Feasibility Analysis of Solid Waste into Energy conversion in Gazipur City Corporation

Submitted By

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Supervised By
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,

A Thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Technical Education with specialization in **Mechanical Engineering.**

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, **"Feasibility Analysis of Solid Waste into Energy Conversion in Gazipur City Corporation"** is the outcome of the investigation and research carried out by us under the supervision of ***DR. MOHAMMAD MONJURUL EHSAN, PROFESSOR, DEPARTMENT OF MPE.***

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Recommendation of the Thesis Supervisors

The thesis titled **"FEASIBILITY ANALYSIS OF SOLID WASTE INTO ENERGY CONVERSION IN GAZIPUR CITY CORPORATION"** submitted by Abdullah Al Mamun, Student No: 220032102, and Likhon Ahmed, Student No. 220032104 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of BSc. TE in Mechanical Engineering **on 29 September 2025.**

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CO-PO Mapping of ME 4800 -Theis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and determine/Setting aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	**PO2** **Problem analysis**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	**PO3** **Design/development of solutions**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	**PO4** **Investigation**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	**PO5** **Modern tool usage**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO5	Apply moral values and research/professional ethics throughout the work, and justify genuine referencing on sources, and demonstration of own contribution.	**PO8** **Ethics**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO6	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	**PO9** **Individual work and teamwork**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO7	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present	**PO10** **Communication**	Thesis Book	
			Performance by research	

	the work to wider audience using modern communication tools and techniques.		Presentation and soft skill	
CO8	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	**PO12** **Life-long learning**	Thesis Book	
			Performance by research	
			Presentation and soft skill	

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Professor

K-P-A Mapping of ME 4800 -Theis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
CO1	PO2	√	√	√	√					√											
CO2	PO3					√				√	√	√				√	√	√	√		
CO3	PO4								√	√	√	√					√	√			
CO4	PO5						√			√				√							
CO5	PO8							√													
CO6	PO9																				
CO7	PO10																				
CO8	PO12																				

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List of Sustainable Development Goals (SDGs) Addressed in this Project

SDG No.	Goals	Targets	Relevance to the Thesis (put √ if valid)	Remarks
1	No Poverty	1.1 Eradicate extreme poverty (people living on less than $1.25/day).		
		1.2 Reduce poverty in all its forms by at least half.		
		1.3 Implement nationally appropriate social protection systems.		
		1.4 Ensure equal rights to economic resources, services, property, inheritance, technology, and financial services.		
		1.5 Build resilience of the poor and reduce exposure to climate-related and other shocks.	√	
		1.a Mobilize resources to end poverty.		
		1.b Create pro-poor policy frameworks.		
2	Zero Hunger	2.1 End hunger and ensure access to safe, nutritious food year-round.		
		2.2 End all forms of malnutrition.		
		2.3 Double agricultural productivity and incomes of small-scale producers.		
		2.4 Ensure sustainable food production systems and resilient agricultural practices.		
		2.5 Maintain genetic diversity of seeds, plants, and animals.		
		2.a Increase investment in rural infrastructure, research, and technology.		
		2.b Correct and prevent trade restrictions/distortions in global food markets.		
		2.c Adopt measures to ensure proper functioning of food commodity markets.		
3	Good Health and Well-Being	3.1 Reduce global maternal mortality ratio.		
		3.2 End preventable deaths of newborns and under-5 children.		
		3.3 End epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases.		
		3.4 Reduce premature mortality from NCDs and promote mental health.		
		3.5 Strengthen prevention and treatment of substance abuse.		

		3.6 Halve global deaths/injuries from road traffic accidents.		
		3.7 Ensure universal access to sexual and reproductive healthcare.		
		3.8 Achieve universal health coverage.		
		3.9 Reduce deaths from hazardous chemicals, pollution, and contamination.	√	
		3.a Strengthen tobacco control (WHO FCTC).		
		3.b Support R&D of vaccines and medicines.		
		3.c Increase health financing and workforce.		
		3.d Strengthen capacity for early warning and risk management.		
4	Quality Education	4.1 Ensure all complete free, equitable, quality primary and secondary education.		
		4.2 Ensure access to quality early childhood development and pre-primary education.		
		4.3 Ensure equal access to affordable technical, vocational, and higher education.		
		4.4 Increase skills for employment and entrepreneurship.		
		4.5 Eliminate gender disparities in education.		
		4.6 Ensure literacy and numeracy for youth and adults.		
		4.7 Ensure learners acquire knowledge/skills for sustainable development.		
		4.a Build and upgrade education facilities that are inclusive and safe.		
		4.b Expand scholarships for developing countries.		
		4.c Increase supply of qualified teachers.		
5	Gender Equality	5.1 End all forms of discrimination against women and girls.		
		5.2 Eliminate violence against women and girls.		
		5.3 Eliminate harmful practices (child, early, forced marriage, FGM).		
		5.4 Recognize and value unpaid care and domestic work.		
		5.5 Ensure women's participation in leadership and decision-making.		

		5.6 Ensure universal access to reproductive health and rights.		
		5.a Undertake reforms to give women equal rights to resources.		
		5.b Enhance use of enabling technology to empower women.		
		5.c Adopt and strengthen policies and laws for gender equality.		
6	Clean Water and Sanitation	6.1 Achieve universal and equitable access to safe drinking water.		
		6.2 Achieve access to adequate sanitation and hygiene.		
		6.3 Improve water quality by reducing pollution.	√	
		6.4 Increase water-use efficiency and sustainable withdrawals.		
		6.5 Implement integrated water resources management.		
		6.6 Protect and restore water-related ecosystems.		
		6.a Expand international cooperation in water and sanitation.		
		6.b Support participation of local communities.		
7	Affordable and Clean Energy	7.1 Ensure universal access to affordable, reliable, modern energy services.	√	
		7.2 Increase substantially the share of renewable energy.	√	
		7.3 Double global rate of improvement in energy efficiency.	√	
		7.a Enhance international cooperation on clean energy research/technology.		
		7.b Expand infrastructure and upgrade technology for sustainable energy.		
8	Decent Work and Economic Growth	8.1 Sustain per capita economic growth.		
		8.2 Achieve higher levels of productivity through diversification, tech, and innovation.	√	
		8.3 Promote policies for decent job creation and entrepreneurship.		
		8.4 Improve resource efficiency in production and consumption.	√	
		8.5 Achieve full and productive employment for all.		
		8.6 Substantially reduce youth not in employment/education/training.		

		8.7 Eradicate forced labour, modern slavery, and child labour.		
		8.8 Protect labour rights and safe working environments.		
		8.9 Promote sustainable tourism.		
		8.a Increase aid for trade support.		
		8.b Develop a global youth employment strategy.		
9	Industry, Innovation, and Infrastructure	9.1 Develop quality, reliable, sustainable infrastructure.		
		9.2 Promote inclusive and sustainable industrialization.		
		9.3 Increase access of SMEs to financial services and integration into value chains.		
		9.4 Upgrade infrastructure for sustainability and resource efficiency.	√	
		9.5 Enhance scientific research and technology development.	√	
		9.a Facilitate sustainable infrastructure in developing countries.		
		9.b Support domestic tech development and value addition.		
		9.c Increase access to ICT and internet.		
10	Reduced Inequalities	10.1 Achieve income growth of bottom 40%.		
		10.2 Empower and promote inclusion regardless of status.		
		10.3 Ensure equal opportunity and reduce inequalities of outcome.		
		10.4 Adopt policies for fiscal, wage, and social protection equality.		
		10.5 Improve regulation of global financial markets.		
		10.6 Ensure enhanced representation in global institutions.		
		10.7 Facilitate safe, regular, and responsible migration.		
		10.a Implement special treatment for developing countries.		
		10.b Encourage development assistance and investment in least developed areas.		
		10.c Reduce remittance costs.		

