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Techno-economics and environmental sustainability of agricultural biomass-based energy potential

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HIGHLIGHTS

- Mathematics, engineering, economics and environmental modeling explored renewable energy.
- Techno-economics and environmental sustainability validated the proposed methodology.
- Bioenergy-based electricity could supply 88% of the national energy demand of Bangladesh.
- A case study was provided as a proof-of-concept (PoC) to validate the approach.

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ABSTRACT

This paper explores the viability of utilizing agricultural biomass-based energy potential, employing mathematical, engineering, and economic modeling techniques. Moreover, the potential of a biogas-based co-digestion (CD) system, integrating its techno-economic performance and environmental sustainability in terms of electricity generation, has also been studied. In this investigation, the categorization of 25 different plant species into two groups: arable field crops (AFCs) and horticultural plants (HPs), was performed. Data was collected during the 2021-–2022 cropping season in Bangladesh from various sources, including literature reviews, governmental, and non-governmental organizations. The findings revealed that the available agricultural biomass residues, totaling 1,02,585.75 KT, have the capacity to generate 1,33,815 million m^3/year of biogas. This energy potential corresponds to 291,125.85 TJ/year or 9231.60 MW of electricity, which can fulfill 88% of the national total energy demand. In terms of levelized cost, the proposed approach is more competitive and shows a greater promise compared to other technologies. Furthermore, it demonstrates environmental friendliness by reducing CO_2 emissions by 156 tons at a cost of $7/ton while earning $1092 annually from the potential carbon-credit market. This approach presents a potential solution to address Bangladesh's energy crisis. The payback period of the system ranged from 2.93 to 3.75 years, with and without the inclusion of a slurry, respectively. The recommended methods hold significant promise for meeting national energy demands. A case study was provided as a proof-of-concept (PoC) to validate the approach. This study is the first of its kind, providing valuable insights into the renewable energy potential in Bangladesh. The results will assist policymakers in formulating sustainable energy policies.

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1. Introduction

Energy is critical to economic progress and improving the standard of life. Electricity demand in Bangladesh has risen exponentially in recent decades because of accelerated urbanization and industrialization [76]. Bangladesh heavily relies on its abundant indigenous natural gas for power generation, constituting 89% of the country's power needs. The remaining power is sourced from coal, liquid fuel, and hydropower. Renewable energy contributes a modest 2.5% to the total energy requirement ([60]; [3]. Globally, 16% of energy is derived from renewable and nuclear power, with the majority, 84%, coming from fossil fuels (FFs) [22]. Due to the continuous depletion of FFs and the associated ecological and environmental problems worldwide [96,98], it is crucial to explore alternative renewable energy resources. Bangladesh is actively investigating renewable energy sources, focusing particularly on solar panels and biogas plants [42].

Bangladesh, as an agriculture-centric nation, holds vast potential for implementing biogas technologies. The country generates a substantial amount of crop residues (CRs) in rural areas, including agricultural and horticultural residues. In these rural areas, households heavily depend on these residues, such as twigs, straw, leaves, and husk for animal feed and cooking fuel, constituting 98.3% of biomass energy consumption [56,100]. Despite widespread use, the conversion efficiency of CRs is notably low, leading to significant unutilized or wasted portions, as observed by Alatzas et al., [6]. Their findings suggest that excessive residue removal from the soil adversely impacts fertility and agricultural productivity in the long term. This overuse creates a shortage of essential nutrients. Properly managing leftover CRs presents a considerable challenge [55,99], contributing to a significant environmental burden on society. The incineration of crop residues has significant adverse effects on both human health and the environment. Studies indicate that in-situ burning of CRs in Asian countries contributes to over one-third of total biomass burning [83]. The release of particulates (PM), including PM_{10} and $PM_{2.5}$, along with greenhouse gases (GHGs), further contributes to environmental pollution [25,84,93]. The increasing energy demand, diminishing fossil reserves, sustainable CRs management, and pollution from conventional fuel consumption have sparked interest in biomass for sustainable energy generation in Bangladesh. The literature contains similar case studies [21,25,75,82,85] that explore the utilization of CRs for energy production and discuss the environmental issues associated with their excessive use. Limited literature provides a comprehensive methodology for assessing CRs harvesting and supply, considering sustainability criteria. Studies on CRs potentials yield varied results due to a poor understanding of determining factors, leading to simplistic assumptions in quantification. Notable international studies evaluating sustainable CRs removal, such as Ozturk and Bascetincelik [72], Huda et al. [46], Portugal-Pereira et al. [74], Batidzirai et al. [16], Amante et al., [8] and Usmani [95] serve as good examples. However, most studies only assess part of the supply chain or overlook economic feasibility. Cyranka et al. [29] employ a methodology for the economic bioenergy potential of various CRs in Croatian counties, considering critical sustainability criteria and incorporating supply chain economics up to the final conversion facility.

Biomass utilization for electricity generation has seen increased adoption worldwide. Famoso et al. [35] and Yang et al. [98] highlighting its potential as a renewable energy source and an effective waste management solution. The choice of biomass is driven by recent advancements in conversion technologies, environmental benefits, improved energy security, increased employment, rural development, and the restoration of degraded lands, potentially enhancing biodiversity [53]. Compared to other renewable energy sources, biomass is often more economical due to lower capital investment and per-unit production costs [4].

Various techniques exist for producing diverse biofuels like bioethanol [4,53,75], biomethane [101,105], and biohydrogen [98], using crop residues as raw materials. Prasad et al. [75] identified two commercially viable technologies for biomass-based electricity production: 1) Biomass gasification coupled with an internal combustion engine, and 2) anaerobic digestion (AD). AD, recognized as an environmentally friendly approach, contributes to GHGs balance and is

Nomenclature

kWh	Kilowatt-hours
MWh	Megawatt-hours
BkWh	Billion kilowatt-hours
MT	Million tonnes
KT	kilo tonnes
TJ	Terajoules
MW	Megawatt
Mtoe	Million or mega tonnes of oil equivalent
MHU	Mann-Whitney U
HRT	Hydraulic retention time
LPG	Liquid petroleum gas
IDCOL	Infrastructure development company limited
IEA	International energy agency
EIA	Energy information administration
SREDA	Sustainable and renewable energy development authority
FFs	Fossil fuels
BE	Biomass energy
HHs	Households
AD	Anaerobic digestion
AFCs	Arable field crops
HPs	Horticultural plants
ARs	Agricultural residues
ED	Energy demand
GHGs	Greenhouse gases
CD	Co-digestion
BBS	Bangladesh bureau of statistics
GAR	Gross agricultural residue
RPR	Residue-to-product ratio
RRF	Residue recovery factor
SAF	Surplus availability factor
CP	Crop production
M	Moisture content
TBP	Theoretical biomass potential
TEP	Theoretical energy potential
AEP	Available energy potential
RDF	Residue dry matter
RVS	Ratio of volatile solid
LHV	Lower heating value
LCoE	Levelized cost of electricity/energy
LCoB	Levelized cost of biogas
CHP	Combined heat and power
CSTR	Continuous stirred tank reactor
$C_{O\&M}$	Operation and maintenance cost
Cf	Fuel cost
NCF	Net cash flow
IRR	Internal rate of return
CDM	Clean development mechanism
CRs	Crop residues
ARs	Agricultural residues

a cost-effective technology in rural contexts [60]. Previous literature lacks a clear and systematic process for assessing agricultural residues' potential and their conversion to electricity through the AD process ([40,52,76,77,96]; [17,43,68,96]).

A potential solution for reliable, economical, and environmentally sustainable energy could involve establishing small, decentralized biomass power plants near residue sources ([64,72]; [1,12,92]). However, the economic feasibility of such plants needs confirmation, and the viability of agricultural residue as a bioenergy source requires further study. Considering these issues, the present study aims to develop a standardized technique for evaluating the economic aspects of agricultural residues (ARs) in power generation, specifically through anaerobic digestion (AD) for AFCs and HPs. While biogas has diverse applications, such as cooking, heating, and lighting, our primary focus is on electricity generation due to limited availability in rural areas and global/local policies promoting rural electrification. Using this methodology, we compile data and estimate the power generation potential of ARs, validated through a case study in rural Bangladesh.

Our proposed methodology is supposed to give an accurate estimate of the CRs' energy potential. This study incorporated the engineering and techno-economic relationship between the theoretical and practical total biomass potentiality while considering affordable and clean energy (SDG 7). The recommended methods hold significant promise for meeting national energy demands. A case study was provided as a proof-of-concept (PoC) to validate the approach. This study is the first of its kind, providing valuable insights into the renewable energy potential in Bangladesh. The results will assist policymakers in formulating sustainable energy policies.

This paper was structured as follows: Sections 1 and 1.1 represent the background of the research and current state-of-art literature review and existing research gaps, respectively. Section 2 detailed the in-depth experimental design and a precise methodology for estimating energy potential from CRs exploring mathematics, engineering, economics, technical and environmental aspects of CRs characterization and energy potential evaluation. In addition, this section also detailed the design of anaerobic co-digestion (CD) technology for the conversion of biomass into bioenergy. Moreover, we evaluated the application of our approaches to a real-world case study incorporating a regional of area of Bangladesh as a testament of our technology by examining population and sampling procedures in this section. Section 3 addressed the critical discussion and presentation of the acquired findings, and the uncertainties associated with the present study. Finally, Section 4 provides conclusions and outlines the future scope of the current work.

1.1. Extensive literature review and identification of the research gaps

Recycling agricultural waste (CRs) is essential, aligning with circular economy principles. Additionally, unprocessed CRs can be harnessed for heat and electricity generation. Ensuring the strategic placement of processing plants is crucial, and various optimization methodologies, as discussed by Memon et al. [59], are employed to determine their optimal allocation. The evaluation of optimal waste-to-energy facility locations involves the use of both integer mathematical, engineering, and economic models [24,52,76].

The economic effectiveness of utilizing CRs is influenced by the uneven distribution of waste incinerators and landfillsSivabalan et al. [89] suggested that a fraction of CRs can be removed, adverse changes occur only with excessive removal. Some studies suggest that removing 30% to 50% of corn stover in the US Corn Belt region may not severely negatively impact the soil ([9,16,74]; [78,80,81,88]). Excessive CRs usage can impact soil properties, soil organic matter dynamics, water quality, and crop production. Similarly, the burning of CRs raises significant concerns as it releases a substantial amount of air pollutants and toxic gases, including aerosols, particulates, soot, elemental and black carbon smoke, leading to adverse effects on human health, particularly causing asthma and other respiratory disorders ([44,49,53,54]). Moreover, crop residue burning contributes to greenhouse gas emissions (CO_2, CH_4, N_2O), aiding global warming and climate change. Recognizing these issues, Zając et al. [103], conducted a study for biomass ash management. He found that the use of biomass ash as a soil amendment and fertilizer is indicated to be the most ecological and sustainable disposal method due to the mechanism of returning the macro- and micronutrients taken by plants back to the soil. To identify this issue, Mehta et al. [58] conducted a sub-regional review of crop residue management in Bangladesh, India, Nepal, and Pakistan to identify optimal solutions. In a related study, Cyranka et al. [29] investigated CRs-to-energy plants in Poland, assessing their impact on national energy security and the associated benefits of energy production.

Numerous researchers have explored the utilization of agricultural biomass for energy production. Okello et al. [71], specifically examined the potential of utilizing agricultural biomass for energy production in Poland. Their study categorized biomass utilization into three groups: vehicle fuels, electricity, and heat generation. The economic energy potential of the accessible biomass was estimated to be approximately 600 PJ, with CRs accounting for 48.7% of the total value.

