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Exploring the Potentials of Using Household Level Biomass for Electricity Generation: A Case Study of Khulna City

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ABSTRACT
As one of the most densely populated countries in the world, Bangladesh faces an increasing demand for energy. Consequently, environmental pollution from fossil fuel burning has highlighted the need for alternative energy sources in the country. In this context, the study aims to assess the potential of household-level biomass for electricity generation in Khulna City, Bangladesh. The objective was to quantify different types of household biomass and determine their electricity generation potential. Data were collected through a survey of 186 households, categorized into low, middle, and high-income groups. Household waste, including kitchen scraps, animal dung, paper and garden waste, was measured, and its energy content was calculated using proximate analysis and higher heating value (HHV) equations. The analysis revealed that household waste generation ranged from 0.129 to 4.81 kg per day, with high-income households producing the most waste. A strong positive correlation between income level and per capita waste generation was observed ($r_{xy} = 0.787$, $p < 0.01$), which indicates that high-income individuals produce more waste daily. The study estimated a total energy potential of 7,692.04 GJ, equivalent to 2,137.69 MWh of electricity, which could contribute 8.39 % to the national grid. The findings underscore the feasibility of utilizing household-level biomass for electricity generation in urban areas. The implementation of waste-to-energy systems would not only enhance waste management practices but also contribute to the local economy. This study opens avenues for further research into optimizing biowaste conversion technologies for energy generation. It highlights the need for continued exploration of advanced methods to convert biowaste into energy more efficiently. Additionally, the study recommends increased investment in waste management infrastructure, particularly in composting, biogas digesters, and landfill gas recovery, to maximize energy recovery and support sustainable urban development.

Keywords: Renewable Energy, Household Biomass, Electricity Generation, Sustainable Urban Development.

1. Introduction

Electricity is the key to economic development for any country. Bangladesh is one of the most densely populated countries in the world, with about 1,118 people per square kilometer, and was classified as a lower-middle-income country by the World Bank in 2018 [1]. The fossil fuel reserves used for power generation in Bangladesh are depleting rapidly to meet the growing demand, and there is increasing concern about the environmental degradation associated with conventional power plants [2]. About 65% of the total electricity generation depends on natural gas, a resource anticipated to be depleted in the near future [3], [4]. In response to these challenges, the generation of power from non-conventional resources assumes greater importance. Among the various renewable energy sources, biomass conversion technologies are particularly well-suited for the production of shaft power and electricity. Bangladesh is geographically well-positioned and its strategic location provides numerous opportunities to utilize its abundant natural and human resources, including biomass. This potential establishes the country as a promising hub for renewable energy development, with the capacity to drive sustainable growth through innovations in biomass utilization, solar, wind, and other renewable energy sectors [5].

Currently, many countries around the world are using biomass to produce renewable energy [6]. Generating energy from biomass offers several advantages, including the low cost of biomass residues and higher energy conversion efficiency compared to other fossil fuel-based generation methods. As a result, this approach reduces the overall cost of electricity. Bio-energy allows for operation at multiple scales and makes it suitable for both decentralized power generation at the village level as well as for integration into national grids [7].

Khulna is the third largest city in Bangladesh and is experiencing a steady increase in population density, which is leading to a rapid rise in household waste production [8]. Household-level biomass is readily available as food waste, paper, garden waste and animal dung and represents a promising yet underutilized resource for decentralized electricity generation [9,10]. However, no studies have been conducted to explore the potential of converting household biomass into electricity in Khulna city. This study aims to investigate the potential for converting household biomass into electricity, thereby transforming waste into energy and empowering communities with cleaner, locally sourced energy. For this purpose, different types of household-level biomass produced in Khulna City were quantified and the electricity generation potential and heating value of produced household level biomass were determined.

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2. Study Area

Ward No.9, mainly the "Mujgunni" area was selected as study area (Fig.1) in Khulna City Corporation (KCC). The study area profile is provided below in Table 1.