11	Sustainable Cities and Communities	11.1 Ensure access to adequate, safe, and affordable housing.		
		11.2 Provide sustainable transport systems.		
		11.3 Enhance inclusive urbanization and capacity for planning.		
		11.4 Protect cultural and natural heritage.		
		11.5 Reduce disaster impact and losses.		
		11.6 Reduce environmental impact of cities (air quality, waste).	√	
		11.7 Provide access to safe, inclusive green/public spaces.		
		11.a Support positive links between urban, peri-urban, rural.		
		11.b Increase disaster risk reduction strategies.		
		11.c Support least developed countries in sustainable building.		
12	Responsible Consumption and Production	12.1 Implement 10-Year Framework on sustainable consumption/production.		
		12.2 Achieve sustainable management and use of resources.		
		12.3 Halve per capita global food waste.		
		12.4 Manage chemicals and waste sustainably.	√	
		12.5 Substantially reduce waste generation.	√	
		12.6 Encourage companies to adopt sustainable practices.		
		12.7 Promote sustainable public procurement.		
		12.8 Ensure people have relevant information for sustainable development.		
		12.a Support developing countries' scientific and technological capacity.		
		12.b Develop tools to monitor sustainable tourism impacts.		
		12.c Rationalize inefficient fossil-fuel subsidies.		
13	Climate Action	13.1 Strengthen resilience and adaptive capacity to climate-related hazards.		
		13.2 Integrate climate measures into national policies.	√	
		13.3 Improve education and awareness on climate change.		
		13.a Implement UNFCCC commitments (mobilize $100 billion annually).		

		13.b Promote mechanisms for capacity-building in least developed countries.		
14	Life Below Water	14.1 Reduce marine pollution.		
		14.2 Sustainably manage and protect marine ecosystems.		
		14.3 Minimize and address ocean acidification.		
		14.4 Regulate harvesting and end overfishing.		
		14.5 Conserve at least 10% of coastal and marine areas.		
		14.6 Prohibit harmful fisheries subsidies.		
		14.7 Increase economic benefits from sustainable marine resources.		
		14.a Increase scientific knowledge and marine technology transfer.		
		14.b Provide access for small-scale artisanal fishers.		
		14.c Implement international law for oceans.		
15	Life on Land	15.1 Conserve terrestrial and freshwater ecosystems.		
		15.2 Promote sustainable management of forests.		
		15.3 Combat desertification and restore degraded land.		
		15.4 Ensure conservation of mountain ecosystems.		
		15.5 Take urgent action to reduce biodiversity loss.		
		15.6 Promote fair benefit-sharing from genetic resources.		
		15.7 End poaching and trafficking of protected species.		
		15.8 Prevent introduction of invasive alien species.		
		15.9 Integrate ecosystem values into policies/planning.		
		15.a Mobilize resources for biodiversity.		
		15.b Finance sustainable forest management.		
		15.c Support local communities for forest and wildlife.		

16	Peace, Justice and Strong Institutions	16.1 Reduce violence and related death rates.		
		16.2 End abuse, trafficking, and violence against children.		
		16.3 Promote rules of law and equal access to justice.		
		16.4 Reduce illicit financial/arms flows, organized crime.		
		16.5 Reduce corruption and bribery.		
		16.6 Develop effective, accountable institutions.		
		16.7 Ensure inclusive, participatory decision-making.		
		16.8 Broaden participation of developing countries in global governance.		
		16.9 Provide legal identity for all (including birth registration).		
		16.10 Ensure access to information and protect freedoms.		
		16.a Strengthen national institutions for prevention of violence.		
		16.b Promote/enforce non-discriminatory laws and policies.		
17	Partnerships for the Goals	17.1 Strengthen domestic resource mobilization.		
		17.2 Developed countries to implement ODA commitments.		
		17.3 Mobilize additional financial resources.		
		17.4 Assist developing countries with debt sustainability.		
		17.5 Invest in least developed countries.		
		17.6 Enhance access to science, technology, innovation.	√	
		17.7 Promote environmentally sound technologies.		
		17.8 Fully operationalize technology bank for LDCs.		
		17.9 Enhance international support for capacity-building.		
		17.10 Promote a universal, rules-based trading system (WTO).		
		17.11 Increase exports of developing countries.		
		17.12 Timely implementation of duty-free, quota-free market access.		

		17.13 Enhance global macroeconomic stability.		
		17.14 Enhance policy coherence for sustainable development.		
		17.15 Respect national policy space.		
		17.16 Enhance global partnerships.		
		17.17 Encourage multi-stakeholder partnerships.	√	
		17.18 Enhance data capacity of developing countries.		
		17.19 Support capacity-building for sustainable development indicators.		

DEDICATION

This work is dedicated to our beloved family whose unlimited support, prayers and sacrifices have been the pillar of our journey.

We also dedicate this thesis report to the dream of the future Bangladesh which is sustainable, and where waste itself is not a bane but a boon in the form of energy and opportunity.

ACKNOWLEDGEMENT

First of all, we would like to offer all praises and expressions of thanks to Allah (SWT), the Most Merciful and the Most Gracious, for sustaining us with strength, patience, and guidance to successfully carry out this thesis work. We would like to express our deepest gratitude to our respected supervisor, Prof. Dr. Mohammad Monjurul Ehsan, Department of Mechanical and Production Engineering (MPE), Islamic University of Technology (IUT), for his valuable guidance, helpful suggestions, and continuous support throughout the process of this research. His mentorship was instrumental in shaping our academic thinking and developing this thesis. We also acknowledge Dr. Arafat Ahmed Bhuiyan, Department of Mechanical and Production Engineering (MPE), Islamic University of Technology (IUT), for his initial valuable guidance & support.

We acknowledge our lab instructors for providing support during lab experiments. We also acknowledge Gazipur City Corporation (GCC) for providing essential data and logistical support, which significantly enhanced the practical dimension of our work. Our heartfelt appreciation goes to our families, for their constant prayers, encouragement, and sacrifices, which served as a constant source of strength and motivation for us. Finally, we would like to thank our friends and well-wishers whose encouragement and support have always inspired us throughout this academic journey.

ABSTRACT

The study evaluates the potential of implementing Waste-to-Energy (WtE) technology in Gazipur in terms of calorific energy generation and the overall technical, economic, and environmental feasibility of a proposed incinerator plant. The analysis shows that plastic has the highest calorific value of 30 MJ kg^{-1}, next comes wood (19.735 MJ kg^{-1}), leaf (16.78 MJ kg^{-1}), paper (15.75 MJ kg^{-1}), and textiles (17 MJ kg^{-1}). Such measurements suggest that plastic, paper, and wood should serve as suitable feedstock's to be incinerated, and leaf waste seems to be more suitable to be digested anaerobically. The total daily energy potential of the waste streams chosen is calculated as 3279.55 MWh/day -1, with an electrical output of 655.91 MWh/day -1 to 983.865 MWh/day - according to the efficiency of incineration. The technological analysis indicates that the incineration of WtE is feasible, since the mixture of waste in Gazipur provides enough calorific values to warrant this type of technology. However, the efficiency of plants depends both on the features of the waste feedstock and the operation technologies that are used. In terms of the money, the project faces severe challenges that are occasioned by high capital and operating costs. The negative Net Present Value (NPV) of = -60.59 Additionally, 15.44 years and a 6.47 per cent payback horizon and internal rate of return (IRR) indicate that the project needs more performance and cost reduction to make it economically viable. Regarding environmental impacts, the incineration plant is estimated to have a net negative CO_2 footprint, with the emissions being higher than the CO_2 offset of the energy generated. The Net CO_2 Impact value of -887 630.4 kg/day determined is negative to indicate that the plant cannot have a significant impact on the environment unless the emission-controlling technologies are optimized and the efficiency of the plants is improved. In conclusion, despite the strong technical potential of the incineration plant, the encountered economic and environmental barriers should be overcome to achieve the long-term sustainability and success of the incineration plant.