Many researchers have developed and employed spatial methods to estimate biomass energy potential [95,102]. Anand et al. [9] evaluated the availability of surplus CRs and their potential for energy generation in 2018–2019, anticipated that 35.834 MT of surplus CRs could provide 42.560 TWh of energy, meeting 68.60% of total electricity demand in rural areas. Some researchers argue that due to high production costs, renewable energy might surpass fossil energy carriers in terms of expenses ([13]; [20,26,32,33,36,38,39] explores the potential of biomass gasification to address Nigeria's energy needs, with techno-economic analysis indicating 5.5 exajoules of biomass potential in 2020. Das and Hoque [30], investigated Bangladesh's biomass-based power generation potential using gasification technology, revealing higher production costs compared to other techniques. Conversely, Wu and Zhai [96] and Rahman and Paatero [77], delved into power production from CRs using digestion techniques, finding that cultivating CRs on poor land incurs high production costs, rendering their use financially unviable.

Biomass co-digestion technologies present a cost-effective alternative when compared to gasification, fermentation, and digestion methods. This technology has the potential to achieve a competitive production cost for electricity [75,82]. Hence, the anaerobic co-digestion of agricultural leftovers emerges as a promising avenue. Anastassiadou et al., [10]; Górecki et al., [41] and Bedana et al. [17] utilized a cost-minimizing transport model to optimize the allocation of rice straw among primary power plants in Punjab. The model considers their capacities and co-digestion constraints, resulting in minimized straw costs, encompassing production and transportation expenses. Their estimates suggest that CRs could account for approximately 36% of the fuel required for power generation in Punjab.

The existing literature exhibits several significant shortcomings, encompassing the absence of (i) a designed bioenergy network for converting second-generation biomass into bioenergy through anaerobic co-digestion (CD), along with its spatial distribution; (ii) an evaluation of the required biomass feedstock from crop residues, encompassing assessments of the theoretical biomass potential, theoretical energy potential, and available energy potential in Bangladesh; (iii) an integration of the engineering and techno-economic model that bridges the gap between theoretical and practical total biomass potential; and (iv) a practical validation of the models through the execution of a real-world case study as a proof-of-concept (PoC).

2. Experimental design and methodology

2.1. Experimental design

This paper presents an innovative solution for meeting the energy demand (ED) of Bangladesh by utilizing small-scale biogas plants (BPs), which are designed using an integrated evaluation methodology for renewable energy potential and its spatial distribution. The study was focused on producing biogas through the anaerobic digestion (AD) of arable field crops (AFCs) and horticultural plants (HPs) residues, rather than through direct combustion of these residues in a regional area of Bangladesh. The size of the BP digester and the gas generator capacity were determined by the annual availability of residues and the theoretical total biogas produced, respectively. To fully utilize the energy potential of agricultural residues (ARs) throughout the country, it is necessary to understand the actual amount of these residues that are available for use.

The methodology for utilizing ARs involves using AFCs and HPs residues as primary system inputs, with biogas, electricity, and fertilizer as primary outputs. In addition to assessing the levelized cost of biogas (LCoB) and electricity (LCoE) generation, the study incorporates a sensitivity analysis to evaluate how crucial assumptions and design parameters can influence the overall cost. Furthermore, the study calculates the payback period and internal rate of return (IRR) to assess the financial feasibility of the project. of the proposed technology. Environmental sustainability analysis was also conducted to avoid greenhouse gas (GHG) emissions including the ash management techniques. Fig. 1 depicts a flowchart illustrating the methodological process for satisfying electricity needs.

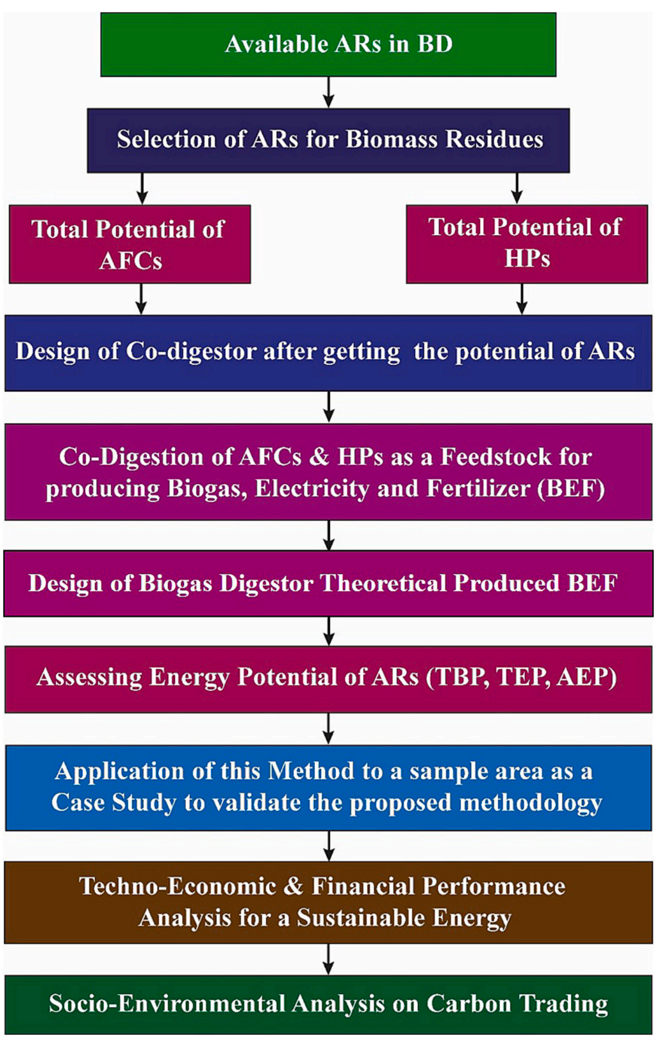

Fig. 1. Experimental design for meeting energy demand.

2.2. Methodology

2.2.1. Study area, data sources and data preparation

Bangladesh has a total land area of 130,170 km^2, with agricultural land accounting for approximately 62.8% or 90,500 km^2, and arable land accounting for 55.3% or 79,700 km^2. According to a 2019 report by the Bangladesh Bureau of Statistics (BBS), agricultural practices utilize around 52.54% of the country's land, while forests cover 17.50%. In 2020, the agricultural sector contributed 13% to the country's total GDP, and the employment rate was 38%. Notably, Bangladesh has tripled its food grain production from 10 to 34 million tonnes (MT) from 1972 to 2021 [50], despite the challenges posed by rapid population growth, urbanization, and industrialization, which are driving up ED. Each year, Bangladesh generates a significant number of ARs, used for cooking and heating in remote regions, contributing to around 60% of the country's total ED [63]. In the present study, AR potential supplies for crops cultivated in 92.7% of the gross planted area have been assessed, which is 34.90 million acres, with minor crops being grown in the remaining 6.3% of the area ([45]; [30,57,65,66]). In 2022, the total supply of ARs was estimated at 115 MT, of which 4 MT was Rice straw harvested during the rainy season, the fraction (39 MT) used as feed was not considered in the thermal balance calculation. It indicated that 43 MT ARs were used as fuel [18].

In Bangladesh, the primary agricultural crops include rice, maize, wheat, coconut, groundnut, bean, vegetables, jute, and sugarcane. These crops generate residues that can be used to produce energy. In regions where commercial gas is not available, agricultural crop residuals like straw and husk are the main source of cooking fuel for people. Other sources include dry cow dung, leaves and twigs, woods, and kitchen by-products [51]. The main data source used to determine the agricultural biomass residue potential of Bangladesh is agricultural crop statistics [50].

2.2.2. Characterization of agricultural biomass residues

The features and properties of agricultural crop residues are influenced by several factors related to crop production, including local climatic conditions and cultivation methods (e.g., harvest cutting height), crop type, and production values [2,71,94]. As a result, the properties and number of crops grown in different regions may vary. In order to calculate the yearly residue potential and energy capacity of sustainable ARs, it is necessary to consider the essential properties of the main AFCs and HPs (i.e. residue-to-product ratio (RPR), residue recovery factor (RRF), surplus availability factor (SAF), residue dryness factor (RDF), ratio of volatile solid (RVS) to dry matter, moisture (M), and lower heating value (LHV) and biogas production rate per unit of volatile solid was calculated using data from accessible literature sources. A wide range of literary sources were used to identify AFCs and HPs characteristic factors, which are provided in Tables 1 and 2, respectively. In this study, 25 plant species have been studied in two distinct groups to estimate the biomass potential in Bangladesh, which are as follows:

1. Arable field crops (AFCs): Rice *(Oryza sativa)*, Maize *(Zea mays)*, Sugarcane *(Saccharum officinarum)*, Pulses (various species, such as *Vigna radiata* (Mung bean), *Phaseolus vulgaris* (Common bean), Wheat *(Triticum aestivum)*, and *Cicer arietinum* (Chickpea), Rape and Mustard *(Brassica napus and Brassica juncea)*, Groundnut *(Arachis hypogaea)*, Cotton *(Gossypium spp)*, Sweet potato *(Ipomoea batatas)*, Vegetables (summer and winter), Betelnut (*Areca catechu*), etc.

2. Horticultural plants (HPs): Jackfruit *(Artocarpus heterophyllus)*, Litchi *(Litchi chinensis)*, Guava *(Psidium guajava)*, Orange *(Citrus sinensis)*, Lime and lemon *(Citrus aurantifolia and Citrus limon)*, Banana *(Musa acuminate)*, Papaya *(Carica papaya)*, Pineapple *(Ananas comosus)*, Water Melon *(Citrullus lanatus)*, Coconut *(Cocos nucifera)*, Wood Apple *(Malus domestica)*, Ber (Kul) (*Ziziphus mauritiana*), Mango (*Mangifera indica)*, Black Berry *(Rubus fruticosus)*, Amra *(Spondias mombin)* etc.

Table 1
Characteristic factors of AFCs residues in Bangladesh [14].

