor demands [4]. The technologies used for biomass conversion can be categorized into two types. The first type, known as biochemical conversion technologies, involves the degradation of biomass using different enzymes and microorganisms. The second type, termed thermochemical conversion technologies, relies on heat for the degradation of biomass. Among these thermochemical conversion technologies, hydrothermal processing stands out as it enables the conversion of biomass into different product forms, including solids, liquids, and gases [77]. Fig. 13 illustrates the wide range of products obtained through biomass conversion technologies, encompassing thermochemical, biochemical, and chemical processes.

6.1. Anaerobic digestion

Anaerobic Digestion (AD) refers to the conversion of biodegradable material into biogas, primarily composed of methane and CO_2, along with small amounts of other gases like hydrogen sulfide [79]. This process involves the use of microorganisms to convert biodegradable

Table 6
Main chemical components of MSW generated in different cities in Bangladesh [72].

City	pH	Moisture Content (% Fresh Matter)	Volatile Solid (% Dry Matter)	Ash Residue (% Dry Matter)	C/N	Nitrogen (% Dry Matter)	Phosphorus (% Dry Matter)	Potassium (% Dry Matter)
Dhaka	8.60	70	71	29	10.17	0.89	0.31	0.62
Chittagong	8.20	62	54	46	17.22	0.17	0.23	0.57
Khulna	7.70	68	56	44	16.08	1.62	0.41	1.37
Rajshahi	7.70	56	48	52	12.15	0.56	0.31	0.38
Barisal	7.70	57	43	57	12.44	1.23	0.40	1.18
Sylhet	7.70	69	65	35	11.96	0.90	0.32	0.42

Table 7
Energy potential of MSW residues [65].

MSW Residue	Recovery Factor	Waste Recovery (ton)	Moisture (%)	Dry Recover Waste (ton)	LCV (GJ/ton)	Energy Content (Pj)	Electricity generation (TWh)
Urban	0.70	7031806.41	0.45	3867493.53	18.56	71.78	19.94
Rural	0.70	3955391.11	0.45	2175465.11	18.56	40.38	11.22
Total		**10987197.52**	**0.90**	**6042958.63**	**37.12**	**112.16**	**31.16**

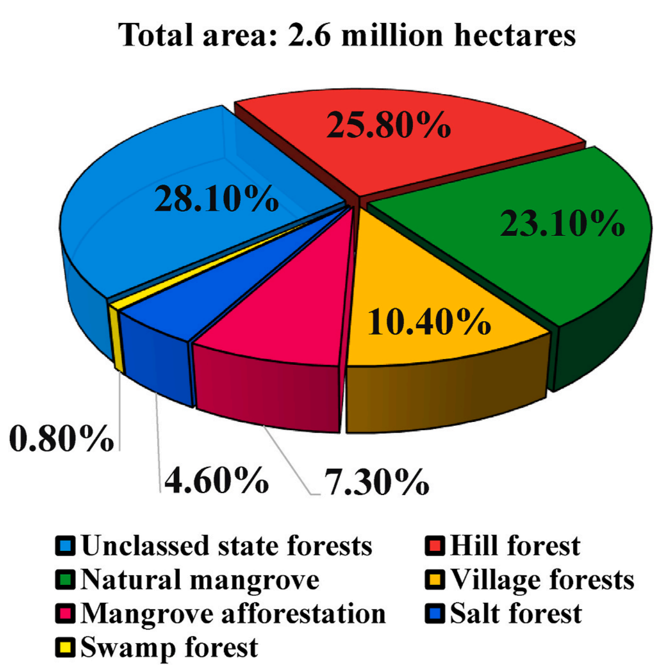

Fig. 11. Total forest land of Bangladesh [73].

non-lignocellulosic (non-woody) material, known as feedstock, in an oxygen-free environment. This conversion results in the production of stable and commercially valuable compounds. While similar to composting in breaking down organic matter, AD differs in being anaerobic, whereas composting is aerobic, relying on oxygen (O_2). The biomass is converted by bacteria in an oxygen-free environment, leading to the formation of a gas with an energy content typically ranging from 20 to 40% of the lower heating value (LHV) of the feedstock. AD is a well-established technology utilized for treating organic wastes with high moisture content, typically ranging from 80 to 90% moisture content [80]. The feedstock appropriate for anaerobic digestion comprises organic waste and residues such as animal dungs, along with energy crops like maize silage cultivated expressly for the anaerobic digestion plant. Anaerobic digesters establish an environment conducive to the natural decomposition of organic material by bacteria in the absence of O_2, resulting in the generation of biogas. Biogas, consisting of approximately 50–60% CH_4, 40–50% CO_2, and other gases, can be utilized for electricity and heat generation. Fig. 14 exhibits the district wise agro-industrial biogas plant along with the contributions of different waste for producing biogas and probable electricity generation from biogas in Bangladesh. It also has the potential for enhancement to bio methane, which can be infused into the gas grid or utilized as a fuel for transportation. Additionally, AD produces a valuable by-product in the form of organic fertilizer, making it a highly promising technology with diverse applications [81].

Like any biological process involving chemicals, overseeing AD

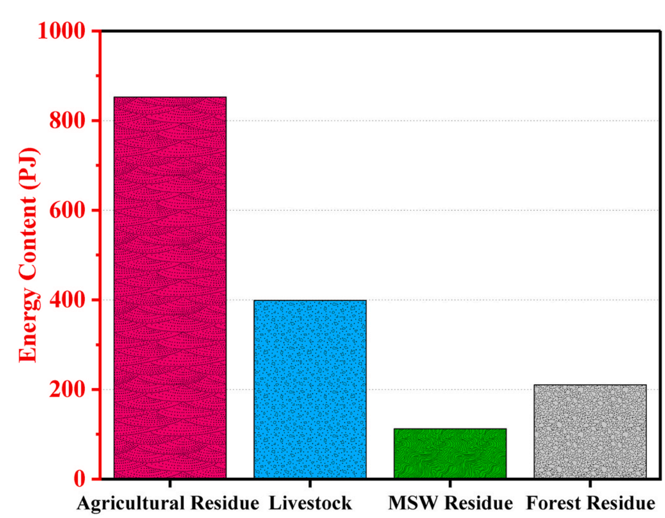

Fig. 12. Potential energy Content of Biogas product.

Table 8
Energy potential of forest residues in Bangladesh [74,75].