Table 1: Study Area Profile

Area size	3.540 sq. km
Population	39542
No. of Household	9710
Average Household size	3.87

Source: BBS, 2022

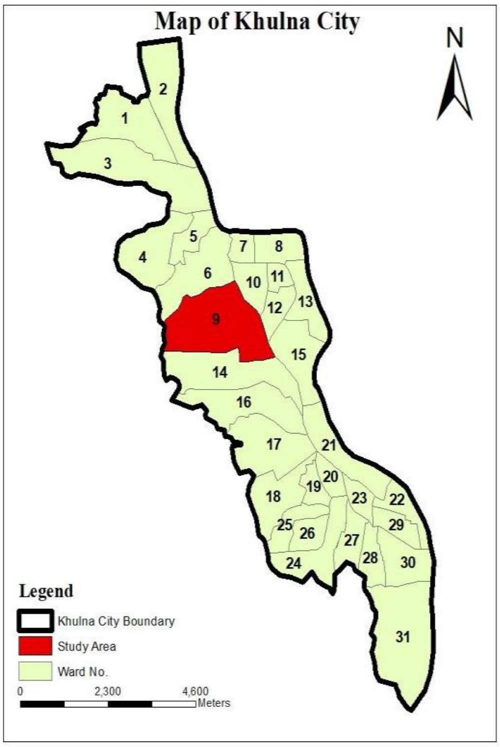

Fig. 1 Study Area

Three clusters of settlements were selected for the study to gain a comprehensive understanding of the area.

1) Mujgunni Planned Residential area as "High Income Area"
2) Mujgunni Mixed Residential area as "Middle Income Area"
3) Bastuhara Slum Colony as "Low Income Area"

3. Data Collection

Both qualitative and quantitative methods were employed to gather data. Two types of primary data were collected by surveying 1) waste generation rate from households 2) household characteristics.

The whole study area was classified into three different income groups on the basis of the household's monthly income: low income (LI) (monthly income < Tk. 20,000), middle income (MI) (monthly income between Tk. 20,000 and Tk. 40,000) and high income (HI) (monthly income above Tk. 40,000). A structured questionnaire was utilized to collect household-level data on socioeconomic factors and bio waste generation characteristics. Demographic data, including family size and education level, as well as daily waste generation rates, were collected from 62 households across each income group. Households were randomly selected from each group to participate in the questionnaire survey, resulting in a total of 186 households studied from the three income groups within the study area.

During the questionnaire survey, each household was provided with coded polythene bags to collect their residential waste. The waste from each bag was weighed and recorded, followed by segregation, where each item was weighed individually. Since data from a single day cannot provide a comprehensive view, the process was repeated for each household over 7 days, and the generation data was averaged to obtain a more representative overall picture. Waste was spread on clean plastic sheets and sorted by hand according to the established methodology [11]. Wastes were categorized into four classes- kitchen waste, wood and garden waste, paper waste and animal manure [12].