Agricultural crop residues (AFCs)	Residue types	Annual agricultural crop production (MT)	Ratio of product residue (RPR)	Moisture content (%)	Lower heating value (LHV) (MJ/Kg)	Residue recovery factor (RRF) (Kg/Kg)	Surplus availability factor (SAF) (Kg/Kg)	Residue dryness factor (RDF) (Kg/Kg)	Residue of volatile solid to dry matter (RVS)	References
Rice	Straws	32,84,710	1.76	12.70	8.8–16.0	0.60	0.80	0.87	0.54	[90]
	Husks		0.267	12.40	12.9–19.9	0.80	0.46	0.876	0.69	[48]
	Bran		0.083	9.00	13.97	1.00	0.68	0.91	0.50	Memon et al. [59]
Wheat	Straws	10,85,368	1.75	7.50	13.9–19.50	0.35	0.20	0.92	0.94	[97]
Maize	Stalk	41,16,438.46	2.00	12.00	13.8–17.60	0.60	1.00	0.88	0.50	[97]
	Cob		0.273	15.00	15.5–18.50	0.80	1.00	0.85	0.50	[2]
	Husks		0.20	11.10	17.27	1.00	0.50	0.889	0.50	[64]
Barley	Straws	12,24.2012	1.08–1.36	11.00	17.5–19.50	0.36	0.63	0.75	0.35	[48]
Millet	Straw, Cob	75,72.1342	0.30–2.00	15.00	12.5–15.50	0.10	0.04	0.36	0.32	[2]
Sugarcane	Tops	37,24,718.35	0.30	50–63	15.80	0.70	1.00	0.50	0.50	[71]
	Bagasse		0.25	50–75	8.6–15.40	1.00	0.21	0.51	0.74	[71]
Jute	Stalks	77,25,321.23	3.00	9.50	16.91	0.35	0.50	0.90	0.50	[64]
Pulses	Straws	4,08,631	1.90	20.00	12.80	0.35	0.68	0.88	0.50	[64]
Rape and Mustard	Stalks	396,594.28	1.60–1.80	45.00	17.10	0.25	0.63	0.50	0.45	[91]
Groundnut	Straws	36,72,829.34	2.30	12.11	14.4–15.20	0.35	0.64	0.87	0.50	[48]
	Husks		0.47	8.00	11.2–16.90	1.00	0.50	0.918	0.50	[48]
Cotton	Stalks	1,01,926.86	2.75	12.00	14.6–18.20	0.35	0.20	0.92	0.94	[27] a
Tobacco	Stalks	89,002.21	2.00	8.90	17.70	0.26	0.21	0.36	0.35	[31]
Sunflower	Stems and Leaves	281,920.10	0.70–3.50	19.00	13.20	0.14	0.18	0.26	0.65	[34]
Soybeans	Straw	2,93,189.32	0.76–3.50	15.00	14.90	14.9	0.60	0.17	0.74	[28]
Sesame	Trash	29,103.2	2.00	6.00	15.50	0.90	0.98	0.99	0.82	[71]
Potato	peels	1,01,678.23	0.40	20.00	16.00	0.24	0.50	0.87	0.65	[71]
Vegetables	Stalks, Sheat	45,87,323.00	0.40	20.00	13.00	0.35	0.50	0.80	0.50	[64]
	Total	**305,06,499.34**								

Table 2
The **c**haracteristic factors of HPs residues in Bangladesh [14].

Horticultural Plants (HPs)	Residue types	Annual crop production (CP) (MT)	Ratio of product residue (RPR)	Moisture content (%)	Lower Heating Value (LHV)(MJ/Kg)	Residue recovery factor (RRF) (Kg/Kg)	Surplus availability factor (SAF) (Kg/Kg)	Residue dryness factor (RDF) (Kg/Kg)	Residue of volatile solid to dry matter (RVS)	References
Jackfruits	Peels and Seeds	10,97,001.00	0.36	70.00	17.50–19.50	0.60	0.80	0.87	0.54	[5]
Papaya	Prunings	1,25,758.00	0.29–0.40	87.00	17.40	0.80	0.46	0.87	0.69	[7]
Litchi	Prunings	87,183.80	1.13–1.15	56.94	18.30	1.00	0.68	0.91	0.50	[45]
Guava	Prunings	2,43,957.00	0.19	87.00	17.11	0.35	0.20	0.92	0.94	[47]
Orange	Prunings	3739.31	0.20–0.50	35.00–45.00	17.60–18.50	0.60	1.00	0.88	0.50	[97]
Pomelo	Prunings	891.28	0.17–0.40	80.00	16.00	0.80	1.00	0.85	0.50	[7]
Lime & Lemon	Prunings	81,604.46	0.19–0.40	35.00–45.00	17.60	1.00	0.50	0.88	0.50	[11]
Banana	Stalk	8,26,151.76	2.00	85.00	13.10	0.36	0.63	0.75	0.35	[71]
Pineapple	Prunings	2,08,141.88	0.18–0.35	84.00	17.30	0.10	0.04	0.36	0.32	[94]
Watermelon	Seeds	3,45,955.44	0.20	89.00	23.47	0.70	1.00	0.50	0.50	[79]
Grapefruit	Seeds	27,557.76	0.11	20.38	17.00	1.00	0.21	0.51	0.74	[97]
Olive	Prunings	2,93,401.45	1.14–1.25	35.00–45.00	18.00–18.80	0.35	0.50	0.90	0.50	[97]
Coconut	Shells	4,02,852.00	0.12	8.00	10.60	0.35	0.68	0.88	0.50	[2]
	Husks		0.41	11.00	18.53	0.25	0.63	0.50	0.45	
Apple	Prunings, Pomace	30,009.00	0.19	40.00	17.80	0.35	0.64	0.87	0.50	[52]
Almond	Prunings	18,391.00	0.60–0.61	35.00–40.00	18–18.40	1.00	0.50	0.91	0.50	[97]
Mango	Prunings	12,14,597.00	0.39–0.46	84.00	16.80–19.20	0.35	0.20	0.92	0.94	[37]
Black Berry	Prunings	56,928.21	0.19	40.00	21.70	0.26	0.21	0.36	0.35	[5]
Plum	Prunings	14,440.20	7.00	88.86	17.30	0.14	0.18	0.26	0.65	[70]
	Total	**160,18,560.56**								

2.2.2.1. Spatial distribution of CRs throughout the Bangladesh. The spatial distribution of the CRs, more precisely the theoretical biomass potential (TBP) throughout the country was investigated by the inverse distance weighted (IDW) interpolation model with the ArcGIS (Version 10.2) software. In this study we considered divisional distribution of TPB because Bangladesh has been divided into 8 regional divisions i.e., Dhaka, Mymensingh, Rajshahi, Chittagong, Barisal, Khulna, Syllhet and Rangpur based on the different agroecological zones.

2.3. Mathematical approach for assessing ARs and its energy potential

2.3.1. Assessing the potential of ARs

This paper presents a method for calculating the gross agricultural residue amount (GAR) generated annually by using Eq. (1),

$$GAR = Y \times (RPR) \tag{1}$$

Here, the annual crop yield (t/year), denoted by Y, and the residue-to-product ratio (RPR) are related factors in this context. The RPR is influenced by several variables, including crop variety, harvesting methods, soil and weather conditions, fertilizer usage, and the time of harvesting. However, in developing countries, not all biomasses can be collected and utilized for energy production due to economic, social, environmental, and political considerations. Therefore, the theoretical net available ARs can be obtained by multiplying GAR by the residue recovery factor (RRF) and the surplus availability factor (SAF), as shown in Eq. (2).

$$AR = GAR \times RRF \times SAF \tag{2}$$

where, the RRF in kg/kg of residue and the SAF in kg/kg of residue for field or process-based residues are the key parameters involved. The total residue amount is determined by combining the quantities of both residue types (i.e., AFCs and HPs).

2.3.2. Assessing the energy potential of sustainable ARs

The initial phase of assessing energy potential for ARs involves estimating the annual quantities of ARs generated in Bangladesh. Subsequent steps involve the design of mathematical models for the calculation of the surplus biomass available to determine the BE potential of various ARs in Bangladesh is depicted in three phases, along with a flow diagram in Fig. 2, and their energy content is considered, and their power potential can be calculated using the AD process.

2.3.3. Calculation of theoretical biomass potential (TBP)

The total amount of biomass produced annually from ARs can be

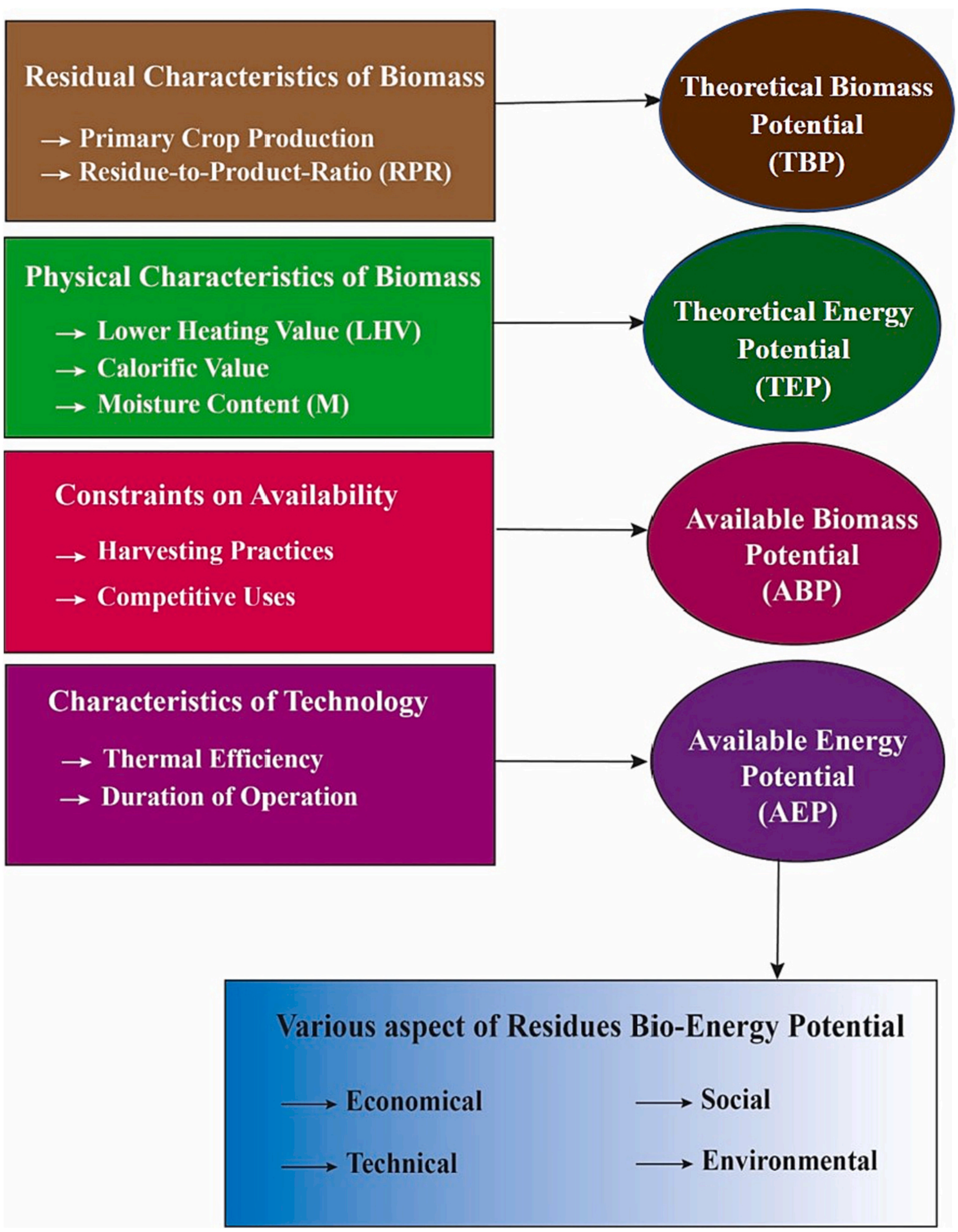

Fig. 2. Flow diagram illustrating the information necessary to determine the EP of ARs.

represented by TBP. The value of TBP is influenced by the annual production amount of the plants, as well as their RPR and moisture content. TBP of plant residues can be determined using the equation provided below, utilizing the data presented in Tables 1 and 2.

$$TBP = \sum_{i=1}^{n} CP(i) \times RPR(i) \times \left[\frac{100 - M(i)}{100}\right] \quad (3)$$

In this equation, CP (i) represents the yearly product yield in tons, M (i) indicates the percentage of moisture content. TBP (i.th) is used to determine the amount of residue obtained from the dried plant.