Forest products	Amount (Million tons)	Moisture Content (%)	Net amount (Million tons)	LCV (GJ/ton)	Energy content (PJ)	Electricity generation (TWh)
Wood fuel	15.46	20	12.37	15	185.51	51.53
Tree residue	1.82	0	1.82	12.52	22.80	6.33
Wood residue	0.16	20	14.32	18	2.33	0.65
Total	**17.44**				**210.64**	**58.51**

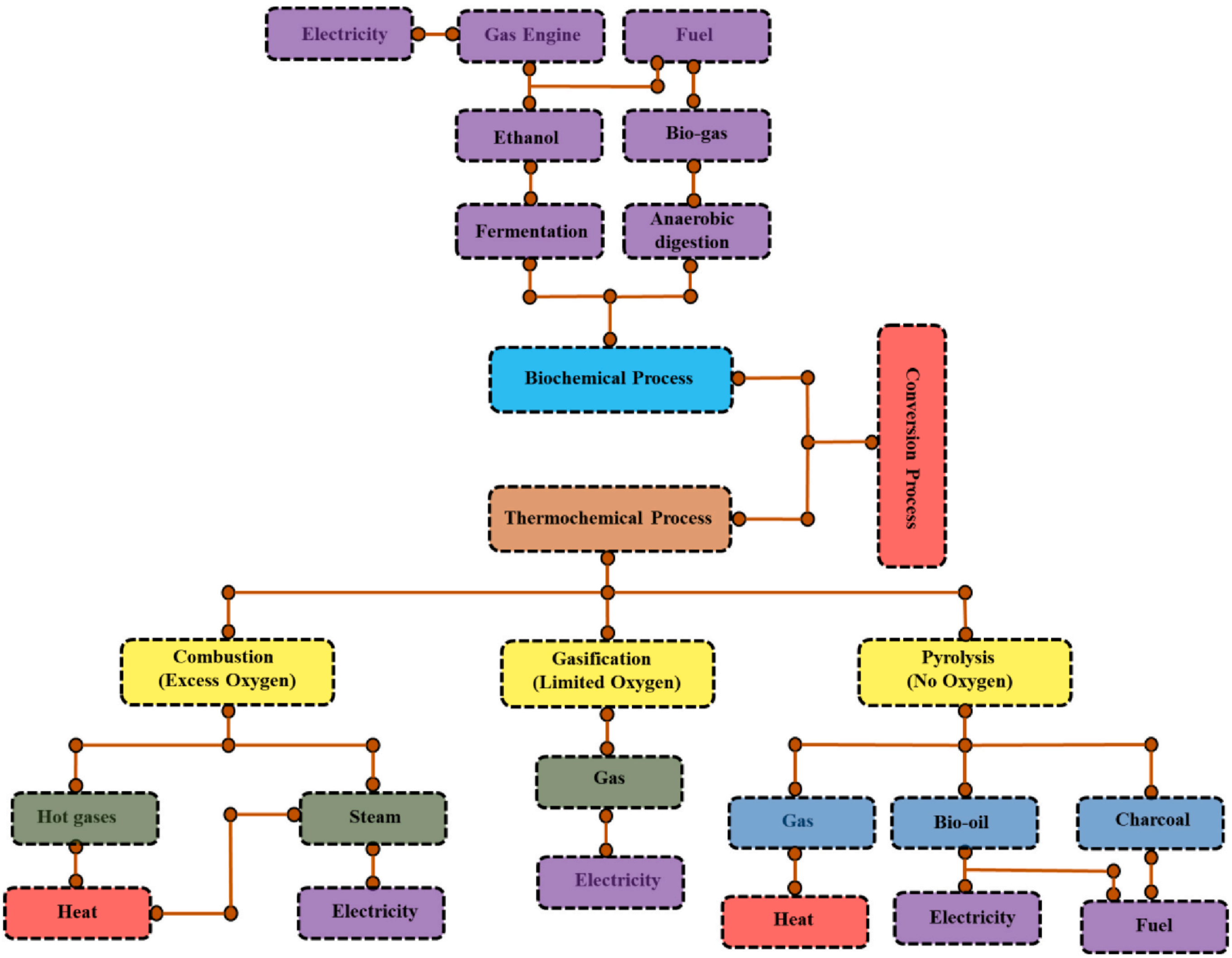

Fig. 13. Different conversion process of biomass [78].

operations is vital for ensuring they run smoothly. Issues or failures in anaerobic reactors may arise from excessive hydraulic or organic loads, the presence of harmful organic or inorganic substances, and sudden shifts in operating temperature. Key indicators such as VFA, alkalinity, VFA/alkalinity ratio, biogas production rates and composition (methane and CO_2), p^H, COD, and volatile solids reduction are commonly used to monitor AD processes. Typically, a combination of these parameters is observed simultaneously, as they offer interconnected insights into the system [82]. These parameters are effective for identifying continuous changes in reactor performance and ongoing process upsets. However, abrupt overloads, temperature changes, or the presence of toxins necessitate immediate corrective actions. Swift and more precise techniques are essential to prevent substantial process deterioration and reactor breakdown, particularly in high-rate anaerobic reactors with short hydraulic retention times, often as low as 12–24 h. An optimal metric should be readily quantifiable, accessible in real-time, ideally online, and possess inherent significance by precisely representing the present metabolic condition of the system. Anaerobic digestion involves three interconnected phases—solids, liquids, and gases—where data from one phase can directly signify the status of the others. To gain comprehensive understanding and ensure efficient monitoring of reactors in the anaerobic digestion process, diverse parameters associated with these three phases have been employed [83,84]. AD involves intricate biological interactions between various living and non-living elements, influenced by a multitude of environmental and operational factors. Table 9 shows the most favorable environmental and operational circumstances for anaerobic digestion of the organic fraction within municipal solid waste [85,86].

6.2. Biomass gasification

The process of gasification involves the thermochemical conversion of an organic feedstock, such as solid or liquid fuel, into its gaseous constituents. The composition of the resulting gas depends on the gasification temperature. Specifically, at higher gasification temperatures (above 1200 °C), synthesis gas or syngas, consisting primarily of H_2 and CO, is formed. At lower gasification temperatures, a product gas is generated, which includes CO, H_2, CH_4, and CO_2. This product gas may also contain pitch compounds that can have a negative impact on gasification performance and subsequent applications [99]. The produced gas, characterized by a low calorific value (approximately 4–6 MJ/m^3), can be directly burned or utilized as a fuel for gas engines and gas turbines [100]. Table 10 shows the summary of new technologies applied for biomass gasification [101,104].

The transformation of biomass into syngas involves a sequence of four stages: drying, DE volatilization, oxidation, and reduction. In the first stage, moisture is removed from biomass through drying, and this released moisture undergoes further reactions to form H_2. DE volatilization, the second stage, occurs within a temperature range of 225–500 °C, releasing volatile compounds from the biomass [30].