4. Methodology

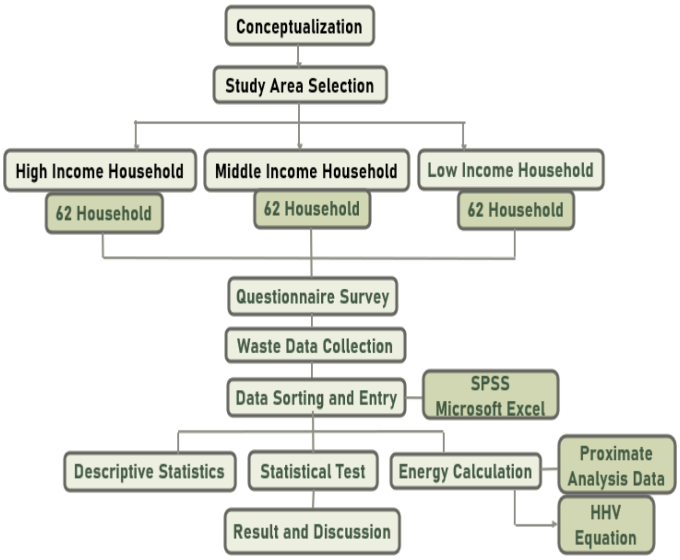

Fig. 2 Methodological Framework

The data obtained from 186 households were used to estimate the probable electrical energy that can be generated from it. The Proximate Analysis method and Higher Heating Value Calculation was used for the process. The biomass samples were physically dried prior to analysis to effectively eliminate the influence of moisture, which can reduce the actual energy content of the biomass. This is crucial because wet biomass inherently contains less usable energy due to the energy required to evaporate the moisture. Fig.2 provides an overview of the methodology.

Proximate Analysis Method:

The viability of biomass as an alternative fuel is contingent upon its energy content or heating value, which can be indirectly determined from proximate analysis data. Proximate analysis provides the weight fractions of moisture, volatile matter (VM), fixed carbon (FC), and ash content. These data can be used to calculate the heating value using empirical equations [13]. The proximate analysis results, including ash content (P_{Ash}) and volatile matter (P_{VM}), were reported on a dry basis. Consequently, the calculated Higher Heating Values (HHV) in this study represent the intrinsic energy content of biomass on a dry basis.

Higher Heating Value (HHV) Calculation:

HHV measures the total energy content of waste or biomass. It represents the amount of heat released when the material is burned completely. The HHV was calculated using an empirical equation developed by Ebeling and Jenkins [14], which correlates ash content (P_{Ash}) and volatile matter (P_{VM}) on a dry basis with the HHV. Although fixed carbon (FC) is typically a component of proximate analysis, it is not included in this equation as per the base methodology. The equation was selected due to its simplicity and prior validation in similar studies [13]. The formula for HHV depends on the composition of the waste, which was calculated based on the proximate analysis results.

Equation: $$\boldsymbol{HHV = A + BP_{Ash} + CP_{VM}} \quad (1)$$

Where, P_{Ash} = % of Ash, P_{VM} = % of Volatile Matter.
A, B, C are constants, A= 26.601, B = -0.304, C= -0.082.

By reviewing the proximate analysis data of various conventional and unconventional biomass resources in Bangladesh, along with published data from other countries with similar biomass resources, the Higher Heating Value (HHV) for each type of household biomass was calculated using Equation (1). To account for the heterogeneous nature of kitchen waste, proximate analysis was conducted separately for major identifiable components including vegetable peels and scraps, fruit peels and pulp, eggshells, leftover cooked food, coffee grounds and tea leaves, and other organic waste [15-19]. The individual ash content, volatile matter, and HHV values were calculated for each type to allow for a more nuanced representation of the energy potential. These values were then weighted based on their proportional contribution to the total biomass to determine an aggregate HHV for the waste stream.

Demographic data and bio-waste production figures were analyzed using IBM SPSS Statistics 26 and Microsoft Excel to determine which income level contributes the most to waste generation, and consequently, to the potential for waste-to-electricity generation. Descriptive statistical methods, including Pearson Correlation, were applied to explore the relationship between various factors such as income, the quantity of waste generated, family size, and the education level of family members. The findings provided insights into household characteristics and their impact on waste generation, which can be utilized for energy production. By understanding these relationships, it becomes easier to determine which households produce the most waste and, consequently, have the greatest potential for contributing to waste-to-energy initiatives.

5. Findings

Waste Generation Rate

Household daily bio-waste generation ranged from 0.129 kg to 4.8 kg, with an average of 1.49 kg per day across a sample size of 186. The waste generation patterns differed significantly across various income levels in the city. Per capita bio-waste generation was calculated by dividing the daily waste output by the number of residents in each household [20].