2.3.4. Calculation of theoretical energy potential (TEP)

The TEP of dry biomass was determined using the equation shown below [76]:

$$TEP = \sum_{i=1}^{n} AR\ (i) \times RDF(i) \times RVS(i) \times V\ (i) \times LHV(i) \quad (4)$$

where, RDF (i) represents the dry matter fraction of residues (kg/kg of residue), RVS denotes the ratio of volatile solid (VS) to dry matter (DM), V (i) indicates the volume of biogas generation rate (m^3/kg of VS) for crop species i, and LHV (i) stands for the lower heating value of BP measured in MJ/m^3.

2.3.5. Calculation of available energy potential (AEP)

In this study, the AEP refers to the amount of energy that can be produced using CRs, based on its calorific value and the efficiency of BE conversion into electrical energy through co-generation system. According to Buragohain et al. [24], gasification-based biomass power plants have an energy efficiency range of 32%. In the present study, the available energy potential (AEP) of AFCs and HPs residues was calculated using the equation shown below:

$$AEP = \sum_{i=1}^{n} TEP(i) \times SAF(i) \quad (5)$$

AEP were calculated in many literature in similar ways [13,48,62,71,72,87,97].

2.4. Economic aspects: Conversion of biomass into bioenergy

Biomass is a renewable resource but burning it for energy has its drawbacks. In contrast, AD is recognized as an economical and environmentally viable method for converting biomass into biogas, especially in rural areas. Thus, it is crucial to assess the energy potential of residual biomass via AD to optimize its use and minimize any negative environmental impacts. The cost of energy production must be assessed, and a selling price for the produced energy must be established that is both acceptable to consumers and attractive to investors, in order to ensure the biomass power sector's continued expansion and success in Bangladesh [52]. This section aims to determine the financial feasibility of decentralized biomass power from ARs. The indicators used to assess financial viability are the levelized cost of electricity (LCoE) and net present value (NPV), which help determine the feasibility of decentralized electricity generation systems.

2.4.1. Technical specifications of biogas digester: System and component description

To deliver the necessary quantity of biogas, a plug flow digester is utilized which is fed with ARs. The plug flow (or channel) digester is a cost-effective and efficient option for handling larger volumes of feedstock. These digesters make sure a consistent flow rate, resulting in increased biogas production. They are considered the most successful among various anaerobic digestion (AD) designs followed by Khan et al. [52] digestion design, accounting for 50% of installations. Temperature plays a crucial role in biogas production during the digestion process. Digesters primarily operate under mesophilic or thermophilic conditions, with optimal temperatures of 35 °C and 55 °C, respectively. The retention time of the digester also significantly affects biogas production, particularly at higher operating temperatures. For a plug flow digester under mesophilic conditions (35 °C), the recommended retention time is approximately 20 days. Maintaining a constant temperature is vital for optimizing the digestion process.

In the integrated poly-generation process described here, one advantage is the ability to maintain a temperature of approximately 35 ± 2 °C (mesophilic condition) inside the plug flow digester. This contributes to efficient biogas production. Table 3 presents the properties of the produced biogas [17,77].

The digester size V_{dig} (m^3) is determined by taking into account the annual feedstock quantity available and the hydraulic retention time (HRT) at mesophilic temperature by Rahman and Paatero [77],

$$\text{Digester volume (size)}, V_{dig} = \frac{CR \times HRT}{365} \quad (6)$$

$$\text{Capacity of Gas generator}, C_{gen} = \frac{\sum_{c=1}^{n} CR\ (c) \times RVS(c) \times V\ (c) \times LHV(c)}{365 \times H_d \times 3.6} \quad (7)$$

where, CR, RVS, V, LHV contain information from Eqs. (2) and (4). H_d represent generator operating hour per day.

Power generation from produced biogas annually E_{annual} (kWh/year) can be determined by-

$$E_{annual} = C_{gen} \times 0.24 \times 365 \times H_d \quad (8)$$

where 0.24 is electric efficiency factor.

2.4.2. Techno-economic model assumptions

The viability and the economic potential and analysis of the ARs based biomass AD can be evaluated in terms of the following indices:

2.4.3. Capital investment cost

The overall cost of biogas production is significantly influenced by the investment required for the digester and gas engine. The capital expenses associated with small gas engines suitable for biogas utilization, vary from one region to another. To find the capital cost equations for gas engines (1–5 kW) and bio-digesters (1.6–77 m^3), a polynomial curve fitting technique was used to analyze cost data from various markets. The resulting cost function equations are provided below.

$$\text{Cost of digester}, C_d = 0.024\, S^3{}_d – 0.41\, S^2{}_d + 40\, S_d + 241 \quad (9)$$

The above equation applies while 1.5 $m^3 \leq S_d \geq 77\ m^3$. Where C_d (BDT) is the capital cost of digester and S_d (m^3) is its size.

$$\text{Capital cost of gas generator}, C_g = 20.07\, S^3{}_g + 202.39\, S^2{}_g + 727.88\, S_g - 234 \quad (10)$$

This equation is applicable when 1 kW $\leq S_g \geq$ 5 kW. Where C_g (BDT)

Table 3
Major properties of digester input parameters.

Digester properties	Parameters
Digester type	Plug flow
Feedstock	ARs
Total solids	10–16%
Temperature	35 ±2 °C
Pressure	1 bar
Hydraulic retention time	20 ±2 days
CH_4 content	60%
CO_2 content	38–40%
Calorific values of methane, (LHV)	35.80 Mj/m^3
Calorific values of biogas	21.48 Mj/m^3
Density of biogas	1.23 kg/m^3

is gas generator capital cost and S_g (kW) is the generator size [77].

2.4.3.1. Operation and maintenance cost.

(i) Operation and maintenance cost (CO&M)

The operation and maintenance cost (BDT/y) of the digester gas engine system are given below-

$$C_{O\&M} = 0.0002\, S^3{}_d – 0.035\, S^2{}_d + 2.72\, S_d + I \quad (11)$$

(ii) Fuel cost (C_f)

To calculate the fuel price (i.e., residues) for electricity energy production, we developed a model with an equation that provides the annual fuel cost C_f (BDT per year).

$$C_f = \frac{E_{annual} \times 3.6}{n_t \bullet n_g \times 1000} C_{res} \quad (12)$$

where n_g (%) is the electric efficiency, n_t (GJ/y) is the residues heating value, and C_{res} is the residues cost per tonne (BDT/t).

(iii) Levelized cost of electricity (LCoE)

The LCoE is a commonly used tool to assess the feasibility of an energy system. To determine the LCoE in BDT per kWh, equations are used based on the biogas heating value.

$$Plant\ Capacity, P_c = \frac{E_{total}}{3.6 \times 8.76} \times n_e \quad (13)$$

$$LCoE = a.I + C_{O\&M} – R + C_f \quad (14)$$

The total annual thermal potential of ARs is denoted by E_{total} (GJ/y), while P_c (kW) represents the plant capacity. The annual electricity generation from biogas to electricity, with a conversion efficiency of around 26% for gas engines, is represented by E_{annual} (kWh/y) ([61]; [67]). Other factors include the plant capacity factor (P^{cf}), annuity coefficient of capital cost (a), capital investment cost (I) in BDT, and revenue generated from by-products (R) in BDT per year.

(iv) Annual net cash flow (NCF)

The NCF (BDT per year) represents the discrepancy between the annual revenue (REV) and the operation and maintenance cost ($C_{O\&M}$) of the BP, i.e.,

$$NCF = REV - C_{O\&M} \quad (15)$$

2.4.3.2. Net present value (NPV).

The financial feasibility of a project is determined by whether its NPV is positive or not. The greater the net present value, the more profitable the project. When the NPV of a project is zero, it is considered to have reached its break-even point [74]. The formula for calculating NPV is given by the equation below.

$$\text{NPV} = \sum_{i=1}^{n} \left[NCF \times (1+i)^{-1} \right] - I_0 \quad (16)$$

2.4.3.3. Internal rate of return (IRR).

The IRR is the discount rate factor at which the NPV equals zero. If the IRR (%) exceeds the discount rate, the project is viable [77]. The IRR is calculated using the following formula:

$$IRR = \sqrt[1]{\frac{NCF}{I_0}} - 1 \quad (17)$$

2.4.3.4. Payback period.

The payback period is the time it takes to recover a project's investment. The net present value of all benefits (NPV_B) equals the net present value of all costs (NPV_C) at this moment (Sobamowo and Ojolo, 2018). It can also be described as the time required to recover the initial investment in the project.

$$\text{Payback period} = \frac{I}{NCF} \quad (18)$$

2.5. Population and sampling procedure for the application of ARs data

The sample size for the studied area was determined through discussions with NGOs and by using the widely accepted equation by Bedana et al. [17]. The sample size (n) was chosen to yield a 95% precision level in statistical interference. The sample size was calculated to be 82,695 households (HHs) with an average of 5 family members per household, using Eq. (19) with a precision rate of 5%. This method was used to calculate residue potential and determine the financial sustainability of electricity production.

$$N = \text{P}\,(1 - \text{P}) \left(\frac{Z}{e}\right)^2 \quad (19)$$

Data on annual crop production in the study area were collected through a local survey of all HHs. The HHs estimated their crop production, and this data is presented in Table 4 for 2022. This sampling procedure was chosen to size a biomass-based representative power system from ARs. During the energy and mass analysis, the digester was designed to fulfill the requirements for cooking gas and/or electricity generation throughout the day. Additionally, a sensitivity analysis was conducted to account for uncertainties in assumptions and important parameters.

3. Results and discussion

In Bangladesh, during the 2021–2022 cropping period, the energy potentials (EP) of ARs were calculated using the proposed approach. To satisfy the ED of the countryside HHs, a methodical strategy was initially employed in a regional district of Bangladesh to assess the sustainable ARs at the national level. The suggested approach was then used in a case study to confirm the methodology and show in-depth economic viability.

3.1. Data application and potential of ARs

3.1.1. AFCs biomass and EP

In the year 2022, the field harvested 54,950.21 KT of agricultural crops in Bangladesh. Additional information on the production of these crops and the residues obtained can be found in Table 5 and Fig. 3. The total TBP of biomass obtained as a dry substance has been calculated to be 102,585.75 KT. Among the crops, rice had the highest dry biomass residue from field production at 70683.01 KT, followed by jute at 23753.82 KT, and maize at 9775.76 KT. Rice straws, husks, and bran had TBPs of 53,308.93, 8426.19, and 2721.04 KT dry mass, respectively. Similarly, maize stalks, cob, and husks had estimated TBP values of 6957.28, 917.29, and 702.84 KT of dry mass, respectively.

Rice straw, jute stalk, and maize stalks were the most significant AFCs in Bangladesh. The TBP obtained from vegetable stalks and sheaths was 1440.87 KT of dry mass. Millet had the lowest TBP at 1.05 KT, followed by barley straws with a TBP of 0.11 KT. To follow that, the total energy potential (TEP) of all ARs was determined to be 488,053.45 terajoules (TJ). The range of values obtained from the calculations using the data from Table 1 can vary widely due to factors like geographical location, crop yield value, and harvesting method. For instance, the energy potential of rice straw can range from 1,547,116.68 to 1,862,107.20 TJ, depending on the minimum or maximum values of these characteristics. The EP for rice, jute, and maize residues were found to be 1,969,638.46, 911,069.08, and 414,682.85 TJ, respectively.

Table 4
Annual agricultural crop production of Debidwar Upazilla, Cumilla, Bangladesh [14].