ABBREVIATIONS AND ACRONYMS

WTE – Waste-to-Energy

GCC – Gazipur City Corporation

MSW – Municipal Solid Waste

CV – Calorific Value

HHV – Higher Heating Value

LHV – Lower Heating Value

CO_2 – Carbon Dioxide

NPV – Net Present Value

IRR – Internal Rate of Return

LCOE – Levelized Cost of Energy

CAPEX – Capital Expenditure

OPEX – Operational Expenditure

WTE – Waste-to-Energy

SCR – Selective Catalytic Reduction

SNCR – Selective Non-Catalytic Reduction

FGD – Flue Gas Desulfurization

PPE – Personal Protective Equipment

PPP – Public-Private Partnership

GIS – Geographic Information System

GCV – Gross Calorific Value

GWP – Global Warming Potential

AD – Anaerobic Digestion

FOM – Fraction of Organic Materials

PM – Particulate Matter

PVA – Polyvinyl Alcohol

VOC – Volatile Organic Compounds

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Chapter 1 Introduction

1.1 Background of the Study

Solid waste management is emerging as one of the most significant challenges in rapidly urbanizing cities, particularly in developing countries like Bangladesh. One of the cities that is growing at the fastest rates, both in terms of population and industries, is Gazipur. As the nation produces about 4000 metric tons of solid waste daily, only approximately 3000 metric tons are collected and processed by the Gazipur City Corporation (GCC). This leaves a considerable portion of waste untreated, often ending up in open dumps or canals. Such unmanaged waste contributes to severe environmental pollution and poses a significant risk to public health. With continued urbanization, it is expected that the amount of solid waste will increase significantly in the coming years. Traditional waste disposal methods like open dumping and uncontrolled landfilling are unsustainable and have detrimental impacts on air, soil, and water quality.

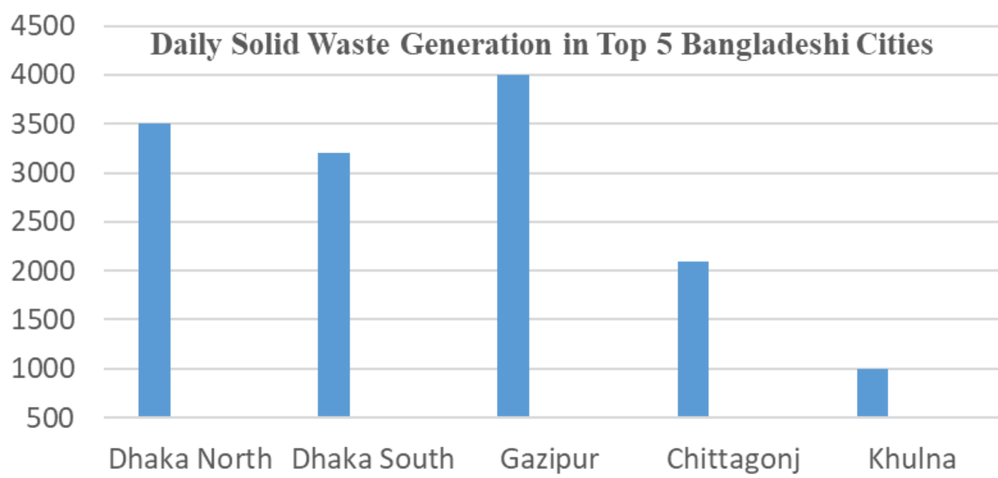

Figure 1: Solid Waste Generation (in Tons/Day) for the Top 5 Cities in Bangladesh [1]

Figure 1 illustrates the daily solid waste generation across the five largest cities in Bangladesh, with Gazipur producing the highest amount of solid waste, followed by Dhaka North, Dhaka South, Chittagong, and Khulna. The data highlights the challenges of managing growing waste volumes in urban areas and emphasizes the need for sustainable solutions like WTE.

With more and more pressure on land and the environment, we need to look for new ways to handle waste. One idea that seems promising is Waste-to-Energy, often shortened to WTE, which basically turns trash that can't be recycled into usable power like electricity or heat. The process may cut waste volume by as much as ninety percent, and it appears to make renewable energy. That double benefit could be particularly useful for places such as Gazipur, a city that struggles with both garbage pile-up and rising demand for electricity. WTE plants already exist in a handful of countries, but Bangladesh has not really adopted them yet. Certain studies have analyzed whether it can be possible to implement waste-to-energy (Waste energy) within Dhaka or Rajshahi, but there is a lack in the number of studies that specifically concentrate on Gazipur. The waste flow within the said municipality is a collection of domestic waste and industrial waste, and this factor brings along with it some challenges that differ from those faced in other municipalities [2]. This is the gap that is aimed to be filled in this paper. It will initially measure the amount of solid waste produced by Gazipur and outline its compositional behavior, after which it will assess the technical, economical, and environmental viability of setting up a Waste facility. By doing so, the work hopes to give useful pointers that could significantly lower reliance on landfills and push Gazipur toward a cleaner, sustainable future.

1.2 Problem Statement

Gazipur City Corporation (GCC) is indeed currently experiencing a major challenge while trying to handle its burgeoning population. Solid waste. Although the city produces about 4000 metric tons of waste daily, 3000 tons are collected and managed. That is equivalent to almost 1000 tons of waste that has not been managed every day, which leads to open dumping and environmental hazards. The situation is getting from bad to worse as a result of the fact that the population and industrial activities in the region are growing rapidly. Currently, there is no waste-to-energy (WTE) plant or integrated system in place in Gazipur to convert the waste to energy. Waste into something useful, for example, heat or electricity. Instead, the majority of the waste finds its way into the landfills or open space, which emits harmful gases and long-term pollution. This current waste disposal system is not only outdated but also unsustainable in the long run [3].

In spite of the fact that WTE technology has been implemented in a number of countries, it has even been discussed in other cities. In Bangladesh, there is no in-depth feasibility study towards Gazipur in particular. The city's waste has its own character, and if one does not do any research, it is difficult to say which of the technologies is preferable and would actually work here. Without a proper, research-based plan, Gazipur is in danger of losing a significant chance of reducing waste, generating clean energy, and ensuring the future generations enjoy a clean environment.

1.3 Research Questions

The study plans to know how Gazipur may turn its total producing waste problem into a source of power. It asks several things. First, how much solid trash is made each day in the city? Second, what kind of energy could be pulled from that trash? Third, which waste-to-energy methods seem doable for Gazipur when we consider tech, environment, and cost? Fourth, could the city actually afford and run such a system? Fifth, what future ideas and tips could help the city later? These queries try to fill a gap and provide real answers for a place that is growing fast.