Table 2: Waste Generation Rate

Waste Generation Rate						
	Low Income		**Middle Income**		**High Income**	
	Kg/HH/ day	Kg/c/ day	Kg/HH/ day	Kg/c/ day	Kg/HH/ day	Kg/c/ day
Mean	0.804	0.172	1.354	0.291	3.142	0.638
Max	2.531	0.516	3.722	0.754	4.812	1.121
Min	0.129	0.034	0.343	0.068	0.732	0.156

The rate of bio waste generation exhibited a range of variability, with values ranging from 1.12 kg per capita per day to 0.034 kg per capita per day (Table 2). The mean waste generation rate in high income areas is 0.638 kg per capita per day, while in middle income areas it is 0.29 kg per capita per day and in low income areas it is 0.172 kg per capita per day. The mean values were calculated as the arithmetic average of all waste generation rates across households within each income category and the minimum and maximum values represent the range of observed waste generation rates.

Average bio waste generation in high income households has the highest quantity of 3.142 kg/HH/day (Fig.3), where middle income household has an average of 1.354 kg/HH/day and low income household has an average of 0.804 kg/HH/day. The maximum bio waste generation in high income households is 4.812 kg/HH/day, in middle income households is 3.722 kg/HH/day, and in low income households is 2.531 kg/HH/day. As high income households have a higher rate of consumption, the waste generation rate is also higher than low and middle income households.

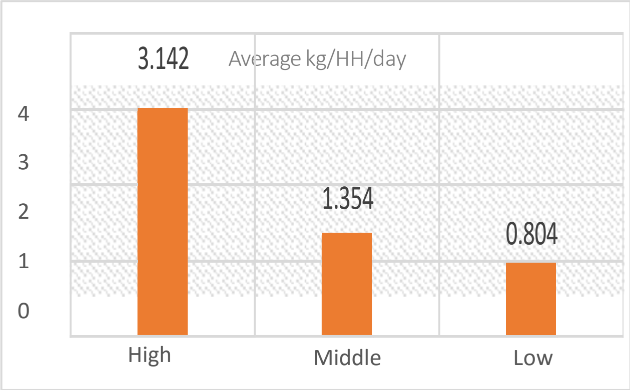

Fig.3 Average waste generation rate per HH per day

Characteristics of household bio-waste

Household waste composition varies based on factors such as socioeconomic status, cultural conditions, consumption patterns, time, and geography. Among the four main types of household bio-waste—kitchen waste, wood and garden waste, animal manure, and paper waste—kitchen waste consistently accounts for the largest portion. In high-income households, kitchen waste constitutes 81.25%, followed by paper 13.54%, wood and garden waste 4.16%, and animal manure 1.05%. In middle-income households, kitchen waste accounts for 79.33%, paper for 8.76%, wood and garden waste for 9.22%, and animal manure for 2.69%. In low-income households, kitchen waste makes up 75.67%, paper 3.56%, wood and garden waste 13.51%, and animal manure 7.26%. Fig. 4 provides an overview of the composition of biomass types in households.

In high-income households, kitchen waste is the largest contributor to bio-waste, making up a significant portion of the total waste. Paper waste follows, as these households tend to use more newspapers, books, and magazines. Wood and garden waste are less common due to the smaller yard sizes in urban areas, although some rooftop and container gardening can still be seen. Animal manure is the least produced in high-income households because urban spaces are smaller, which limits the possibility of owning animals. Only a few families may keep chickens or ducks on their rooftops, but this is not very common.

In middle-income households, the amount of paper waste is lower compared to high-income households. However, there is more wood and garden waste, as these families often have slightly larger yards or more space for gardening. Low income households, on the other hand, generate more animal manure, as they often own cows, goats, and chickens, benefiting from open yards and more space for animal rearing.

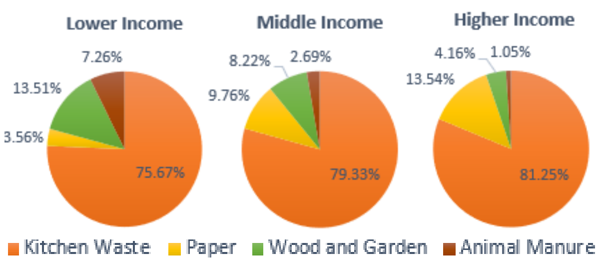

Fig.4 Compostion of house-hold biomass by waste type

Relationship between waste generation rate and socio-economic factors

The quantity of bio-waste produced in households is influenced by both income levels and household size [21]. Correlation analysis was conducted to explore the relationship between different socio-economic factors including household income level, education level, household size and the amount of waste generation.