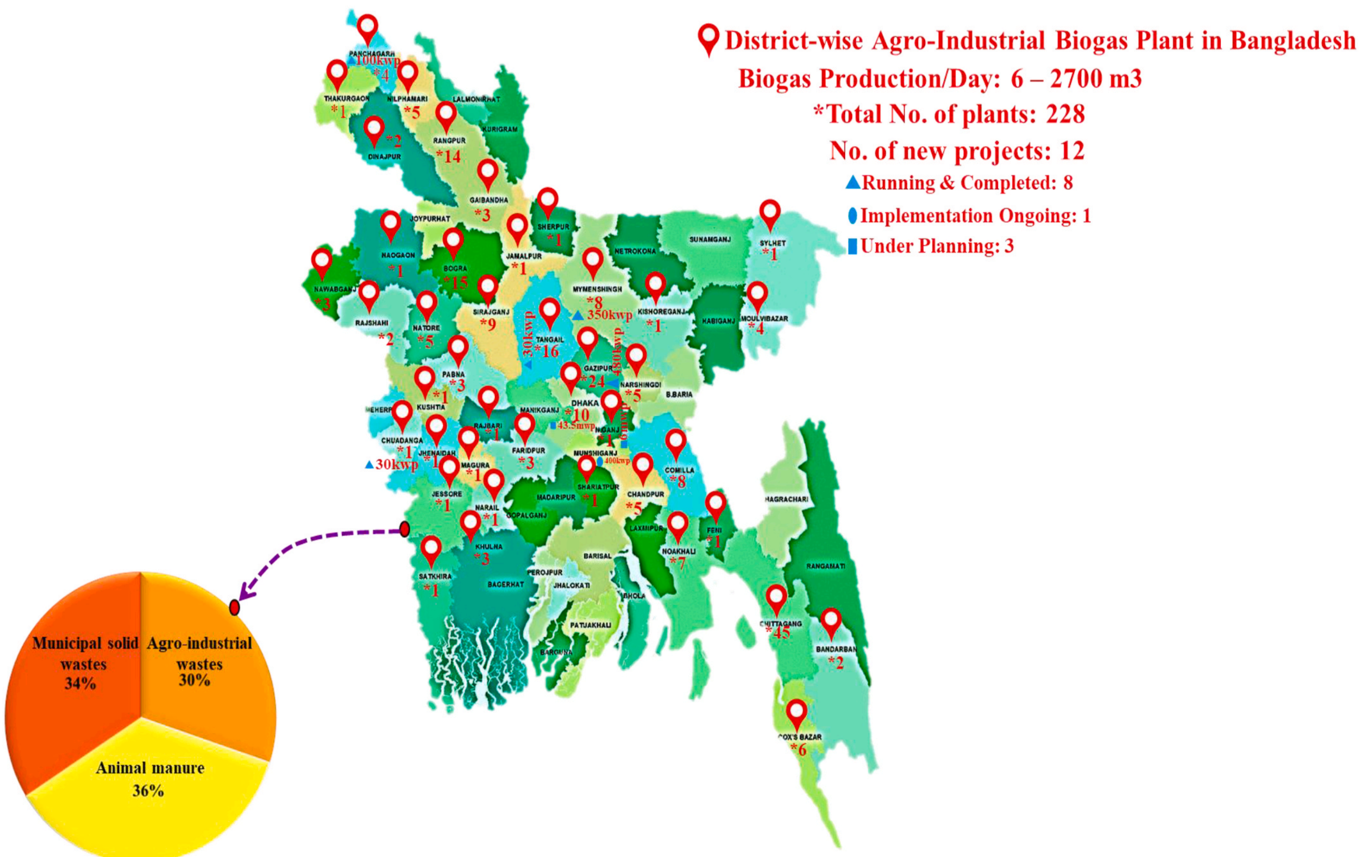

Fig. 14. Contribution of different wastes for producing biogas and district wise agro-industrial biogas plant in Bangladesh [87].

Table 9
Favorable environmental and operational circumstances for anaerobic digestion of the organic fraction within municipal solid waste.

Indicators	Ideal State		References
pH	Acidogens	4–8.50	[88]
	Methanogens	6.50–7.20	[88]
	Combined Digestion System	6.50–7.50	[89]
Alkalinity		1000–5000 mg $CaCO_3$/L	[90]
Temperature	Psychrophilic	range 5 °C –15 °C optimum 10 °C	[91]
	Mesophilic	range 20 ° C- 40 °C, optimum 35 °C	[91]
	Thermophilic	range 50 °C –65 °C, optimum 55 °C	[91]
C/N ratio	25		[92]
Hydraulic Retention Time	Depending on the type of feedstock and temperature, should not be less than 2–4 days		[89]
Solid Retention Time	Depends upon operating condition		[93]
Loading rate	15.20 g/L COD		[94]
Seeding (VS basis)	0.50–1.10		[88]
Moisture content	60–75% in Dry AD		[95]
	85–90% in Wet AD		[95]
Headspace pressure	up to about 20 bar		[96]
Headspace Flushing	Mixture of N_2/CO_2 (mixing volumetric ratio 80/20)		[97]
ORP	−200 to −350 mV		[98]
Free Ammonia	600–800 mg/L		[88]

Table 10
Summary of new technologies applied for biomass gasification [101,102].

Strategy employed	Advantages	Limitations
Combination of gasification and gas clean-up in one reactor	•Robust process design •Cost-effective	•More research is needed for large-scale commercial applications
Multi-staged gasification concept	•High quality clean syngas •Improved process efficiency	•Enhanced complexity
Distributed pyrolysis plants with central gasification plant	•Usage of distributed, low-grade biomass •Cost-effective transportation of char oil slurry	•Gasoline and olefins production via this process is not economically viable
Plasma gasification	•Decomposition of any organic matters •Treatment of hazardous waste	•High investment cost •High power requirement •Low efficiency
Co-generation of thermal energy with power	•Enhanced process efficiency	•Only decentralized heat and power production is feasible as heat needs to be produced near consumers
Poly-generation of heat, power, and H_2/SNG	•Enhanced process efficiency •Generation of renewable H_2/renewable fuel for transportation	•Enhanced complexity in process design •Not economical in the absence of a natural gas distribution system

Proceeding to the third phase, oxidation involves the devolatilized products (char, tar, and gases) engaging with an oxidizing agent to generate crucial heat necessary for endothermic reactions. The fourth and conclusive stage in gasification is reduction, wherein the hot combustion products (formed during oxidation) are predominantly converted into CO and H_2. Gasifiers are classified based on two factors: the availability of heat for facilitating reactions (direct or indirect) and the type of bed. Direct gasification utilizes air and/or O_2 as an oxidizing agent, interacting with biomass within the gasifier and producing the essential heat for endothermic gasification reactions. In indirect gasification, the gasifier is externally heated to supply the required heat for the gasification reactions. When employing direct gasification with air (referred to as air-gasification), the resultant syngas is diluted with N_2 (50–65%) and exhibits lower concentrations of H_2 and CO. Conversely, indirect gasification, typically utilizing steam or, O_2 as the oxidizing agent, yields syngas with higher concentrations of H_2 and CO [103]. Table 11 shows the conditional effects on the performance of the gasifier. Gasification is a technology that presents challenges and uncertainties, making it less competitive and immature compared to other options. Therefore, it is not considered a viable solution for electricity generation. One of the complexities lies in selecting the appropriate gasifier, considering factors such as plant size and the specific biomass to be used. With a variety designs and setups available, many of which are still in the research phase, finding the suitable configuration can be challenging. Furthermore, biomass exhibits different characteristics compared to fossil fuels, making it less predictable in terms of behavior and performance.