1.4 Objectives of the Study

1.4.1 General Objective

The main aim seems to be to check if turning garbage into energy is a realistic choice for Gazipur City Corporation. The city is adding more waste while land for dumps shrinks. It appears to need ideas for handling trash. This research wants to see if waste-to-energy (WTE) could work and also lower waste volume and produce clean power. By doing that, the study hopes to back up future waste plans and long-term energy goals for the city.

1.4.2 Specific Objectives

To address the primary objective, the objectives of the given study are the following:

1. In order to measure and study the level of solid waste that is being generated in the GCC: The research will collect new data on the daily amount of accumulated garbage in various

wards of Gazipur City. Household and commercial waste, industry waste, etc., are included. Understanding the actual waste load is relevant to developing the appropriate WTE system and calculating energy output.

2. To test waste samples at the laboratory level: Some of the waste samples will be examined in the lab with a view of establishing the important physical and chemical properties. Moisture content, ash content, and calorific value are some properties. These tests are necessary for deciding on the waste type that can be used for energy recovery and selecting corresponding WTE technologies.
3. In order to determine and examine the WTE technologies that may be used: The different technologies that will be explored in the study include incineration, gasification, pyrolysis, etc., and anaerobic digestion. Each of them will be compared with such aspects as efficiency, cost, and land, among others. The comparison will also take into account the environmental impact, requirements, and other relevant factors. The aim is to make a short table of the most suitable technologies to use in the waste of Gazipur.
4. To perform a feasibility analysis: A comprehensive technical and economic feasibility study and interviews will be carried out. This would entail establishing whether the selected Waste management systems can be practiced in Gazipur City and what quantity of energy they would generate. They had the capacity to produce, the extent to which the investments were made at the beginning and the cost of operation, and whether the technology is eco-friendly. Local constraints, i.e., space availability, transportation, logistics, and the current infrastructure, also will be given attention.
5. To make recommendations to implement: The last step will be the study, which will give some practical recommendations and advice on the process of establishing waste systems in Gazipur. This section will include long-run and short-run term plans, sources of funds, and policy support required. And public-private partnership models. The policymakers and stakeholders who are the target of these recommendations are also sought. Start laying the foundation for a cleaner and energy-secure future for the city.

1.5 Scope and Limitations

In the given research, there is a chance of converting the solid waste into energy in Gazipur City. The primary field is the examination of the amount, the forms, and the structure of solid waste produced in the city, evaluating the suitable waste-to-energy (Waste-to-energy) technologies, and establishing their technical and environmental capability and their economic viability. Unlike other research works that lacked the primary laboratory analysis of the waste samples, this research has been done and received at the various zones of GCC. The lab tests will aid in identifying some of the properties, such as moisture content, calorific value, and chemical composition, this is a vital factor for the selection of the PCPP's most effective WTE technology. This feature makes the study have a good experimental base. Enhances the results' reliability.

International case studies and technical specifications reviews will also be a part of the analysis. The analysis will include cost data to identify the best-fit solution for Gazipur. Technologies such as incineration, gasification, and anaerobic digestion will be evaluated based on their suitability for local waste characteristics. However, the research is still subject to certain limitations. It does not go in depth into politics, law, or regulation. Impediments that can be experienced during implementation. In addition, where financial estimations are to be made, it is given that they are dependent on secondary data, and they may differ when actual costing is used. Social acceptance and stakeholder feedback lie outside the scope; however, they are recommended for future studies. In other words, this study should be viewed as a technologically supported and realistic evaluation of the situation in Gazipur; the waste problem can be turned into a sustainable energy solution.

1.6 Research Gap

While several studies have explored waste-to-energy (WTE) alternatives in large cities such as Dhaka and Rajshahi, focusing on technology selection and energy production [1], [2]. There is a significant lack of research specifically addressing Gazipur City Corporation (GCC). Gazipur is a rapidly growing urban area, marked by high rates of waste generation and industrial activities. The city's waste composition is unique, with a blend of household and industrial waste, which can influence the selection and efficiency of WTE technologies.

Moreover, many existing studies fail to consider critical real-world factors such as land availability, financial constraints, and environmental risks specific to Gazipur. The absence of location-specific data and comprehensive feasibility analysis creates a major research gap. Without such focused research, policymakers and city planners are unable to make informed decisions about the implementation of WTE technologies in Gazipur.

Chapter 2 Literature Review

2.1 Global Perspective on Waste to Energy

Waste-to-energy (WTE) has become one of the central technologies of sustainable urbanism on the international level. In fact, some developed nations, such as Japan, Sweden, and Germany, have recorded significant success in this field. Rolled out advanced incineration and gasification technologies in order to convert the solid from the municipal waste (MSW) into electricity and heat. For example, Sweden recycles about 50% of its waste. The above nations are getting about half the residual waste converted to energy, which is also a policy that includes importing waste materials from other jurisdictions to meet their energy needs [4]. The advantage of these countries is a clear framework of policies, strong public-private joint ventures, and state-of-the-art technology.

The adaptation of WTE is not only viewed as a waste reduction plan, but it is also viewed as a clean energy generation solution corresponding to the circular economy. Incineration with energy recovery is still the most commonly used technology in the whole world because it is mature, efficient, and can be used. Handle unsorted waste. The modern WTE plants have a pollution control system to reduce emissions and have high environmental standards [2]. In developing nations, however, the adoption has been slow with regard to the high capital cost, lack of technical know-how, and policy deficiencies. As the cities expand and the land for landfills diminishes, WTE is gaining global traction as a viable source of power. Transition technology to lower methane emissions and extract value from waste. This global shift offers a reference model on which Bangladesh can take context of its own in adopting WTE.

2.2 Solid Waste Status in Bangladesh

Solid waste management (SWM) has become a critical challenge in Bangladesh due to rapid urbanization, population growth, and changing consumption patterns. Current estimates indicate that Bangladesh generates approximately 23,000–25,000 tons of municipal solid waste (MSW) daily, with urban centers contributing the majority of this waste. Per capita waste generation typically ranges from 0.4 to 0.6 kg per person per day, with higher values observed in large cities such as Dhaka, Chattogram, and Gazipur.

This amount of waste is likely to multiply tremendously. In the next few decades, with the increase in urbanization [5]. One of the biggest shortcomings in the country is the low collection efficiency, which is only at 40-60 percent. The created waste is being picked up by the local authorities. The rest is usually dumped in open places. Space, drains, or water cause serious pollution of the environment. In larger cities like Dhaka, the collection rates may be 70-80; however, in the small cities, the rates may be lower than 40. Poor infrastructure, poor budgets, and the ignorance of the people are among the factors. This is due to the poor collection efficiency [6]. The beneficial composition of solid waste in Bangladesh indicates the socio-economic and dietary composition of the country. Patterns. The waste stream is mainly composed of organic materials, mostly food and vegetable remains. Consisting of 50-70% of the total waste. The rest comprises plastics (8-12%) and paper. And cardboard (5-10%), textiles, metals, and glass (2-5%), and inert materials like ash, dust, and others. And construction debris (10-15%). The moisture and organic content of the waste are high and hence are reduced. The calorific value of which makes it difficult to recover energy by means of incineration. However, presuming the availability of plastics and paper will provide a considerable potential to convert the energy given. These materials are well segregated [7]. In general, the MSW industry in Bangladesh is characterized by high production rates, poor collection, and a composition that is very rich in organic matter and which is more effectively managed and valorized. Technologies necessary for sustainable urban development.