In Table 3, we can observe that there is a strong positive correlation between income level and average per capita waste generation per day (rxy = 0.787, $p < 0.01$), which indicates that individuals in high-income groups produce more waste daily. Additionally, a strong positive correlation exists between income level and average waste generation per household (rxy = 0.698, $p < 0.05$), which suggests that high-income households generate larger quantities of bio-waste each day. Furthermore, the correlation between average per capita waste generation and average household waste generation is very strong (rxy = 0.725, $p < 0.01$), indicating that households producing greater amounts of bio-waste also exhibit higher per capita waste generation. Table 4 shows a moderately positive correlation between household size and the daily average waste generation rate (rxy = 0.664, $p < 0.01$). This indicates that as household size increases, the amount of daily waste generated also tends to rise. Table 5 indicates a positive correlation between the education level of the family (average years of schooling) and bio-waste generation (rxy = 0.350, $p < 0.05$). This suggests that families with higher education levels tend to generate more bio-waste daily.

Table 3: Relationship between income and waste generation

		Income Level	Average waste [kg/capita/day]	Average waste [kg/HH/day]
Income level	Pearson Correlation	1	.787**	.698**
	Sig. (2-tailed)		.000	.000
	N	186	186	186
Average waste [kg/capita/day]	Pearson Correlation	.987**	1	.725**
	Sig. (2-tailed)	.000		.000
	N	186	186	186
Average waste [kg/HH/day]	Pearson Correlation	.698**	.725**	1
	Sig. (2-tailed)	.000	.000	
	N	186	186	186

*** Correlation is significant at the 0.01 level (2-tailed).*

Table 4: Relationship between HH size and waste generation

		Number of family members in the household	Average waste generated [kg/HH/day]
Number of family members in the household	Pearson Correlation	1	.664**
	Sig. (2-tailed)		.000
	N	186	186
Average waste generated [kg/HH/day]	Pearson Correlation	.664**	1
	Sig. (2-tailed)	.000	
	N	186	186

*** Correlation is significant at the 0.01 level (2-tailed).*

Table 5: Relationship between education level and waste generation

		Average number of years in school	Average waste generated [kg/HH/day]
Average number of years in school	Pearson Correlation	1	.350**
	Sig. (2-tailed)		.000
	N	186	186
Average waste generated [kg/HH/day]	Pearson Correlation	.350**	1
	Sig. (2-tailed)	.000	
	N	186	186

*** Correlation is significant at the 0.01 level (2-tailed).*

Energy Generation Rate:

Table 6: Energy Generation from Each Income Group

HHV LI (MJ)	HHV MI (MJ)	HHV HI (MJ)
2234.54	2689.34	3173.76

The HHV values in Table 6 represent the total energy generation from 62 households in each income group, with a total of 186 households across the three income groups. High-income households contribute the most to energy generation, producing 3173.76 MJ from 62 households. This is due to the larger quantity of organic waste, primarily kitchen waste, generated by these households. As income levels rise, consumption increases, leading to higher kitchen waste production. However, a significant amount of energy is derived from animal manure in low income households, as even a small amount of animal waste has the potential to generate substantial energy.

Potential Energy Generation

Table 7: Waste & Energy Generation from 186 households

Sources (186 HH)	Biomass Generation (kg)	Energy Content (MJ)	Electricity Generation (kWh)
Kitchen Waste	454.60	6374.52 [22]	1772.87
Wood and Garden Waste	47.79	488.03 [23]	135.56
Paper	65.567	608.12 [24]	168.92
Animal Manure	40.45	626.97 [25]	174.79

From 186 households, a total of 454 kg of kitchen waste was collected, capable of producing 6374.52 MJ of energy, equivalent to 1772.87 kWh of electricity (Table 7), which represents the highest energy output among waste types. Additionally, wood and garden waste could generate 135.56 kWh, paper waste 168.92 kWh, and animal manure 174.79 kWh of electricity. This generated electricity could be supplied to the national grid and utilized to meet current demand.