6.3. Biomass briquetting

Biomass briquette refers to a compressed solid form made from various loose biomass materials, including agricultural residues and residues from the wood industry. The production process involves applying pressure to compact the biomass. Biomass briquettes offer several advantages, as highlighted in studies [110,111]:

- They have a greater calorific value per unit volume compared to conventional biomass.
- They are convenient for transportation, storage, and disposal of residues.
- The briquettes provide a uniform shape, which aids in handling and usage.
- Their use helps reduce indoor air pollution, contributing to improved air quality.

Non-waxed wood briquettes have an average heating value of 17.91 MJ/kg, while waxed briquettes have a higher average heating value of 28.89 MJ/kg. In an experimental study conducted on a domestic wood stove, both types of briquettes, whether waxed or non-waxed, exhibited similar combustion efficiency. The average combustion efficiency for both types of briquettes was determined to be 74% [112]. Two primary methods for briquetting exist: low-pressure and high-pressure. However, the high-pressure technique, which involves applying high compaction pressure and temperature, proves especially efficient in producing briquettes characterized by enhanced durability and higher energy density. A range of machines, such as the screw press extruder, roller press, and piston press (either mechanical or hydraulic), are employed for briquetting. Securing adequate financing is pivotal for the success of briquetting operations. Furthermore, assessing economic viability is essential, considering that the objective of briquettes is to function as sustainable alternatives to current fuel sources [113]. Fig. 15 indicates the available places for briquette production in Bangladesh and the number of machines.

The process of compacting biomass or crops is known as Densification/Briquettes technology. This technique involves applying varying levels of pressure to biomass residues to form solid biomass fuel particles. Various machines such as extrusion devices, hydraulic piston presses, screw presses, piston-type machines, roller press machines, and pallet presses (ring & flat die) are utilized to create briquettes or pellets by exerting appropriate pressure [114–116]. The quality of these briquettes/pellets is influenced by factors such as strength, mechanical durability, moisture content, calorific values, and density. These factors play a crucial role in handling, storage, and transportation of solid biomass fuels [25,26]. Binders, including substances like molasses, cassava, starch, corn, bio solids, gelatin, and microalgae, are employed to enhance the strength or solidify crushed biomass residues during the densification process [27]. Table 12 shows the comparison of different types of densification/briquetting technologies. During the densification of biomass residues, the moisture present in the raw materials or residues undergoes a transformation into steam under elevated pressure. This process results in the hydrolysis of lignin and hemicellulose, breaking them down into lower-molecule carbohydrates, sugar polymers, lignin products, and various other derivatives. These products, generated within the machine's die through the application of heat and pressure, serve as adhesives, effectively binding the particles together [28].

6.4. Pyrolysis

Pyrolysis is a heat-driven process that facilitates the breakdown of biodegradable materials, resulting in the formation of carbon-rich solids known as biochar, condensable liquids referred to as bio-oil, and non-condensable gases. This thermal decomposition occurs in an O_2-free environment [123]. Biomass pyrolysis primarily involves the utilization of wood chips or agricultural residues derived from lignocellulose biomass as the raw materials [124]. Studies on the mechanism of real biomass pyrolysis predominantly focus on determining the kinetic parameters associated with the overall thermal decomposition processes or exploring the distribution of pyrolysis products from various types of biomass [125,126]. In Table 13, different types of Pyrolysis techniques are shown.

Table 11
Different gasification technologies and their operating conditions [104–109].

System Configurations	Operational Conditions								
	Moisture content (%)	LHV of gas (MJ/Nm^3)	Fuel Size (mm)	Reaction temperature (°C)	Tar (g/Nm^3)	Gas exit temperature (°C)	Ash melting point (°C)	Carbon conversion efficiency	Ash content (%db)
Updraft gasifier	60	5–6	<51		30–150	200–400	>1000	Higher	<15
Downdraft gasifier	25	4.50–5	<51	1090	0.02–3.0	700	>1250	Higher	<5
Circulating Fluidized Bed	<55	4.50–13	<6		4–20			Higher	<25
Entrained Flow Bed	<15	4–6	<15	1990	0.01–4	>1260	>1250	Higher	<20
Bubbling Fluidized Bed	<55	3.70–8.40	<6	800 to 1000	3.70–61.90	800–1000	>1000	Higher	<25
Rotary Klin	No problem	17.30	Any size	>1450		500	No problem	Higher	<40
Moving grate	<60	5.57	<200	1000	0.01		>1200	>90%	<20