2.3 Urban Solid Waste Composition Trends Relevant to Gazipur

In cities of Bangladesh, such as Dhaka and Gazipur, the composition of solid waste (SW) is an image of both conservative consumption and the new urban trends and lifestyles. The waste product is mostly organic and normally constitutes 55-70% of the total waste, mostly comprised of food scraps, vegetable scraps, and yard waste. This organic superiority refers to the diet of urban families, which is heavily based on fresh food and, therefore, produces large amounts of biodegradable waste. The organic waste in Dhaka amounts to. Organic matter constitutes 65 percent of municipal solid waste, and in Gazipur, it is a bit less at 60 percent. Consumption patterns of these cities. Meanwhile, plastics are an emerging element of the waste stream. Plastics now share approximately 10-12% of MSW in Dhaka and Gazipur, which gradually increases because of the popularity of packaged goods, single-use plastic bags, and consumer products. Of the total waste in Dhaka, plastics take 11 percent, and in Gazipur, the percentage is less: 10%. The increasing presence of plastics has its challenges and opportunities: on the one hand, it has caused some difficulties. It makes the conventional ways of waste disposal a bit more complex, and it also causes pollution of the environment. It has a superior calorific value, which might increase the possibility of energy recovery.

So that with waste-to-energy (WTE) technologies, in the case of adequate segregation. The paper and cardboard also represent a significant portion of waste, reaching between 6 and 10%overall. The percentage of the waste in Dhaka is 8% paper and cardboard, and in Gazipur, this category is 8% paper and cardboard constitutes 7% shown in **Table 1**.

Table 1: MSW Composition in Dhaka and Gazipur [8]

Waste Category	Dhaka (%)	Gazipur (%)
Organics (Food, Vegetables)	65	60
Plastics	11	10
Paper & Cardboard	8	7
Others	16	23

This proportion has been relatively stable, offsetting slight increases with economic growth, greater involvement of the population in education, and greater use of packaging materials. Plastics and paper waste have a significant potential of energy through their flammability. The municipal solid waste structure in Gazipur, just like in other urban centers in Bangladesh, is that of a high ratio of biodegradable organic waste, augmented by an increasing contribution of plastic and paper waste. This trend highlights the need to develop combined waste management plans whereby biological processes like composting or anaerobic digestion processes are used on the organic part, which should be supplemented with energy recovery methods.

2.4 Waste-to-Energy (WtE) Technologies

Waste-to-Energy (WtE) is a practical waste-management strategy, which can handle the soaring amounts of waste. Volume within cities, while also offering quality energy. These technologies convert non-recyclable waste products into valuable resources, including electricity, heat, or fuel, thereby minimizing the environmental impact of the waste and providing a renewable energy source. The three major WtE technologies, now under discussion, include Incineration and Cogeneration, Gasification/Pyrolysis, and anaerobic Digestion/Landfill Gas.

2.4.1 Incineration and co-generation

Incineration is one of the most widely used waste-to-energy technologies. The process involves the high-temperature combustion of solid waste to generate heat, which is then converted into electricity or used for heating purposes. The basic principle behind incineration is that organic materials, such as food waste and biodegradable matter, can burn at temperatures between 800°C and 1000°C, breaking down the complex organic compounds in the waste [9]. In a typical incineration facility, waste is first sorted to remove recyclable materials, followed by its transportation to a furnace or combustion chamber where it is incinerated. The heat generated from combustion is used to produce steam in a boiler. The steam then forces a turbine, which is linked to a generator, generating electricity. Also, the steam may be used in the district heating systems, which directly supply heat to neighboring structures or factories.

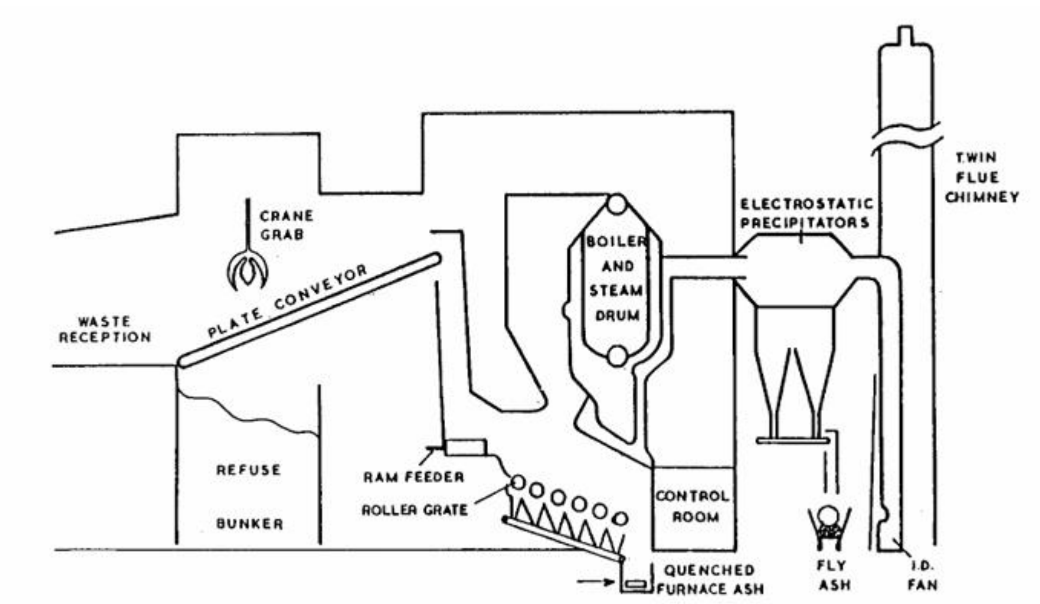

Figure 2: The general layout of Sheffield MSW incinerator. [10].

The incineration process is described in **Figure 2,** showing the steps, which are taken in it, beginning with the original material treatment and ending with the stage of burning the material and production of power. Environmental controls are very important in this process so that the damaging gases like CO2, nitrogen oxides (NOx) and other particles are reduced. These are done by scrubbers, filters, and other air pollution control devices that trap the harmful gaseous emissions and particulates before they get into the atmosphere. The ash that is produced during the combustion process is generally separated into fly ash (that is collected in filters) and bottom ash (that is retained in the furnace), which can be further processed or safely disposed of. The most important merit of incineration is that it is able to process a great variety of waste products.

At the same time producing electricity, using hazardous waste. But, there are also problems with this approach. It involves huge initial investments in infrastructure and maintenance expenses [11]. Also, although it minimizes the use of landfills and proves to be an energy producer, it might not be the most effective with regard to the amount of energy that is salvaged out of garbage, especially compared to other processes such as gasification.

2.4.2 Gasification/Pyrolysis

Thermal treatment process Gasification and pyrolysis are some of the developmental forms of thermal treatment that offer cleaner substitute methods to conventional burning. These are processes that are used to break down organic materials at high temperatures, when there is little or no oxygen available, in order to form energy-rich gases, liquids, and solid by-products. The main distinction between the two processes is based on the temperatures in which they operate and how they manipulate oxygen. In gasification the organic substances undergo temperatures of 800°C to 1200°C under a controlled, oxygen-limited atmosphere. This is used to convert the feedstock into the syngas (synthesis gas), which consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4) as its main constituents [12]. Syngas can be utilized in numerous ways, such as to produce electricity and as the heating fuel. Among the major advantages of gasification in comparison with incineration, the fact that it produces a more energy-rich and cleaner gas with fewer pollutants needs to be listed.