The combined higher heating value (HHV) from high, middle, and low-income households totals 8.09 GJ or (3173.76 +2689.34 +2234.54) MJ. If extrapolated to Khulna City's approximately 176,889 households, this would result in 7,692.04 GJ of energy, equivalent to 2,137.69 MWh of electricity, assuming a 100% conversion efficiency. Depending on the method used to convert biomass into electricity, such as gasification, pyrolysis, incineration, or anaerobic digestion, the efficiency can vary. Assuming optimal efficiency, this contribution would account for 8.39% of the city's electricity needs, which is a notable amount. Implementing efficient organic waste management systems, such as composting, vermicomposting or biogas digesters, could significantly increase the conversion of waste into renewable energy. This bioenergy could power homes, small businesses, or be fed into the grid and contribute to a more sustainable and cost-effective energy mix. This will eventually reduce the reliance on non-renewable energy sources.

6. Discussion:

This research highlights the broader potential of household-level biomass to contribute to sustainable energy solutions. The study shows that high-income households in Khulna generate the most bio-waste (3.142 kg/day), with the highest energy potential (3173.76 MJ), as indicated in Table 6, compared to middle and low income households. This disparity is driven by higher consumption levels, particularly in kitchen and paper waste, which are major contributors to biomass. From the 186 households in the study area, a total of 8.09 GJ of energy could be produced. Scaling this to the entire city of Khulna, the potential energy contribution from biomass could reach 2,137.69 MWh, which could contribute 8.39% to the city's energy demand. This shows that biomass could become a crucial renewable energy source to help alleviate the city's energy shortages if an efficient conversion technology can be used. Recommendations include promoting waste segregation at the source, enhancing recycling facilities, and converting organic waste into valuable resources such as compost or biogas to reduce landfill usage and environmental impact. Future studies should focus on improving biomass conversion efficiency and exploring similar models in other cities.

7. Limitations

Due to practical constraints, including resource availability and time limitations, the study employed a limited sample size, which was carefully chosen to represent households across all income groups for diversity and a reasonable depiction of the study area. However, the findings may lack broader generalizability. The HHV calculations were conducted using a validated empirical equation, which excludes the fixed carbon component. While the equation has been validated in prior studies, its exclusion of fixed carbon and reliance on constants may not fully capture the variability in biomass composition. Additionally, the HHV values reported in this study are based on a dry basis, excluding the effects of moisture content. While this approach provides a standardized comparison of biomass energy potential, it may not represent the usable energy content for fresh, moisture-rich biomass in practical applications. The study's theoretical approach assumes a 100% conversion efficiency and does not consider losses inherent in real-world energy recovery processes. To address these gaps, future research should include larger and statistically robust sample sizes, integrate direct calorimetric measurements, and analyze moisture content and real-world energy conversion losses to enhance accuracy and applicability.

8. Conclusion

In conclusion, this study underscores the significant potential of household-level biomass to support sustainable energy production in Khulna. The results show that high-income households generate the largest amount of bio-waste, leading to the highest energy potential of 3,173.76 MJ. From 186 households, 8.09 GJ of energy could be generated. Extrapolated to the entire city, this could supply 2,137.69 MWh of electricity and meet 8.39% of Khulna's electricity needs. These findings can be used by policymakers to inform strategies aimed at improving organic waste management systems, such as composting or biogas digestion, and promote the use of renewable energy sources. This could contribute to a more sustainable, cost-effective energy future for the city, enhance resilience to energy demands, and reduce reliance on non-renewable resources.

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NOMENCLATURE

LI : Low Income
MI : Middle Income
HI : High Income
HH : Household
MJ : Mega Joules
GJ : Giga Joules
kWh : Kilowatt hours
HHV: Higher Heating Value