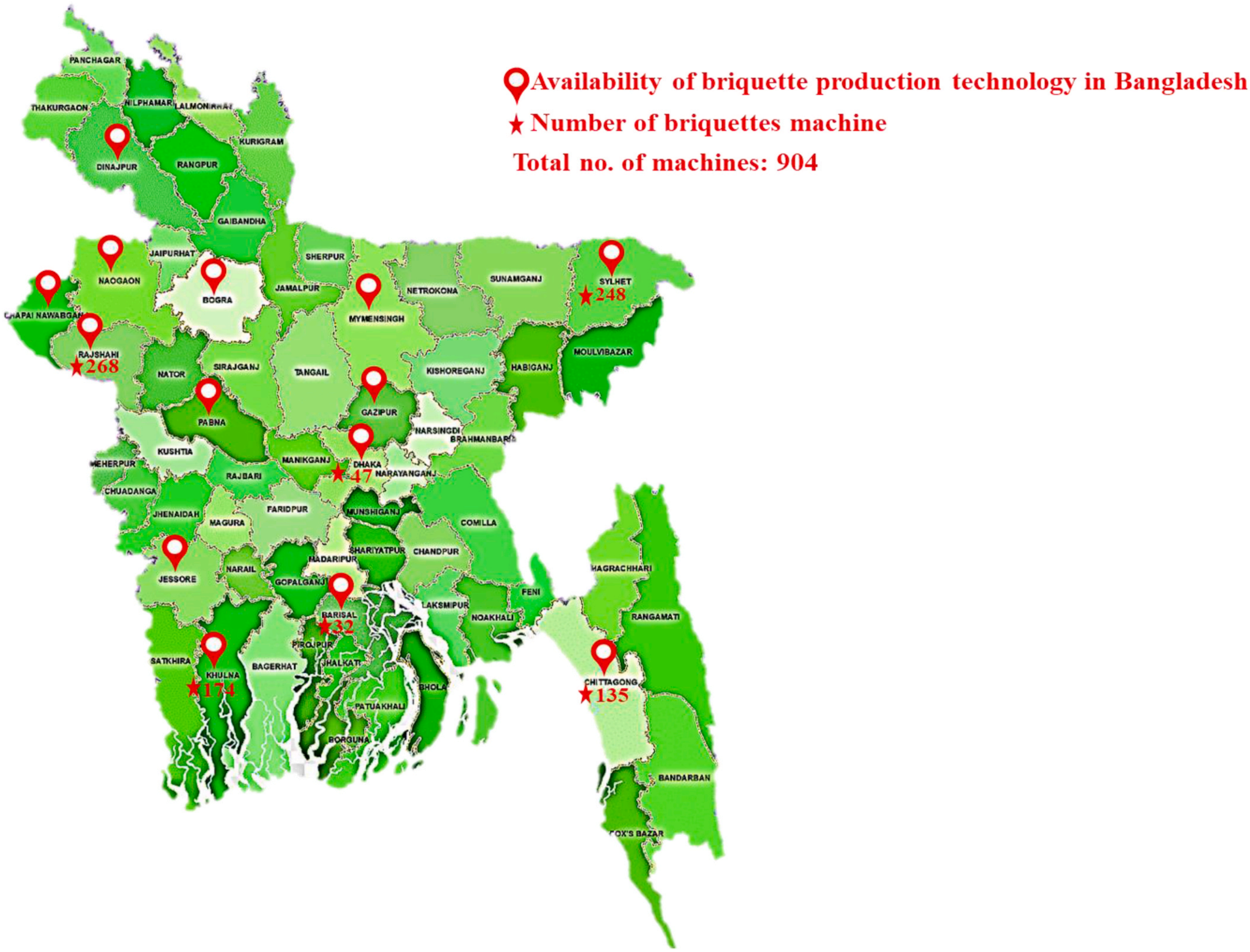

Fig. 15. Available places for briquette production and number of machines [117].

Table 12
Different types of densification/briquetting technologies and their comparison.

Comparing parameters	Screw extruder/ press	Piston pump/ press	Roller mill/press	Pellet mill/press
Requirement of binders	Not required	Not required	Required	Not required
Shape	Cylindrical	Cylindrical	Generally elliptical (relies on shape of die)	Cylindrical
Particle size (mm)	2–6	6–12	Less than 4	Less than 3
Optimum moisture content of the raw material (%)	8–9	10–15	10–15	10–15
Wear of contact parts	High	Low	High	High
Output from machines	Continuous	In Strokes	Continuous	Continuous
Power consumption (kWh/ton)	36–150	37–77	29–83	16.40–74.50
Density of biomass solid fuel (briquettes/pellets) (g/cm^3)	1–1.40	1–1.20	0.60–0.70	0.70–0.80
Maintenance	Low	High	Low	Low
Combustion performance of biomass solid fuel (briquettes/ pellets)	Very Good	Moderate	Moderate	Very good
Suitability in				
(a) **gasifiers**	Suitable	Suitable	Suitable	Suitable
(b) **co-firing**	Suitable	Suitable	Suitable	Suitable
(c) **biochemical conversion**	Suitable	Suitable	Suitable	Suitable
Homogeneity	Homogeneous	Not Homogeneous	Not Homogeneous	Homogeneous
Pressure type	High Pressure	High Pressure	Low Pressure	
References	[118–117]	[118–122]	[113,115,117]	[113,115,117]

Table 13
Different types of Pyrolysis techniques.

Conversion technology	Process condition	Product yield (wt%)			Reference
		Liquid	Gas	Solid	
Fast pyrolysis	Atmospheric pressure, small particle size (<3 mm), short residence time (0.5–2s), moderate temperature (400–550 °C) in absence of O_2	65–75	13–25	12–19	[123, 124]
Slow pyrolysis	Low heating rate, moderate temperature (350–750 °C), atmospheric pressure, long residence time in absence of O_2	30-50 in 2 phases	15–30	30–60	[125]
Intermediate pyrolysis	Moderate temperature (<500 °C), moderate vapor residence time (4–10 s) and atmospheric pressure	45-55 in 2 phases	15–30	30–60	[126]
Flash pyrolysis	Rapid heating (<.5s), very small particle sizes(<.5 mm), temperature (400–1000 °C)	60–70	10–15	15–25	[127, 128]
Vacuum pyrolysis	Moderate temperature (300–500 °C), pressure below atmospheric (<50 kPa)	45–60	17–27	19–27	[129, 130]
Ablative pyrolysis	Moderate temperature (450–600 °C), atmospheric pressure, particle size <3.5 mm	60–80	6–10	12–20	[131]

6.5. Biomass conversion technology in Bangladesh

Bangladesh is blessed with biomass resources including agricultural residues, animal manure, municipal solid waste, and forest residues which can be utilized to generate electricity and heat by adopting conversion technologies like anaerobic digestion, biomass gasification, biomass briquette, and pyrolysis. Anaerobic digestion occurs in an oxygen-free environment with the help of microorganisms to convert biomass, especially animal manure and human excreta into biogas. The potentiality of utilizing AD technology in Bangladesh is regarded as exalted because Bangladesh is an agro-based country having a huge potential of biomass resources and temperatures ranging from 4 to 40 °C which is the ideal temperature for biogas technology. It has been estimated that 1 kg of chicken droppings can produce about 0.07 m^3 of biogas; 1 kg of cattle dung can produce about 0.04 m^3 of biogas whereas 1 kg of human excreta can produce 0.05 m^3 of biogas [132]. In FY 2021–22, approximately 56734000 livestocks can produce waste of around 77298696.25 tons/year which is equivalent to the production of biogas of around 3.09 billion m^3. The total production of biogas in Bangladesh from cattle dung during the FY 2021-22 is around 3.09 billion m^3 in which only cow dung contributing 2.7 billion m^3 of biogas. Furthermore, the poultry feces can produce waste of around 13711042.50 tons/year which is equivalent to the production of biogas of around 0.95 billion m^3 in which the chicken dung only contributes of around 0.79 billion m^3 of biogas in FY 2021–22. Besides, the MSW and agricultural residues can be effectively utilized to produce the biogas.

Biogas is a clean and cheap fuel that is produced from biomass resources with the help of AD conversion technology and this technology requires a biogas plant. The first biogas plant in Bangladesh was installed in 1972 at Mymensingh. However, Bangladesh has only about 65317 biogas plants with an efficiency of 85% and has a potential of about four million biogas plants. Biogas plant can also be installed at any household in Bangladesh where cow dung or poultry feces are available. Table 14 presents the summary of biogas plant installed by different organizations in Bangladesh.

Biomass briquetting is another energy conversion technology which compresses agricultural residues, wood and increase the energy density. Bangladesh started working on this technology in early 1980s and the development of this technology was carried out by BRRI. Recently, Rice husk is used for making briquette by BRRI which provides 20% better efficiency. At present, Bangladesh is operating 1000 briquetting machine although Bangladesh has huge biomass residue to run more than 18000 briquetting machines. Fig. 15 shows the districts wise biomass briquetting machine in Bangladesh. Biomass briquetting is now utilizing in tea stalls, restaurants, and student housing for the better combustion in Bangladesh. Bangladesh is not still well familiar with the thermochemical decomposition (pyrolysis) of organic matter under the temperature of 430 °C in the oxygen-free environment [133]. However, “Radiant Renewable Energy Ltd.” has established a horizontal axis rotary type pyrolysis plant having a capacity of producing liquid oil around 9 ton/day consists of two units at Kainzanul, Vawal Mirjapur, Gazipur, Bangladesh and also intensive research on producing alternative liquid fuel from orgsanic waste through pyrolysis has been conducted by Rajshahi University of Engineering and Technology (RUET) since 2000. On the contrary, biomass gasification is a new established conversion technology in Bangladesh. Gasification requires the biomass resources including agricultural residues, animal manure, municipal solid waste, and forest residues as feedstock and Bangladesh are blessed with those resources. The first commercial biomass gasification plant at Kapasia, Gazipur in Bangladesh was installed by IDCOL which has a capacity of 250 kW production of power. In Table 3, total 2.08 Mt of rice husk residues produce in Bangladesh in FY 2021-22 and a rice husk gasification plant having a capacity of 200 kW has been installed by LGED at Dinajpur. Recently, IDCOL is giving fund for installing 400 kW rice husk gasification plant at Chilar ong, Thakurgaonsadar, Thakurgaon. The total cost estimated for this project around BDT 64.25 million [150].