During pyrolysis, the organic substances are heated at low temperatures (200-500°C) without oxygen, and the materials are degraded. Pyrolysis will lead to the generation of a blend of solid char, liquid tar, and gases. Pyrolysis-resulting gas can be further used to create energy, and the char can be made into a source of carbon to be utilized in many ways. Pyrolysis can be applied especially in handling products such as plastics and tires with a high content [13].

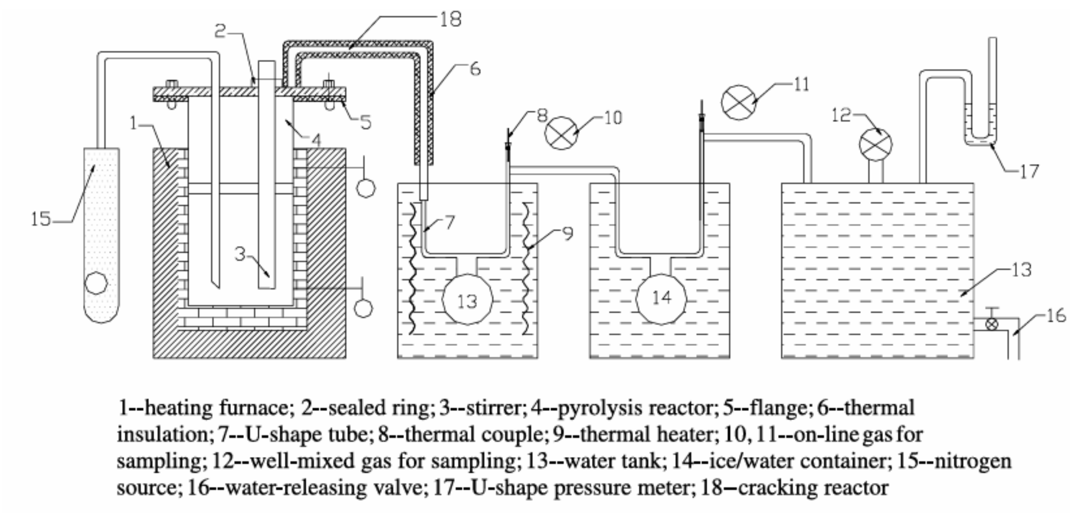

Figure 3: Laboratory-made batch biomass pyrolysis apparatus [14].

The gasification and pyrolysis processes have been elaborated on in **Figure 3** with an illustration of how biomass or waste products can be converted to gases, liquids, and solids. According to the figure, the different stages are indicated, such as drying, pyrolysis, gas-solid reactions, and char gasification. The benefits of the two technologies are enormous, which include minimizing the harmful emissions relative to incineration and increasing the potential of waste energy recovery. Moreover, the resulting solid residues may be utilized in industries or even as a soil amendment, which is an added value. It is also believed that these technologies can handle a broader feedstock than incineration since they can handle biomass, plastics, and municipal waste. They, however, need close control of temperature and oxygen levels to achieve optimal efficiency and mitigate the emission.

2.4.3 Anaerobic Digestion (AD) /Landfill Gas

Anaerobic digestion is a natural process by which organic waste is decomposed without the presence of oxygen, thus producing biogas, which is mainly made up of methane (CH_4) and carbon dioxide (CO_2) in small amounts [15]. This is naturally achieved in landfills; however, when used within controlled environments, it can be optimized to generate biogas, which could be used as a source of renewable energy. Food waste, agricultural waste, wastewater sludge, and animal manure are the organic materials that are capable of being anaerobically digested.

In an anaerobic digestion system, organic waste is placed in a sealed tank, known as a digester, where microorganisms break down the organic matter in a process that typically takes several weeks. The biogas produced can be collected and used for electricity generation, heating, or even converted into bio methane, which can be injected into the natural gas grid or used as a fuel for vehicles [16] . The residual material, called digestate, is rich in nutrients and can be used as a fertilizer or soil amendment.

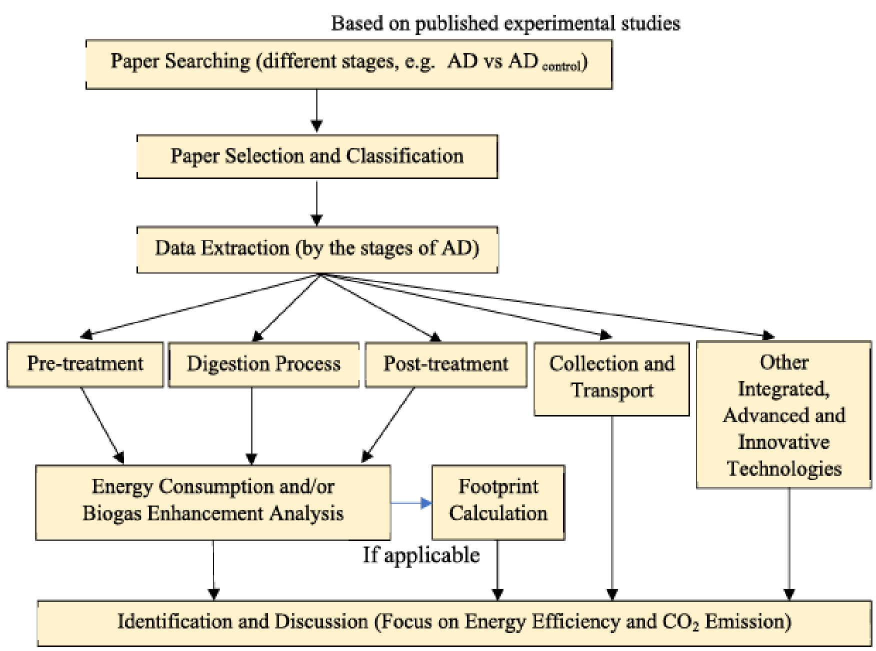

Figure 4: The framework for the assessment of anaerobic digestion process in treating MSW. [17].

Figure 4 shows the anaerobic digestion process, illustrating how waste materials such as livestock waste, crops, and food waste are fed into the digester, where they are broken down to produce biogas and digestate. The figure highlights the by-products of anaerobic digestion, including biogas for power generation and the use of digestate for agricultural purposes. One of the key advantages of anaerobic digestion is that it not only provides renewable energy but also helps in managing organic waste efficiently while reducing the environmental impact of landfills. Landfill gas recovery is a related process, in which methane gas produced in landfills from the decomposition of organic waste is captured and used for energy. While not as efficient as anaerobic digestion, this process helps reduce methane emissions from landfills, which are potent greenhouse gases.