AFCs (MT)	Rice	Wheat	Barley	Maize	Pulses	Oil Seeds	Sugar Crops	Cotton	Jute	Groundnut	Vegetables	Total
	1848.00	687.00	15.00	571.00	57.00	463.00	370.00	862.62	2175.00	82.00	382.00	7512.62
HPs (MT)	Banana	Pineapple	Mango	Jackfruits	Papaya	Litchi	Coconut	Lemon	Amra	Blackberry	Watermelon	Total
	393.00	111.00	2252.00	1910.00	240.00	26.44	587.00	290.00	337.00	153.00	339.00	6638.44

Barley and millet have the lowest theoretical EP of 3.8 and 0.57 TJ, respectively. Agricultural biomass residues have various uses, such as animal feeding, bedding, burning for pruning, and generating electricity from a mixture of dung and straw. Field residues left after harvest can also be used to improve soil quality by providing organic material, water retention, and erosion control. The available energy potentials (AEPs) of AFCs were calculated to be 220,890.92 TJ. Among these crops, Rice (837,233.31 TJ), Jute (363,517.81 TJ), and Maize (124,822.29 TJ) were ranked in the top three in terms of energy potential. On the contrary, Millet and Barley had the lowest available energy potential with values of 0.1 and 0.23 TJ, respectively.

3.1.2. HPs biomass and EP

Based on the data in Table 2, horticultural farming in Bangladesh produced 7680.12 KT of crops in 2022. Table 6 provides information on the types of HPs produced in the country, as well as their pruning values. The top three HPs in terms of dry biomass were coconut shells and husks (1505.87 KT), jackfruit (1419.28 KT), and olive (1222.17 KT). The TEP of all orchards pruning residues was estimated to be approximately 287,068.97 TJ, while the AEP was found to be 70,234.93 TJ. Coconut, jackfruit, and olive were found to be the most significant pruning residues from Bangladeshi fruits, with a TEP of 78,936.39 TJ and an AEP of 21,748.89 TJ. Fig. 4 summarizes the total TEP and AEP values obtained from residues in the AFCs, and HPs cultivation in Bangladesh, expressed as mean values, lowest and maximum values of residual properties.

3.2. Total agricultural biomass and EP

The annual agricultural production of Bangladesh was 46,525,059 MT and the net available sustainable ARs for the cropping period 2021–22 was determined to 110,265.87 KT in the cultivation of field was calculated as 102,585.75 KT dry mass in AFCs (Table 5), and 7680.12 KT dry mass in HPs (Table 6). Using the Eqs. 1–5 and the characteristics of the residues from various sources of literature (Table 1 and 2), EP of ARs were calculated as shown in Table 6 and 7. TEP of these biomass residues was estimated to be about 488,053.45 TJ (11.65 Mtoe) from AFCs and 287,068.97 TJ (6.85 Mtoe) from HPs, respectively. The AEP of ARs for AFCs was estimated around 220,890.92 TJ (5.28 Mtoe), and for HPs farming was about 70,234.93 TJ (1.68 Mtoe).

Table 7 presents the calculation of the overall available agricultural biomass and the resulting net available energy potential. Using Eq. (8), we determined the total TEP from ARs in Bangladesh for the cropping season 2021–22, which amounted to 9868 million m^3/year by utilizing 110,265.87 KT of potential biomass. Among the total AEP of ARs, we found that the residues from AFCs and HPs had the potential for producing 220,890.92 and 70,234.93 TJ/year, respectively. The national ED for the fiscal year 2021–2022 was 25,700 MW, with a per-person electricity consumption of 422 kWh (FY2021) [23]. The annual AEP from ARs was calculated to be 9231.6 MW.

3.2.1. Spatial variations of TPB throughout the Bangladesh

The spatial distribution of CRs in Bangladesh has been presented in Fig. 5 which demonstrated that Dhaka and Khulna divisions had highest TPB density for both AFCs and HPs. Although Chittagong is suitable for HPs but showed less dense production of TPB in terms of AFCs. Rangpur and Mymensingh divisions have moderate density of both AFCs and HPs. However, Barisal and Sylhet divisions showed much less AFCs and HPs cover. (See Fig. 6.)

3.3. Application of the proposed technology in a regional area of Bangladesh as a proof-of-concept (PoC)

In this study, the suggested approach was used to assess the potential and economic viability of the residue for energy generation in the Debidwar Upazila of Cumilla district in Bangladesh. The Upazila contains 82,695 HHs, each with an average of 5 family members. Using an AD and a small-scale gas generator, we turned the annual waste of these HHs into biogas and power based on the data presented in the methodology. We determined the digester volume by using Eq. (6), which considers 20 days for Hydraulic Retention Time (HRT) and 10% of the total feedstock volume for one HRT.

In Eq. (8), we assumed an operational duration of 10 h per day for the gas generator (H_d). The average electrical load per HHs, which includes lighting, cooling, and entertainment, was determined according to the consumption of 3 energy-efficient bulbs, 2 fans, a radio, mobile chargers, and a television for 6 h per day. All the devices were supposed to run at the same time, according to our presumption. The total ED of HHs in the village was calculated to be 74.43 MWh per day, and the cooking gas demand was 2271.78 Nm^3 per day per person and electricity demand for other purposes (farm and productive activities) was 389.48 MWh per day [69]. Table 8 lists the system's primary technical specifications in short, and we calculated the annual production of electricity using equat7ion 7 and 8 depending on the biogas's reduced heating value (23 MJ/m^3).

The proposed system is designed to supply biogas simultaneously for cooking and electricity generation. The digester is anticipated to have sufficient capacity to hold daily residual product gas. With an engine load range of 100% to 40% (10% transmission loss), the gas generator runs at a partial load during the day. The engine electric efficiency varies linearly from 32% to 26% respectively (Bala and Siddique, 2009; [73]). Table 8 lists the overall energy load's estimated and calculated requirements for power, cooking gas, and biogas toward those requirements.

3.4. Techno-economic feasibility and sustainability analysis of agriculture biomass residue-based energy potential

The study highlights the significance of agricultural biomass residue-based potential of enerrgy generation to achieve a secure energy supply and sustainable growth in the near future of Bangladesh shown in Fig. 5. However, it is crucial to consider several conservation issues, such as the total amount and availability of resources, electricity and transportation costs, environmental concerns, and technology, while determining the BE potential of these CRs ([87]; [82]).

3.4.1. Technical aspects

3.4.1.1. Logistics of CRs collection. Efficiently generating energy from agricultural residues requires addressing the technical aspects of collecting and densifying biomass, as well as designing large-scale digestion systems. To efficiently harness biomass resources in rural areas, it's crucial to make CRs from the fields accessible to utility points [17]. The supply chain for biomass-based plants encompasses the collection, storage, and transportation of residue from the field to the user site. This

Table 5
Energy potential of ARs produced from AFCs in Bangladesh.

AFCs	Residue types	Theoretical biomass potential (TBP) (KT)			Theoretical energy potential (TEP) (TJ)			Available energy potential (AEP) (TJ)			Biogas production per year (million m^3)
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	
Rice	Straws	50,308.93	53,308.93	61,064.07	15,47,116.68	16,72,278.27	18,62,107.20	4,69,118.61	6,61,030.77	9,77,025.12	5700.00
	Husks	7426.19	8426.19	9618.94	3,95,831.37	2,55,165.47	4,13,355.66	1,08,697.89	1,38,189.56	1,91,416.94	314.00
Wheat	Bran	2621.04	2721.04	2990.15	40,194.72	42,194.72	46,587.60	38,012.98	38,012.98	41,772.50	517.00
	Straws	1589.65	16,39.38	1772.30	3,41,811.94	4,10,666.14	5,19,729.61	22,787.46	27,377.74	34,648.64	70.00
Maize	Stalk	5988.82	6957.28	7906.00	2,60,627.84	3,53,757.76	4,48,736.00	96,010.46	1,09,229.29	1,39,145.60	535.00
	Cob	868.40	917.29	1079.16	35,083.09	38,639.52	42,877.59	14,218.05	15,593.90	19,964.62	87.00
	Husks	622.80	702.84	790.6	18,156.33	22,286.33	25,219.72	11,138.10	12,138.10	13,653.66	45.00
Barley	Straws	0.11	0.12	0.14	2.50	3.80	4.60	0.20	0.23	0.27	76.00
Millet	Straw, Cob	1.003	1.05	1.35	0.36	0.57	0.78	0.02	0.10	0.02	150.00
Sugarcane	Top and Leaves	2.65	4.62	5.89	3359.08	5844.79	7457.15	41.98	73.05	93.21	96.00
Sugarcane Jute	Bagasse	2.65	3.98	1.32	1828.36	3826.80	1637.02	22.85	47.83	20.46	87.00
	Stalk	19,497.20	21,497.20	23,753.82	8,81,169.08	9,11,069.08	10,00,628.82	3,43,517.81	3,63,517.81	4,01,677.14	895.00
Pulses	Residue	595.40	595.4	744.25	57,271.25	61,271.25	75,589.06	7621.18	7621.18	9526.48	28.00
Rape & Mustard	Stalks	310.06	329.44	634.22	79,531.31	84,502.02	1,62,677.68	5302.08	5633.46	10,845.17	45.00
Groundnut	Straws	121.36	121.36	138.09	39,817.15	43,700.96	67,919.87	1747.71	1796.26	2098.99	15.00
	Shells	11.04	19.88	31.22	19,898.43	22,351.01	32,210.52	123.73	279.38	527.63	10.00
Cotton	Stalks	720.82	820.82	932.75	19,039.92	25,688.68	30,565.27	11,983.99	13,461.47	16,976.08	26.00
Tobacco	Stalks	300.01	312.01	342.50	28,364.52	31,364.52	53,737.12	4722.57	5522.74	6062.28	35.00
Sunflower	Stems and Leaves	0.59	1.50	2.06	469.15	1407.40	1927.95	7.81	23.45	32.13	50.00
Soybeans	Straw	66.75	187.09	361.69	59,681.90	62,524.74	71,011.23	994.69	3208.74	7016.85	42.00
Sesame	Trash	59.20	59.20	62.98	52,064.10	55,064.10	58,578.84	857.86	917.73	976.31	17.00
Sweet potato	Vines and peels	8.33	11.33	14.17	2619.10	2721.10	3401.37	100.4	181.40	226.75	20.00
Vegetables	Stalks, Sheath	1040.87	1440.87	1801.09	4,58,913.20	6,98,513.20	8,73,141.50	18,231.41	18,731.41	23,414.26	179.00
	Total	91,123.93	**1,02,585.75**	1,14,047.56	4,57,381.27	**4,88,053.45**	5,18,725.69	2,33,925.53	**2,20,890.92**	1,87,856.31	**9039.00**

logistical process significantly impacts the economic viability of biomass utilization facilities, particularly for low-density biomass fuels like rice straw, a predominant residue in the village. The costs associated with these operations vary across regions, influenced by the baling techniques employed for collection. Harvesting and transportation costs are pivotal factors affecting the energy potential for implementing bioenergy programs. The use of mechanical harvesting methods and addressing the challenge of open-field burning are essential for the viability of CRs-based power plants [87]. Additionally, biomass transportation costs depend on the quantity of available biomass and transportation distance. Geographic Information System (GIS) serves as a valuable tool for locating biomass conversion facilities to minimize electricity costs, considering all economic parameters [96]. Properly interfacing the collection system with growers' operations, providing economic incentives, and implementing new regulations can enhance cooperation for crop residue collection from the farmers.