7. Improved Cooking Stoves

In rural areas, cooking is commonly carried out utilizing conventional methods like chulha, while in urban areas, current practices such as induction cooktops and LPG burners are more prevalent. Chulha primarily employ biomass fuels such as wood logs, crop residues, and cow dung. However, utilizing biomass fuels for cooking leads to the

Table 14
Summary of biogas plant installed by different organizations in Bangladesh [117].

Organization	Type of system	Number	Capacity (cft/day)
IDCOL's partner	Domestic biogas plant	26311	42–170
GS	Family biogas plant	7000	120–420
BRAC	Family biogas plant; power generating unit	3664	120-420; Each of 800 Wp
LGED	Family biogas plant; community biogas plant	3000	120-420; up to 2000
IFRD of BCSIR	Phase-I; phase-II	22334	100-200; 120-420
Others	Family biogas plant	3008	120–420
Total	–	65317	

release of diverse pollutants, including soot, haze, dust, black smoke, black carbon, fine particles, and ultrafine particle. These by-products contribute to environmental pollution and pose health risks, including respiratory diseases. To minimize both environmental pollution and respiratory illnesses, it is crucial to optimize fuel utilization by reducing pollution and maximizing heat production. Enhanced biomass cooks stoves elevate thermal efficiency, cooking duration, and fuel consumption efficiency. The water boiling test illustrated advancements in burn rate, thermal efficiency, and specific fuel consumption in comparison to the conventional three-stone cook stove. This enhancement led to yearly energy savings of 2.20 GJ [134]. Studies conducted by the IFRD have revealed that the effectiveness of conventional mud cooking stoves, prevalent in Bangladesh, is notably low, varying between 5% and 15%. Yet, the adoption of efficient cooking stoves, furnaces, and boilers holds the potential to conserve a substantial amount of biomass resources. Enhanced stoves incorporate distinctive elements, including a chimney for swift kitchen smoke expulsion, a sealed structure for prolonged heat retention, and a well-crafted potholder to optimize heat transfer from the fire to the pot's base. Government-sponsored programs, facilitated by the IFRD, are actively engaging in the pilot-scale dissemination of these upgraded cooking stoves, promising fuel consumption savings ranging from 50% to 70% compared to conventional stoves [135]. In Table 15, classification of stoves with their advantages and disadvantages are shown.

The primary source of solid biomass, mainly woody biomass, is directly acquired from forests and often transformed into charcoal. The

Table 15
Classification of stoves with their advantages and disadvantages.

Classification of Stoves	Stoves	Popular types of stoves	Advantages	Disadvantages	Ref.
Classification based on the use of technology	Three stone fires	•Not available	•Simple design •No special material, tools, and skills are required for construction. •No cost	•High fuel consumption •High CO and PM25 emissions •Low thermal efficiency of about 20%	[137]
	Built-in stove	•Chullah •Angithi •Haroo	•Simple and easy design •Less radiation loss due to enclosed fire •Less fuel consumption	•Incomplete combustion •High CO and PM_{25} emissions •Low thermal efficiency of about 29%	[138]
Classification based on combustion type	Direct combustion Rocket stove	•Stove Tec •Side Feed Fan Stove •Gusto Wood Flame Stove	•Better thermal efficiency •Less CO emissions of about 86% as compared to traditional stoves • Less fuel consumption	• Wood must be extremely dry and thin • Requires much maintenance	[139]
	Gasifier/forced draft stove	• Turbo Stove • Phillips Stove • Oorja Stove • Champion Stove • Vesto Stove • Karve Stove • Sampada	• Quickly heated • Lighter weight • High thermal efficiency of 84% as compared to traditional stoves • Low CO emissions	• Economically unaffordable • Slow to ignite • Fuel specific	[140]
Classification based on construction materials	Mud stove	• Anagi • Improved clay stove • Rocket mud stove • Mud stove by Escorts Foundation • Parvati	• Inexpensive • Less fuel consumption	• Prone to insects and weather damage. • Need high maintenance • Less life span of about 2 years only	[141]
	Ceramic stove	• Mogogo • Maendaleo • Lakech charcoal stove • Gyapa • New Lao stove • Uhai • Ceramic Jiko	• Burn at high temperature • Better durability • Better insulation.	• Costly and more difficult to construct than a mud stove • Need high maintenance • Limited flexibility for different pot sizes	[142]
	Metallic stove	• Vesto • Philips Natural Draft Stove HD4008 • Bukhari • Vikram • Harsha Magh	• Quick heating • Lighter weight • Portable • Needs little maintenance	• Prone to corrosion • Risk of burns • High cost	[143]
	Cement stove	• Astra • Priya • Mirt • Roi – et • Laxmi.	• Easy installation • Simple design • Low Cost	• High fuel consumption • High CO and PM_{25} emissions • Low thermal efficiency of about 11%	[142]
Classification based on chimney	Chimney stove	• Astra • Uganda 2 –pot • Patsari • Justa • Ecostove • Onil	• Better combustion • Reduced IAP • Emissions reduction from kitchen (~99%)	• High cost • Blockage of chimney • High fuel consumption	[144]
Classification based on portability	Portable stove	• Uthaao challah • Gasifier stove • Rocket stove	• Quickly heated • Lighter weight	• Not efficient in harsh weather • Could not use in fire ban areas • High emissions	[140]
	Fixed stove	• Abhinav • Akash • Alok • Uganda 2 –pot • Patsari • Grihlaxmi	• Reduce IAP about 67% • Less fuel consumption • Better combustion	• Low thermal efficiency of about 20% • Need high maintenance • Take more time to cook	[145]

charcoal and firewood are extensively utilized as cooking fuel in developing nations. However, beyond firewood and charcoal, solid biomass fuels can also be produced from agricultural and forest residues, gaining significant popularity. For instance, agriculture generates an estimated 140 billion tons of biomass residues annually, a quantity comparable to 50 billion tons of oil (UNEP, 2009). Cookstoves have the capability to combust a diverse range of solid biomass fuels, including crop waste, dung, wood, charcoal, briquettes, pellets, coal, and woodchips [136]. A summary of the factors affecting biomass energy conversion technologies and the corresponding energy output is given in Table 16.