2.4.4 Comparison Summary:

Table 2 : Comparison of Waste-to-Energy (WtE) Technologies [9-18]

Feature	Incineration	Gasification/Pyrolysis	Anaerobic Digestion
Process Type	Thermal (combustion at high temperature)	Thermal (controlled heating in limited oxygen)	Biological (anaerobic breakdown of organic waste)
Temperature	800°C to 1000°C	Gasification: 800–1200°C, Pyrolysis: 200–500°C	Typically 35°C to 55°C for mesophilic digestion
Energy Output	Electricity and heat	Syngas (CO, H_2, CH_4), oil, char	Biogas (methane), electricity, heat, biomethane
Feedstock	Mixed municipal solid waste (MSW), including hazardous waste	Organic waste, plastics, biomass, tires	Organic waste (food, agricultural, livestock, etc.)
Emissions Control	Requires extensive air pollution	Cleaner emissions than incineration, but requires	Biogas production minimizes emissions,

	control systems (scrubbers, filters)	control of oxygen and temperature	though methane control is needed
End Products	Ash (bottom and fly ash), electricity, heat	Char, syngas (used for power generation), liquid (oil)	Biogas (used for power, heat, or fuel), digestate (fertilizer)
Efficiency	Moderate, with heat recovery for district heating	High efficiency, especially in gasification for energy recovery	High efficiency for organic waste, but limited by feedstock type
Waste Reduction	Reduces waste volume by about 90%	Reduces waste volume, especially plastics and biomass	Reduces organic waste by converting it into biogas and digestate
Infrastructure Requirements	High capital investment in incinerators, boilers, turbines	High initial setup costs, specialized equipment needed	Moderate investment in digesters, minimal energy infrastructure required
Waste Pre-treatment	Sorting of recyclables necessary	Sorting and drying of feedstock required	Feedstock may need to be shredded or mixed for optimal digestion
Operational Complexity	High; requires constant monitoring of combustion and emissions	Moderate to high; temperature and oxygen control are critical	Moderate; requires regular monitoring of microbial activity
Environmental Impact	Air emissions (CO_2, NOx, etc.) but mitigated with controls	Lower emissions than incineration, but still releases gases like CO_2	Minimal emissions; captures methane, reducing greenhouse gas impact

Scalability	Well-suited for large-scale urban areas	Flexible, can be used for both small and large-scale applications	Typically more effective for organic waste management in urban or rural settings

2.5 Calorific Value (HHV, LHV), Moisture and Ash Effect

The energy recovery potential of municipal solid waste (MSW) is strongly influenced by its calorific value (CV) and physical composition. MSW is a heterogeneous mixture, and therefore, parameters such as moisture content, ash content, and the organic fraction of the waste play a significant role in determining the most suitable Waste-to-Energy (WtE) technology for efficient energy recovery [18].

2.5.1 Higher Heating Value (HHV) vs. Lower Heating Value (LHV)

Waste energy content may be in two forms, which are Higher Heating Value (HHV) and Lower Heating Value (LHV). Both explain the extent of waste energy that can be gained, but these two are applied differently in practice. HHV is the sum of energy in the waste, which also includes the heat of water vapor condensing. It provides the highest possible energy value possible when no energy is dissipated. In practice, however, in a true Waste-to-Energy (WtE) system, condensation of water vapor is not typically possible, and thus HHV tends to overestimate the available energy. LHV demonstrates the amount of energy available to be used, but without the heat of water vapor. LHV is a more practical measure because most WtE plants are not able to utilize the energy of the vapor. This is why LHV is widely applied in practice because it represents the energy that can be converted to electricity or heat [19].

2.5.2 Effect of Moisture Content

The level of moisture content also greatly impacts the level of energy utilizable in waste. Any water present in the waste should evaporate before the process of combustion or gasification takes place, and this requires energy and reduces efficiency. The LHV of the waste is low when the moisture content is high since more energy is utilized in the evaporation of water. Sludge, green waste, and food waste are usually high-moisture materials, which lowers energy recovery in thermal WtE systems. Waste with an LHV of 7-8 MJ/kg or more is normally needed to run incineration and gasification easily. When the moisture causes LHV to drop below this point, then the process will be inefficient. Waste can, in this case, require drying or mixing with drier materials. Anaerobic digestion (AD), on the contrary, is advantageous to moisture. Water aids the process since AD is based on the involvement of microbes to decompose organic matter. Waste that is rich in moisture, such as food scraps and green waste, can be effectively used in AD [20].

2.5.3 Effect of Ash Content

The non-burnable component of waste is called ash, and it consists of soil, dust, metals, and glass. It decreases the amount of energy that may be recovered because ash is not a heat producer during combustion. The high ash content reduces the effective calorific value of the waste and absorbs heat, hence reducing thermal efficiency. It also brings about issues like slagging, fouling, and an increase in residue handling costs. These problems lower the performance of plants and raise the maintenance. Ash is particularly sensitive to processes such as gasification and pyrolysis. The presence of high levels of ash disrupts the generation of syngas and efficiency. Due to these reasons, ash content should be narrowly regulated for operation in WtE systems [21].

2.5.4 Importance of Calorific Value for Technology Selection

The selection of the appropriate WtE technology is highly dependent on the calorific value of waste. Different systems are best suited to various types of feedstock. Incineration or co-generation systems need waste of moderate to high LHV (greater than 7-8 MJ/kg). Dry waste not containing a lot of water is desirable, and it contains high plastic or paper content, which is better in terms of energy value. Moist, or ash, wastes, however, reduce efficiency. Gasification and pyrolysis require dry, sorted, and uniform feedstocks with a calorific value of >10 MJ/kg. The moisture and ash in these systems are sensitive, and therefore, low quantities of both are crucial in the quality and performance of the syngas and landfill gas. They instead rely on biodegradability. Moist, organic wastes like food scraps and sludge are best in this scenario, as water favors the activity of microbes [22].

2.6 Economic, Environmental, and Social Aspects of WtE

Waste-to-Energy (WtE) technologies are becoming a globally recognized option as the preferred method to reduce the increasing amounts of municipal solid waste (MSW) and at the same time produce renewable energy. Economic, environmental, and social aspects of WtE are critical elements in defining the viability and sustainability of such systems, especially in urban centers that address the issue of waste management.

2.6.1 Economic Aspects

The economic viability of the Waste-to-Energy (WtE) technologies is subject to capital cost, operation and energy cost, energy generation, and the ability to lower the cost of waste disposal. A WtE plant is costly to start up due to the premium investment cost due to the presence of waste processing facilities, combustion chambers, gasifiers, turbines, and pollution control equipment [23]. Nevertheless, such expenses could be offset with long-term savings of energy production and less landfill area utilization. There are also unending expenses in running a WtE plant, which include labor, maintenance, and transportation of the waste. Such costs differ according to the technology, i.e., incineration, gasification, or anaerobic digestion. These expenses can be compensated by income generated by electricity or heat production, and even financial autonomy is achieved by the plant. WtE plants transform waste to electricity or heat, which can be sold to the grid or utilized locally. Incentives for renewable energy are also given by many governments, making WtE projects economically appealing. Moreover, where landfills are small, the increasing disposal price of waste renders WtE a viable option for waste management. **Table 3** provides a summary of the economic comparison of various WtE technologies, which reveals the variations in the capital investment, cost of operation, and energy generation and revenue potential.

Table 3: Economic Comparison of Waste-to-Energy Methods [9-17]

Aspect	Incineration	Gasification/Pyrolysis	Anaerobic Digestion (AD)

Capital Investment	High	Very High	Moderate
Operational Costs	High	High	Moderate
Energy Production	Electricity and heat	Syngas (electricity, heat, chemicals)	Biogas (electricity, heat, biomethane)
Revenue Generation	Electricity/heat sales, waste disposal fees	Syngas, chemicals, carbon credits	Biogas sales, digestate as fertilizer
Waste Disposal Costs	Reduces landfill disposal costs	Reduces landfill use	Reduces landfill costs
Economic Viability	Viable for large waste volumes	Suitable for high-value waste streams	Viable for organic-rich waste streams
Subsidies/Incentives	Renewable energy subsidies	Green energy subsidies, carbon credits	Biogas production subsidie

2.6.2 Environmental Aspects

The technological advantages associated with WtE are that they result in less waste being disposed of in landfills, less emission of greenhouse gases, and generation of renewable energy. Waste diversion is one of the key advantages [24]. WtE also facilitates the reduction of the emission of methane gases into the environment and the burden on the environment caused by landfills, thereby producing energy using waste. WtE plants, particularly incinerators, have the ability to emit air pollutants such as CO_2, NOx, SO_2, and PM and replace conventional energy, reducing carbon emissions and helping to transition to a circular economy. To reduce these emissions, modern plants rely on scrubbers, filters, and electrostatic precipitators, although there still could be some trace pollutants. WtE also helps to save land and resources. Through the minimization of landfill spread, the land can be used to farm or in housing or natural habitats. The waste materials may be recycled, and this will reduce the need to introduce more new raw materials, which will help in conserving the resources as shown in **Table 4**. Incineration, Gasification/Pyrolysis, and Anaerobic Digestion have varying waste diversion, energy production, pollution control, and other environmental impacts.