3.4.1.2. Densification of biomass. One key factor in utilizing available biomass resources is ensuring accessibility to ARs at the point of use. However, the low energy density and bulky nature of ARs pose challenges for handling, storing, transporting, and converting them into energy. To increase the energy density of biomass, densification, briquetting technology can be a cost-effective solution. Densification increases energy density of biomass and makes transportation and storage economical [13]. National energy policies supporting the use of densified solid biofuels made from ARs, coupled with the ongoing improvements and cost reductions in briquetting technology, make it a profitable option. But careful identification of historical, industrial, geographical, and energy-related similarities must consider finding the feasibility for CRs densification plants in different regions [30].

3.4.1.3. Development of digestion system. Designing efficient large-scale biomass digestion systems requires careful consideration of numerous parameters, as detailed in Table 3 for the design of the full-scale plant. This plant is intended to operate under mesophilic conditions, with a hydraulic retention time (HRT) of 20 days, converting energy through a combined heat and power (CHP) unit into electricity and heat. The estimated power range of the CHP unit is 1 MW, with calculated efficiencies of 34.6% for electricity and 42% for thermal energy [98]. In this model scenario, based on actual laboratory results, the net available electrical energy production of the biogas plant calculated to be 571 MWh per year, showcasing the potential of ARs-based power generation. However, several issues require attention (Saleem et al., 2022). Firstly, optimizing the biogas and electricity potential, especially in terms of overall operational stability, is crucial. Co-digestion emerges as a viable option for optimization. Secondly, exploring the reuse of digestate, including practices like composting and direct application, is essential. The advantage of AD lies in creating bioenergy while retaining the fertilizer value of organic waste. Decentralized energy production in rural areas offers cost advantages in electricity distribution and transmission. AD aligns with a broader bio-refinery concept, fostering synergy between waste treatment and the production of value-added compounds. Further investigation into applying AD feedstocks back to land, directly, as digestate, after composting, or through pyrolysis to biochar, is necessary.

3.4.2. Economic assessment

3.4.2.1. Cost of energy. The cost of an energy system is determined by the capital cost of the digester and gas engine, the operation and maintenance cost of the system, and the cost of the fuel. To evaluate the feasibility of an energy system, the levelized cost of energy (LCoE) is commonly used. The proposed plant operates for 6 h per day with a capacity factor of 25%, resulting in 571 MWh of electric energy per year. The costs associated with transporting and storing the agricultural

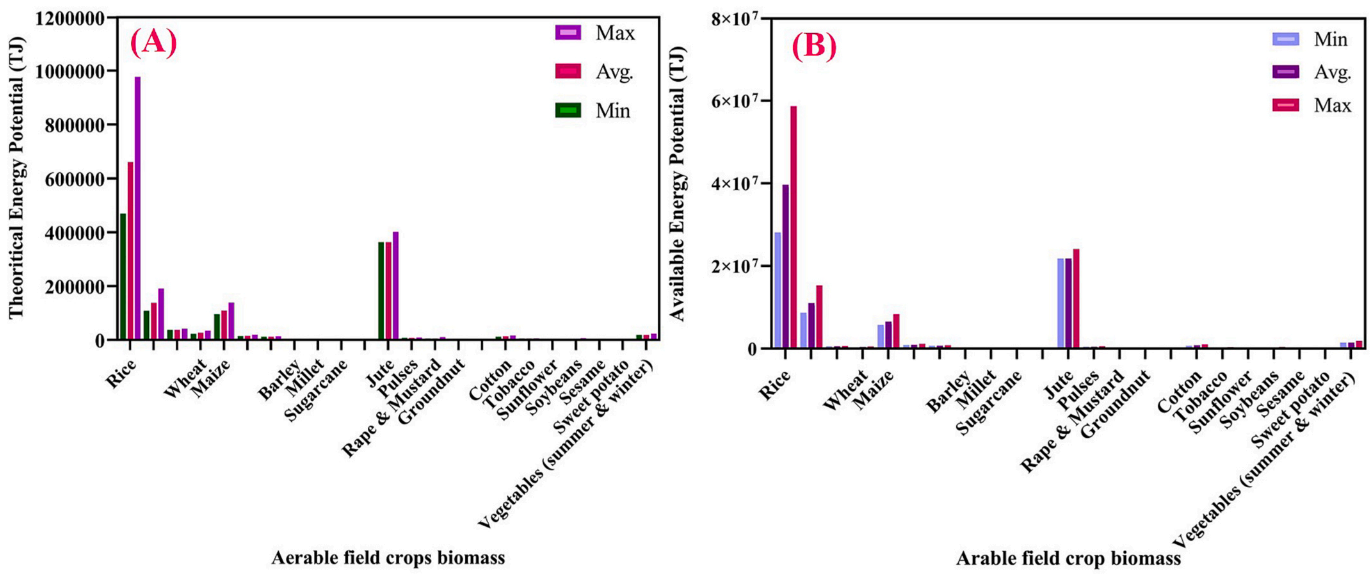

Fig. 3. Comparison of the calculated TEP and AEP for AFCs.

Table 6
Energy potential of ARs produced from HPs in Bangladesh.

HPs	Residue types	Theoretical biomass potential (TBP) (KT)			Theoretical energy potential (TEP) (TJ)			Available energy potential (AEP) (TJ)			Biogas production per year (million m^3)
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	
Jackfruit	Peels and Seeds	1318.95	1419.28	1820.61	16,538.77	17,552.68	18,605.60	2081.73	2206.82	2332.57	67.00
Papaya	Prunings	108.44	194.47	301.5	7577.98	9015.19	10,452.39	394.72	512.68	130.65	35.00
Litchi	Prunings	42.44	43.82	44.21	3603.61	4166.47	6729.33	795.04	802.08	809.11	15.00
Guava	Prunings	75.15	86.15	97.15	8422.65	9242.65	10,722.65	105.28	105.28	105.28	10.00
Orange	Prunings	200.42	381.69	590.9	605.29	1002.78	1345.90	7.56	12.53	16.82	20.00
Pomelo	Prunings	34.03	51.08	72.14	1885.77	1254.37	1342.98	48.57	81.42	114.28	18.00
Lime	Prunings	78.03	135.51	195.3	11,308.98	16,208.01	20,145.55	141.36	202.6	251.81	12.00
Banana	Peels	76.35	81.35	95.35	37,141.42	41,241.42	47,341.42	28,513.51	32,514.51	35,515.51	89.00
Pineapple	Prunings	91.16	134.22	277.27	7293.55	9037.73	14,181.91	91.16	134.22	177.27	39.00
Watermelon	Seeds	521.99	703.99	912.99	9277.93	9377.93	9477.93	1115.22	1316.22	1717.22	110.00
Grapefruit	Seeds	712.97	843.12	986.97	5540.60	8640.60	9740.60	978.25	1088.25	1209.25	12.00
Olive	Prunings	1066.7	1222.17	1381.64	12,304.80	13,072.48	14,821.60	7156.09	9161.44	11,066.43	45.00
Coconut	Shells	381.14	562.14	850.14	40,521.84	41,521.84	42,521.84	5413.52	7320.52	9531.52	56.00
	Husks	630.73	943.73	1165.73	5689.39	6789.39	8689.38	3051.11	3060.11	3071.11	87.00
Wood Apple	Prunings, Pomace	293.92	356.92	501.92	40,454.08	41,454.08	45,454.08	3548.17	5558.17	7968.17	26.00
Almond	Prunings	29.48	30.13	32.77	14,539.12	15,613.69	16,866.24	1206.73	1598.67	2202.32	15.00
Mango	Prunings	201.05	291.59	399.13	12,966.96	13,898.24	15,277.81	1412.08	1648.72	1903.47	75.00
Black Berry	Prunings	76.16	87.16	98.16	10,134.50	12,134.50	14,434.50	1135.43	1245.43	1455.43	12.00
Plum	Prunings	110.6	111.6	112.6	13,844.88	15,844.88	18,445.87	1748.06	1848.06	1948.06	86.00
	Total	6049.71	**7680.12**	9936.48	259,652.12	**2,87,068.97**	3,26,597.58	58,943.59	**70,234.93**	81,526.28	**829.00**

KT = Kiloton, TJ = Tera joule.

residues are included in the system's running costs and maintenance expenses under the presumption that the owner of the residues supplies them without charge. The LCoE for the plants with a capacity range of 1 kW to 5 kW was calculated using the cost data from eqs. (9–14) [18].

3.4.2.2. Levelized cost of biogas (LCoB). A 150 m^3 biogas plant costs around 9700 USD, covering the digester's structural building, valves, pipes, heat exchanger, accessories, and water pump. This cost takes into account local market labor and material expenses ([74,82]. To compare, a similar sized digester in Vietnam cost 9000 USD. The biogas subunit system has a total cost of USD 15,000. The production cost of LCoB can range from 0.073 USD/kWh, depending on handling costs, which can vary from 0.5 BDT/kg (i.e., 1.25 USD/ton) to 0.8 BDT/kg (i.e., 6.25 USD/ton) (Islam et al., 2021). Eqs. 9 and 10 demonstrate that the capital costs of the digester and gas engine considerably impact the total cost of generating energy. Table 9 summarizes the economic parameters for a biogas digester power plant, including all costs determined by market research and expressed in USD (2022). The capital investment payback is computed in this analysis using a discount rate of 10% over the lifespan of the technology, and a general price escalation factor of 5% has been applied (Jalil et al., 2010).

3.4.2.3. Levelized cost of electricity (LCoE). The proposed system includes an electricity generation unit as another sub-unit, and the LCoE has been calculated in the present study using data from eqs. 13 and 14. Table 9 provides cost details for the additional equipment required for the sub-unit, such as generators, H_2S scrubbers, pipes, valves, control and protection systems, distribution lines, and other assumptions. The cost of electricity per HHs is 0.053 USD/kWh, and the annual operation cost of electricity generation is estimated to be 3% of the sub-unit's

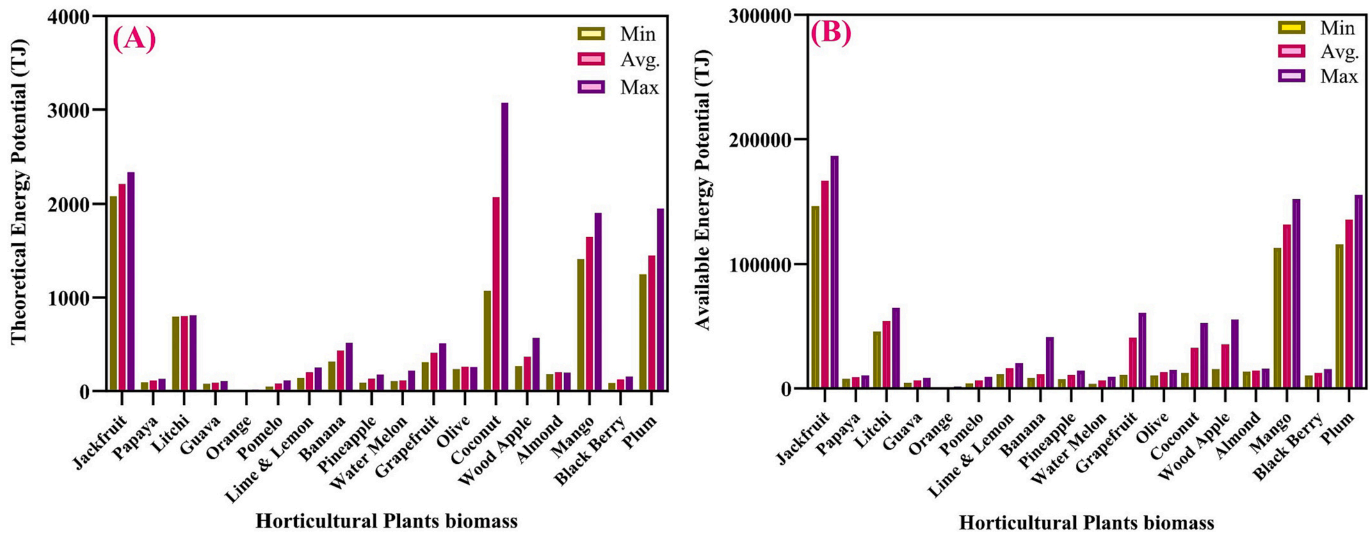

Fig. 4. Comparison of the calculated TEP and AEP for A) AFCs and B) HPs biomass.