8. Steps from government of Bangladesh and NGO's

8.1. Infrastructure development company limited (IDCOL)

IDCOL, a governmental body founded on May 14, 1997, significantly contributes to the extensive implementation of biogas plants in Bangladesh. In 2006, IDCOL commenced a collaborative program with 30 organizations aimed at establishing household biogas plants. As of July 20, 2023, a cumulative total of 61134 small-scale biogas plants and 10 large-scale biogas plants have been erected nationwide under the National Domestic Biogas and Manure Program (NDBMP) [149]. The program received support from the Government of Bangladesh, SNV-Netherlands's development organization, and Kfw. Total capacity of 10 large biogas plants is 1800 kWp. Biogas plants serve a dual purpose, providing cooking gas and producing organic fertilizer for crops and fishponds. This initiative effectively reduces the reliance on biomass fuel for cooking. As of February 2023, IDCOL has financed the construction of more than 65317 biogas plants across Bangladesh in collaboration with its partner organizations. IDCOL offers financing for biogas plants with gas production capacities ranging from 1.20 to 25 m^3 per day, catering to the needs of both households and mid-sized dairy and poultry farms. Two models of biogas plants are currently financed by IDCOL: brick-cement based plants and pre-fabricated bio digester-based plants. The program's impact is significant, saving approximately 63000 tons of firewood annually, valued at BDT 42 Crore, and reducing the consumption of 56000 tons of chemical fertilizer, valued at BDT 124 Crore, by producing 390000 tons of organic fertilizer. Furthermore, the program contributes to the reduction of 252000 tons of CO_2 emissions per year [150].

Table 16
Factors affecting of biomass conversion technology and energy output.

Biomass conversion Technology	Parameter	Energy output (Solid, Oil and Gas)	Ref.
Anaerobic digestion	pH Temperature Moisture content Hydraulic retention time C/N ratio	Gas	[86]
Biomass Gasification	Condition and system configuration Feedstock particle size Temperature Pressure Catalyst Gasification Agent Bed materials	Gas	[146]
Biomass Briquetting	Homogeneity Particle's size Moisture content	Solid	[114]
Pyrolysis	Reactor Conversion techniques Temperature Pressure Moisture Contents	Solid, oil and gas	[147]
Improved Cooking stoves	Types of stoves	Solid	[148]

8.2. Grameen Shakti

Founded in 1996, Grameen Shakti (GS) is a private company with a robust presence, encompassing 46 grameen centers and a workforce of 130 engineers operating in 50000 villages as part of their renewable energy initiative. In 2005, GS embarked on an independent biogas program, collaborating with other organizations alongside. Teaming up with IDCOL and conducting its own initiatives, GS has overseen the construction of approximately 35000 biogas plants, offering technical and financial support for electricity generation through biogas. Furthermore, GS launched its Improved Cooking Stoves (ICS) program in 2006, achieving successful installations of approximately 583982 ICS units nationwide. As of 2023 they installed 950000 ICS which reduces carbon emission 890000 TCO_2 [151].

8.3. Bangladesh council of scientific and industrial research (BCSIR)

BCSIR, a government research organization, has been actively involved in renewable energy technology research. Their focus on biomass research began in 1973, and they were instrumental in patenting the concept of Improved Cook stoves (ICS) in 1978. Later, the IFRD was founded as a separate institute within BCSIR in 1980. In recent surveys, BCSIR has successfully disseminated around 300000 ICS during phases I and II, and they plan to distribute an additional 28000 stoves in seven districts as part of phase III. BCSIR's commitment to renewable energy extends to their biogas program. They initiated the project titled "Mitigation of carbon emission and extension of alternative energy usage through dissemination of biogas plant and improved cook stove," funded by the climate change trust fund under the ministry of environment and forest, is a significant effort by BCSIR. As a component of this initiative, BCSIR has successfully implemented 22334 domestic biogas plants. Furthermore, there are upcoming plans to establish an additional 2800 new domestic biogas plants across seven districts, involving collaboration with seven distinct agencies [152]. Besides these organization LGED, BRAC, and RSF are actively involved in promoting domestic biogas plants and improved cook stoves across Bangladesh.

9. Economic analysis

The implementation of biogas plants in rural areas has emerged as a viable and beneficial alternative energy source, providing various health and environmental advantages. Although Bangladesh possesses significant resources for biogas production, its energy production from biogas is still in its early stages. The goal of this study is to investigate the economic aspects of domestic-level biogas plants and identify the correlation between biogas plant functionality and different influencing factors. To achieve this, 300 biogas plant owners were interviewed from fifteen Upazilas in Bangladesh, selected through a two-stage random sampling method. The findings of the study revealed that the introduction of a biogas plant could generate USD 294.80 per year for a family based on partial budgeting analysis. The cost-benefit analysis indicated that small-sized biogas plants (USD 143.07 per year) were the most profitable, followed by large-sized biogas plants (USD 142.17 per year). When considering discounted cost-benefit analysis, medium-sized biogas plants proved to be the most advantageous investment, with small-sized biogas plants as the next viable option. The average Net Present Value (NPV), Benefit-Cost Ratio (BCR), Payback Period (PBP), and Internal Rate of Return (IRR) for Biogas plants were found to be USD 1629.11, 1.77, 2.93, and 48% with subsidy, respectively, and USD 1525.25, 1.77, 3.75, and 43% without subsidy.

Furthermore, the study demonstrated the economic benefits of a biogas plant in Bangladesh through carbon trading measurements. Additionally, the analysis of the functional efficiency of biogas plants revealed that plant owners with higher education, appropriate training, and support from skilled masons and follow-up services ensured the optimal operation of the biogas plant [153,154].

10. Challenges and benefits

Biomass facilities in Bangladesh present a dual perspective, encompassing both obstacles and advantages, as the nation endeavors to tackle its energy requirements in an environmentally conscious manner. These facilities harness organic materials, agricultural residues, and various biomass sources to produce sustainable energy, necessitating a thoughtful examination of multiple factors during their establishment.

- A notable challenge encountered in the setup of biomass facilities lies in the requirement for suitable technology and expertise. Bangladesh must invest in advanced biomass conversion technologies to effectively harness energy from its available biomass sources.
- Furthermore, a deficiency of skilled personnel may impede the smooth operation and maintenance of these facilities, necessitating training programs and capacity-building initiatives as viable solutions.
- Environmental concerns form another significant challenge. Mismanagement of biomass resources could lead to deforestation and the loss of biodiversity. To counteract these adverse impacts, responsible sourcing and sustainable harvesting of biomass become imperative. Additionally, ensuring proper waste disposal and the treatment of residues resulting from biomass conversion processes is essential to prevent pollution.
- The financial aspect of establishing biomass facilities also poses a hurdle. The initial investment required for infrastructure, technology, and equipment can be substantial. To attract private investments and facilitate the expansion of biomass projects, financing mechanisms and incentives from the government and international organizations become indispensable.
- Policy support and regulatory frameworks play a pivotal role in promoting biomass energy adoption in Bangladesh. Well-defined and supportive policies can incentivize industries and individuals to invest in biomass facilities and adopt sustainable practices. Strengthening the legal framework and providing financial incentives, tax breaks, and subsidies are crucial in encouraging the transition towards biomass-based energy solutions.