Table 7
Total agricultural biomass and EPs.

Agricultural Crops	Annual agricultural crop production (CP) (MT)	Theoretical biomass potential (TBP) (KT)	Biogas production per year (million m^3)	Theoretical energy potential (TEP) (TJ)	Available energy potential (AEP) (TJ/year)	Available energy potential (AEP) (MW)
AFCs	30,506,499.34	1,02,585.75	9039.00	48,8053.45	2,20,890.92	7004.45
HPs	16,018,560.56	7680.12	829.00	28,7068.97	70,234.93	2227.15
Total	**4,65,25,059.90**	**1,10,265.87**	**9868.00**	**7,75,122.42**	**2,91,125.85**	**9231.60**

capital cost. The cost of supplying electricity depends on the type of generator selected. Although there are many different types of generators on the market, this study will focus on an engine made in Europe. If Chinese generators that are readily available locally are utilized, the cost of the power sub-system can be cut in half, but the system's quality may be compromised. To provide context, in Bangladesh, the LCoE production from solar PV is 0.525 USD/kWh, and from wind turbines, it is USD 0.646 USD/kWh [102]. The study conducted a sensitivity analysis of the LCoE by varying the generator capital costs from −50% to +50% using eqs. (5–11). If the generator cost increases by 50%, the LCoE can vary between 0.053 and USD 0.058 USD/kWh, relying on the biogas generation cost ranging from 0.009 to 0.03 USD/kWh. Conversely, if the generator cost decreases by 50%, the LCoE can range from 0.073 USD/kWh to 0.085 USD/kWh, depending on the biogas generation cost (Nandi and Ghosh, 2009). LCoE in this study was subjected to a sensitivity study using eqs. (5–11), where the generating capital costs were modified from −50% to +50%. If the generator cost increases by 50%, the LCoE can range between 0.053 and USD 0.058 USD/kWh, contingent on the biogas generation cost that falls within the range of 0.009 to 0.03 USD/kWh. Conversely, if the generator cost decreases by 50%, the LCoE can range from 0.073 USD/kWh to 0.085 USD/kWh, depending on the biogas generation cost.

3.4.2.4. Financial indicators (payback periods, NPV, and IRR). The proposed system's total cost of USD 33,000 was divided between two subsystems based on their outputs. With the intention of selling the energy, this assessment sought to determine whether it was feasible to produce biogas locally. The payback period, NPV, and IRR were used as indicators. The activities that generate revenue from the integrated system are detailed in Table 10. The figures used to estimate net economic gain and expected payback period were collected based on average data acquired during stakeholder interaction [87,100]. The feasibility of the project in terms of finance was assessed through calculations of payback periods, NPV, and IRR, utilizing eqs. 15–18. Two cases were considered to understand the influential factors affecting the project's financial attractiveness: Case I, where payback was calculated based solely on electricity sales revenue, and Case II, where revenue from both electricity and slurry sales were considered. Results indicated that slurry sales significantly affected the payback period, with a highly attractive payback period of 2.93 years with slurry and 3.75 years without slurry. The estimated net economic benefit and projected payback period values were based on average values collected during stakeholder consultations. NPV and IRR were calculated for a 1 kW electric plant, with electricity marketing prices ranging from 0.0327 to 0.14 USD/kWh and a 10% discount rate. NPV was found to be 1925.11 USD/kWh (with slurry) and 1525.25 USD/kWh (without slurry) at an electricity selling price of 0.053 USD/kWh, while IRR was found to be 43% without slurry sales and up to 48% with slurry sales. The production of electricity from bio wastes at 0.053 USD/kWh is promising compared to other renewable energy sources such as solar PV, tiny wind, micro-hydro, and biomass gasifier ([27]; Bala and Siddique, 2009). This study's positive results in terms of NCF, NPV, and IRR indicate the project's financial feasibility and viability. These findings further validate a previous study's results, which demonstrated that farms producing biogas and organic fertilizers were financially viable, while those producing only biogas or electricity were not economically feasible ([76]; Gojiya et al., 2019).

3.4.3. Social aspects

The production of bioelectricity will create numerous employment opportunities for the locals in terms of biomass management, plant operation, and equipment maintenance. Around 8716 people can be employed during the 18-month constructing phase of an 571 (MWh/y) biomass power project, 500 individuals can be employed full-time in the facility's operation, and 1000 people can be employed in the gathering, processing, and transporting of biomass materials [87].

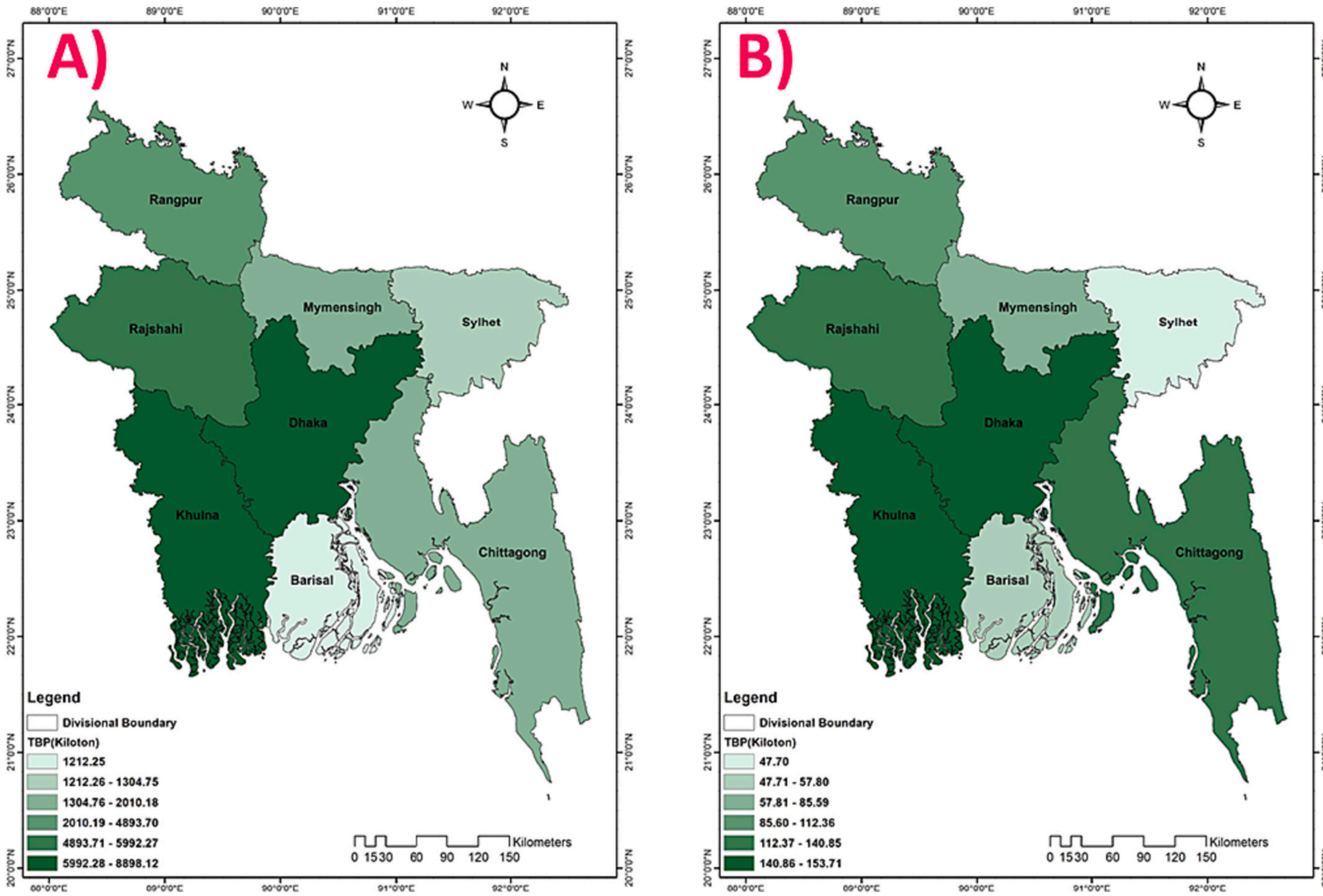

Fig. 5. Division-wise spatial distribution of TPB throughout the Bangladesh; A) TPB of AFCs and B) TPB of HPs.

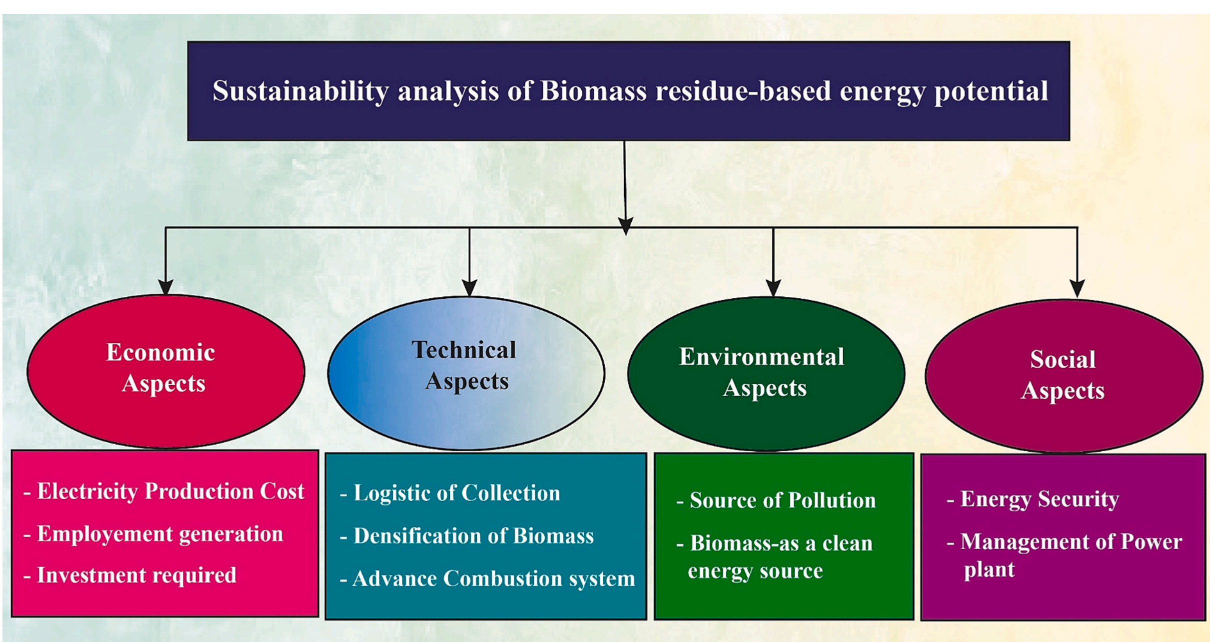

Fig. 6. Techno-economic feasibility and sustainability analysis of biomass residue-based energy potential.

3.4.4. Environmental aspects

The growing ED in Bangladesh has led to the development of FFs-based thermal power plants, which are the primary source of environmental pollution by emitting harmful gases that cause respiratory diseases in humans and endanger the existence of plants and animals [30]. Burning crop residuals in fields also produce atmospheric

Table 8
Technical parameters and key performance data of the proposed system.

Parameters	Per Households (HHs)	Unit (Total)
Number of Households (HHs)		82,695.00
Number of populations	5.00	4,31,352.00
Total HHs electricity demand (ED)	0.90 (kWh/day)	74.43 (MWh/day)
Farm ED	1.36 (kWh/day)	112.46 (MWh/day)
ED for Other productive activities	3.35 (kWh/day)	277.02 (MWh/day)
Gas (cooking purpose)	0.79 Nm^3/person/day	271.78 Nm^3/person/day
EP (thermal) from freely available ARs	230.00 (PJ/y)	19,019,850.00 (PJ/y)
Basic ED	**666,490 (kWh/y)**	**666.5 (MWh/y)**
Average electricity generation potential	**571,500 (kWh/y)**	**571 (MWh/y)**
Total amount of biomass residues		**32,244.50 KT**
TBP used in biogas		8269.00 kg/day
Daily production of biogas		**3,66,619.00 Nm^3/day**
Gas (cooking purpose)		14,645 .00Nm^3/day
Total input of biogas to the engine		2,19,968.00 Nm^3/day
Biogas engine capacity		2.29 Mwe
Engine efficiency (electric) (full load/40% part load)		45.00% /35%
Engine efficiency (thermal)		43.00%
NO_x emission		250.00 mg/Nm^3
CO_2 emission		1000.00 mg/Nm^3

Note: The aim of this hypothetical scenario is to establish a minimum level of demand for renewable energy sources.

Table 9
Techno-economic characteristics of the energy producing unit for biogas digester plant.

Specification for electricity generation	Values
Average discount rate	10.00% /y
Inflation ratio	5.00% /y
Project lifespan	20.00 years
Annual plant capacity	25.00% /y
BP construction cost	15,000.00 USD
LCoB per HHs	**0.073 USD/kWh**
Construction of biogas [a]	6750.00 (10 kWe in USD)
Pipes and valves for the plant	625.00 USD
Life span of generator	10.00 years
H_2S scrubber and moisture absorber for gas quality upgrade [b]	150.00 USD
Life span of H_2S scrubber	10.00 years
Control and protection systems	700.00 USD
Load density in HHs	200 /km^2
Distribution line	4 km/ km^2
Distribution lines cost	1300.00 USD
Transportation and installation of equipment	300 .00USD
LCoE per HHs	**0.053 USD/kWh**

a) Engine cost (Jalil, 2010) b) Scrubber cost [52].

Table 10
Annual revenue from the biomass-based energy production.

Specifications	Revenue
Electricity sales to HHs (0.05 USD/kWh)	7944.53
Electricity sale (different end uses) (0.085 USD/kWh)	9559.54
Biogas sales to the HHs (10 USD/HHs/month)	99,23,400.00
Net profit from slurry as fertilizer (24.4 USD/ton)	3345.00
Payback periods (years) (without slurry)	3.75
Payback periods (years) (with slurry)	2.93
Net present value (NPV) (without slurry)	1525.25
Net present value (NPV) (with slurry)	1925.11
Internal rate of returns (IRR) (without slurry)	43.00%
Internal rate of returns (IRR) (with slurry)	48.00%

brown clouds, the most significant source of black carbon and aerosols contributing to global warming. This also causes fog, which reduces visibility, leading to accidents and transportation delays on roads, railways, and airways. To reduce global warming and climate change, as well as to give rural populations job opportunities in the handling of biomass and the production of electricity, BE offers the cleanest technology. This involves pumping biomass power into the district's electricity grid collectively to minimize direct burning of ARs in fields and thermal energy generation from polluting coal [19]. By using this technology, emission reduction credits can be obtained, decreasing the rate of global warming. Grameen Shakti has been working on constructing 15,000 BPs since 2006 in Bangladesh [104]. According to Infrastructure Development Company Limited (IDCOL), for 2.4, 3.2, and 4.8 m^3 capacity plants, a smaller scale BPs could decrease emissions by 2.5, 3.0, and 4 tons of CO_2 [61]. According to the study, 150 m^3 BP would save 156 tons of CO_2 and earn 1092 USD/year by cutting their CO_2 emissions, respectively. The use of biomass power plants reduces GHGs emissions significantly by reducing the use of firewood and kerosene. In Nepal, for the installed plants, the BSP was able to reduce CO_2 by 4.7 tons annually, for a total of 660,000 tons (Sobamowo and Ojolo, 2018).

3.4.4.1. Sustainable management and disposal options of produced ashes from the proposed AD technologies. The open burning of CRs accounts for the majority of biomass burning which causes air pollution, smog, and human health risks [59]. The use of biomass ash as a soil amendment and fertilizer is indicated to be the most ecological and sustainable disposal method due to the mechanism of returning the macro- and micronutrients taken by plants back to the soil [103]. Numerous research on biomass ash use in road works has been conducted, with various biomass ash types being employed in various pavements and road segments. Ash can be used as a filler, fine-aggregate fraction substitute, binder supplement, or binder itself, depending on its properties. Bottom ash from biomass combustion can be used to reduce soil expansion to the same extent as lime treatment. The mixture of wheat husk and sugarcane straw ash improves soil geotechnical qualities [15]. Several research studies have described productive applications of biomass ash used in cement due to the pozzolanic qualities inherent in wheat straw ash [59]. The most frequent method of managing biomass ash is landfill disposal, which has significant economic and environmental consequences. Biomass ash has potential applications such as cement replacement in mortars, additive in synthetic aggregates, and as a pH buffer controller in AD processes for biogas production [86].

3.5. Major issues impact effective CRs management in terms economics, environment and sustainability

Effective nutrient recycling in the soil-plant ecosystem is vital for sustainable crop production. The incorporation of CRs positively influences the soil environment, affecting microbial populations, soil properties, and nutrient transformations [102]. However, the indiscriminate removal of CRs can have detrimental effects on soil organic matter (SOM) dynamics, water and wind erosion, and crop production.

While Shafie et al. [85] suggested that a fraction of CRs can be removed, adverse changes occur only with excessive removal. Some studies propose 30 to 50% of corn stover in the US Corn Belt region can be removed without severe negative impacts on the soil ([16,74]). Biomass transportation costs are contingent on the quantity of available biomass and transportation distance [76]. Ensuring adequate crop residue availability near power plants is desirable, with GIS tools used for site investigation and cost-effective transportation network planning (Calvert and Mabee, 2014; Havrysh et al., 2021).

In a recent study, Saravanan et al. [82] estimated the cost of rice straw production, harvest, and transportation using GIS, with an overall cost of approximately $25 per ton. They highlighted the predominance of manual residue harvest in parts of India. The characteristics of crop residue fuel, including moisture content, influence the choice of the conversion route. Consequently, various critical issues, such as soil health and collection practices, must be considered for the bioenergy utilization of CRs [17,96]. It is essential to evaluate the potential estimates of this investigation with these varying dynamics in mind. Additionally, the burning of crop residues poses a serious concern due to the release of air pollutants and toxic gases, causing adverse impacts on human health, especially respiratory disorders [75,82]. CRs burning also leads to GHGs emissions (CO_2, CH_4, N_2O), contributing to global warming and climate change.

4. Conclusions and outlook

The current study can be used to draw the following findings:

- Rural Bangladesh is home to a vast quantity of agricultural residues (ARs), which have significant potential as an energy source. The electrical energy potential (EEP) of ARs for the 2021–2022 cropping season in rural Bangladesh was calculated to be 9231.60 MW. This amount is sufficient to meet around 88% of the country's total energy demand (ED).
- The number of residues from field cultivation was estimated to be 102,585.75 KT dry mass in arable field crops (AFCs) and 7680.12 KT dry mass in horticulture plants (HPs). The total EP of these biomass residues was assessed to be approximately 488,053.45 TJ (11.65 Mtoe) and 287,068.97 TJ (6.85 Mtoe) from AFCs and HPs, respectively.
- The agricultural crops with the highest levels of field residuals were ranked as rice, jute, maize, coconut, jackfruit, and litchi.
- The AEP of ARs for AFCs was estimated to be approximately 220,890.92 TJ (5.28 Mtoe), and for HPs it was estimated to be about 70,234.93 TJ (1.68 Mtoe). To produce energy and use biomass as a substitute energy source, effective management of ARs is essential, which can help alleviate environmental problems. The proposed methodology involving anaerobic co-digestion (CD) is an optimal solution for meeting the ED of rural HHs in Bangladesh.
- The 82,695 Bangladeshi HHs whose demands will be satisfied by the proposed biomass-based CD system, which covered a regional rural area. The levelized cost of the two primary services, cooking gas (0.073 USD/kWh) and electricity (0.053 USD/kWh), is one of this system's major advantages.
- The analysis also showed a very attractive payback period, depending on slurry sales, of 2.93 years with slurry and 3.75 years without slurry. Additionally, compared to solar PV and wind turbines, the levelized cost per kWh of electricity from the CD system is around 12 times lower. Moreover, the proposed technology could reduce the CO_2 emissions by 156 tons at the cost of $7/ton and earn $1092 per year, respectively, from potential carbon-credit market.

Despite the socio-economic benefits of biomass-based CD systems, their success may be limited by constraints on the availability of digester feedstock, making it challenging to collect and handle the residues. Therefore, a viable business plan for this type of project, including Clean Development Mechanism (CDMs), needs to be explored further. In addition, investigating dynamic performance aspects of the system could allow for a deeper understanding of its optimization. Future research should also focus on potential institutional, financial, and societal hurdles to the adoption and spread of CD plants. Finally, field tests must be used to illustrate the notion.

CRediT authorship statement

Mst. Mahmoda Akter: Conceptualization, investigation, designed the experiments, methodology, validation, and writing the original draft. **Israt Zahan Surovy:** Conceptualization, investigation, designed the experiments, methodology, validation, and writing the original draft. **Nazmin Sultana:** Conceptualization, investigation, designed the experiments, methodology, validation, and writing the original draft. **Md. Omar Faruk:** Data curation, data interpretation, and statistical analysis. **Brandon H. Gilroyed:** Review, discussion, writing-review, and editing. **Leonard Tijing:** Validation, writing-review, and editing. **Arman:** Data curation, validation**. Md. Didar-ul-Alam:** Validation, writing-review, and editing. **Ho Kyong Shon:** Project administration, resources, funding acquisition, validation, writing-review, and editing **Sang Yong Nam:** Validation, writing-review, and editing. **Mohammad Mahbub Kabir:** Supervision, conceptualization, investigation, designed the experiments, methodology, validation, and writing-original draft.

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.

Data availability

Data will be made available on request.

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