Despite these challenges, biomass facilities offer numerous benefits to Bangladesh.

- The primary advantage lies in the utilization of renewable resources, reducing the nation's reliance on finite fossil fuels and contributing to climate change mitigation. Biomass energy also presents a decentralized energy solution, empowering local communities and fostering rural development.
- Moreover, biomass facilities create opportunities for income generation and job creation in both rural and urban areas. Activities related to biomass feedstock collection and processing can generate employment, particularly in remote regions with limited job opportunities. The revenue generated from biomass energy can significantly contribute to local economic development.
- In the realm of waste management, biomass facilities play a pivotal role in transforming agricultural residues and organic waste into valuable energy products. This not only mitigates environmental pollution but also promotes the circular economy by effectively utilizing waste materials.
- Additionally, biomass facilities strengthen energy security by diversifying the energy mix. They provide a reliable and stable energy supply, mitigating the nation's vulnerability to fluctuations in global fuel prices.

In summary, addressing the challenges associated with biomass facilities in Bangladesh requires strategic planning, investments, and supportive policies. The advantages they offer in terms of renewable energy, waste management, job creation, and energy security make them a promising avenue for sustainable development in the country. Leveraging these advantages and overcoming challenges can lead Bangladesh towards a greener and more sustainable energy future.

11. Conclusions

The main goal of this research was to offer a comprehensive review of the biomass energy resources accessible in Bangladesh for achieving sustainable development goals. By considering the nation's geographical position, energy circumstances, and environmental factors, biomass stands out as a promising energy source in comparison to other alternatives for generating energy. Key biomass sources in Bangladesh include agricultural residues, waste from animals and poultry, municipal solid waste, and forest residues have been highlighted and the key outcomes are revealed as follows:

- The electricity demand in Bangladesh is increasing day by day and estimated that it will reach around 33708 MW in 2030 from 6454 MW in 2010. It is difficult to meet the demands of only relying on fossil fuels and so the need for alternative solutions to generate electricity from biomass is mandatory.
- The current contribution of renewable energy sources in Bangladesh is around 967.37 MW in which the majority around 733.38 MW comes from solar energy and the combination of biomass and biogas contributes only 1.09 MW but biomass resources in Bangladesh has the potential for generating more energy by utilizing the resources properly.
- The existing biomass resources in Bangladesh including agricultural residues, animal manure, municipal solid waste, and forest residues have the potential to produce huge amounts of energy in the form of heat and electricity.
- In Bangladesh, agricultural residues are generated from crops such as rice, maize, wheat, coconut, vegetables, jute, and sugarcane. Rice holds the primary position among all crops and the production of rice has been estimated at around 38145192 Mt in FY 2021-22 which was 37607756 Mt in FY 2020–21. Agricultural residues contain energy of around 852.32 PJ which is equivalent to 236.77 TWh of electricity generation and Rice straws and rice husks are produced from the rice which contains energy of around 458.56 PJ and 29.63 PJ respectively.
- The animal manure is produced from cattle, goats, buffaloes, and sheep. In FY 2021–22, approximately 56.73 million livestock produced 77298696.25 tons of waste whereas 375.65 million poultry produced 13711042.50 tons of waste which contains energy of around 315.74 PJ and 83.29 PJ respectively. However, a total of 432.38 million livestock and poultry produce 91009738.75 tons of waste that contains energy of around 399.04 PJ which is equivalent to 110.84 TWh of electricity generation.
- MSW consists of food, plastic, forest residues, vegetables, paper, plastics, leather, rubber, textiles, and other flammable materials. An urban and rural region in Bangladesh generated around 27521747.20 kg/day and 15480982.80 kg/day of MSW waste in 2022 which contain energy of around 71.78 PJ and 40.38 PJ respectively. The total energy contained in MSW waste of around 112.16 PJ which is equivalent to 31.16 TWh of electricity generation.
- Forest residues refer to the remnant of wood and trees. In Bangladesh, a total of 17.44 Mt of forest residues possesses an energy of around 210.64 PJ which is equivalent to 58.51 TWh of electricity generation.
- The existing biomass resources in Bangladesh possess around 1574.16 PJ of energy equivalent to 437.28 TWh of electricity in which agricultural residues, animal manure, municipal solid waste, and forest residues contain 852.32 PJ, 399.04 PJ, 112.16 PJ, and 210.64 PJ of energy respectively.

- The study has also discussed the available conversion technologies and their operating conditions in Bangladesh including anaerobic digestion, biomass gasification, biomass briquette, and pyrolysis to produce biofuel for harnessing the energy in the form of heat and electricity.
- Recently, Bangladesh has a biogas plant of about 65317 and has a potential of about four million biogas plants. The biogas plants can be used to produce around 3.09 billion m^3 of biogas by utilizing the livestock waste through the anaerobic digestion process in which cow dung waste contributes around 2.70 billion m^3 of biogas production. Furthermore, the waste of poultry feces can be utilized to produce biogas of around 0.95 billion m^3 in which chicken dung contributes of around 0.79 billion m^3 of biogas production.
- At present, Bangladesh is operating 1000 briquette machines to compact the biomass residues especially rice husk to make the fuel for better combustion. Bangladesh is filled with rice husk residues and estimated that around 2.08 Mt of rice husk has been produced in FY 2021–22. However, a rice husk gasification plant having a capacity of 200 kW has been installed by LGED and IDCOL is also financing for installing rice husk gasification plant of capacity 400 kW for utilizing the rice husk to convert into power, heat, syngas etc.
- The contribution of government bodies, NGOs, and different organizations including IDCOL, Grameen Shakti, BCSIR, BRAC, LGED, and RSF has been highlighted to promote domestic biogas plants and improve cook stoves across Bangladesh.
- Finally, economic aspects, benefits, and challenges are presented properly related to biomass conversion technologies.

A comprehensive evaluation of Bangladesh's potential for biomass energy conversion provides a crucial route to achieving sustainable development objectives. The nation can concurrently address energy security, economic growth, and environmental sustainability by utilizing abundant biomass resources, which is in line with important goals delineated in the Sustainable Development Goals. The incorporation of biomass energy solutions represents a game-changing tactic that puts Bangladesh on the path to a more robust and sustainable future.

CRediT authorship contribution statement

Md. Golam Kibria: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Utpol K. Paul:** Writing – original draft, Visualization, Validation, Investigation. **Ashik Hasan:** Writing – original draft, Visualization, Data curation. **Md. Shahriar Mohtasim:** Writing – review & editing, Visualization, Validation. **Barun K. Das:** Writing – review & editing, Methodology. **Monjur Mourshed:** Writing – review & editing, Supervision.

Declaration of competing 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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