Table 4: Environmental Comparison of Waste-to-Energy Methods [9-17]

Aspect	Incineration	Gasification/Pyrolysis	Anaerobic Digestion (AD)
Waste Diversion	Significant diversion from landfills; reduces methane emissions	Reduces landfill dependency; allows for recycling of certain materials	Significant diversion of organic waste from landfills
Energy Production	Electricity and heat generation; reduces reliance on fossil fuels	Generates syngas for electricity, chemicals, and heat	Biogas for electricity, heat, and biomethane for fuel
Pollution Control	Advanced air pollution control (scrubbers, filters, electrostatic precipitators)	This process has lower emissions than incineration and involves the work of installing complete air-control systems.	The system is low emission, and has a strong emphasis on the capture of methane for energy production.
Land and Resource Conservation	Reduces need for landfill expansion, conserves land	It minimizes reliance on landfills, and it creates economic value out of waste streams.	Land conservation is also being realized while the digestate produced is a valuable fertilizer.
Carbon Emissions	Potential CO_2 and NOx emissions, mitigated by controls	Carbon dioxide emissions are less than incineration processes.	The process has low CO2 emissions and is focused on reducing the generation of landfill methane.

Recycling Potential	The recycling potential is reduced, and the concentration is on the energy recovery.	Recycling of metals and other precious materials in part is imposed.	The biogas and fertilizers are made out of organic waste.

2.6.3 Social Aspects

Social impacts of WtE technologies include the impact on the community acceptance, employment, and the general public health. Good waste management practices improve the well-being of the populations because they limit the chances of air and water pollution. WtE makes cities cleaner and reduces the risk of disease outbreaks due to uncontrolled waste. WtE creates working places, both during construction and plant operation, as well as waste collection and maintenance. WtE plants need to have skilled employees, which will encourage innovation and expertise in the renewable energy industry. Social acceptance is a paramount requirement of WtE implementation. There can be community issues with the risk of health or environmental impact, particularly in relation to the quality of the air. To achieve the trust, transparency, involvement, and close attention to the environment should be promoted [25]. Lastly, the implementation of WtE projects must be fair so that everyone benefits due to the production of energy and reduction of waste. Incorporating WtE with other approaches to waste management, such as Recycling and responsible consumption, helps sustainably and socially equitably, as seen in Table 5, which compares the effect on the health of the population, employment creation, social acceptance, and other social outcomes.

Table 5: Social Comparison of Waste-to-Energy Methods [9-17]

Aspect	Incineration	Gasification/Pyrolysis	Anaerobic Digestion (AD)
Public Health Impact	This approach can help to minimize health risks related to	It generates lower emissions to the air when compared to incineration; however, the	Minimal emissions are achieved; landfill methane production

	waste, but may produce air emissions and therefore require strict controls.	proper controls must be implemented to minimise the health risks.	is reduced by minimal emissions, and thus, public health benefits are contributed.
Job Creation	public fears about health risks posed by the emissions remain; acceptance depends on the adoption of good emissions control measures	Public apprehensions about emissions and environmental impacts require good public engagement strategies.	High acceptance by the public is noted, especially in areas with organic-rich wastes as well as environmental benefits.
Social Acceptance	public fears about health risks posed by the emissions remain; acceptance depends on the adoption of good emissions control measures	Public concerns over emissions and environmental impacts; requires effective public engagement	High public acceptance, especially in areas with organic-rich waste; focuses on environmental benefits
Sustainability and Equity	This method can contribute to sustainability by decreasing the utilization of landfills but it is imperative to ensure that the attendant benefits are equitably distributed.	It provides the possibility of sustainable production of energy and diversion of wastes; however, the efficacy of such a solution may be limited by the quality of the feedstock.	There is a strong emphasis on sustainability, particularly with regard to organic waste with the equitable gain from energy generation

Chapter 3 Study Area and Data

3.1 Overview of Gazipur City Corporation

Gazipur City Corporation (GCC) is a fast-developing urban center in Bangladesh, in the central part, bordering the capital city, Dhaka. Gazipur is an area of 49.3 square kilometers with a population of around 3.4 million people. The region has evolved to become an industrial hub rather than a mostly rural area, and there has been a significant investment in the manufacturing sector, especially in the textile and garment sectors. Gradually it has turned out to be a vital station in the Bangladesh industrial environment, with a major contribution to the national economy. The demographic and industrial profile of the city is unique, with a significant number of its population being employed in the light manufacturing industry and the fabric and garment industry. The high rates of urbanization in Gazipur are accompanied by residential, shopping and public infrastructure developments. Also, its closeness to Dhaka has turned it into a popular destination for individuals trying to find jobs in the capital city. Consequently, Gazipur has been experiencing an exponential population growth, which has augmented the need for municipal services such as waste disposal. The city of Gazipur has experienced urban development due to several forces, such as the availability of better infrastructure, industrialization-friendly governmental policy frameworks, and the existence of industries. Nevertheless, the urbanization of the city has also led to numerous urban issues, especially waste management. Although the city is making good advancements in other sectors, there are significant challenges in managing its growing volumes of waste, which have stretched its available waste management facilities and the environmental capacity [26].

3.2 Demography, Economy, and Waste Generation Drivers

The demographic landscape of Gazipur is mainly typified by the high population that is mainly young and rapidly growing, accompanied by the influx of rural migrants seeking improved economic opportunities. Most of its population works in the industrial and manufacturing sectors, especially in garment factories, which are also located in the region. The garment industry, as the so-called backbone of the Bangladesh economy, has had its considerable share. It is a contributor to the urbanization of Gazipur. There are approximations that there are more than 600 textile and garment manufacturing plants in the city, which employ millions of workers. Its closeness to Dhaka also supports its economy, as a lot of inhabitants move to the capital to work, study, and carry out other economic activities. The economic activities in Gazipur are huge contributors in terms of waste generation. The industries located in the city are also a major contributor to the waste stream, generating large volumes of solid waste, such as industrial by-products, packaging waste, and waste generated in the industrial manufacturing processes [3]. Moreover, the household waste has also been on the rise due to the residential industry as well as the rising population. With the growth in the population of middle-income people and consumer culture, there is an increase in consumption of packaged goods, electronics, and other consumable products at a rate that has been escalating the amount of waste. One of the major causes of waste production is urbanization in the city. The housing, food, and other commodity demands have been on the high level, as the population immigrates to Gazipur to find job opportunities, causing domestic waste in the form of food scraps, plastics, and packaging resources. In addition, the increasing consumer goods and food levels of packaging materials have increased the accumulating volumes of plastic waste that pose a significant environmental hazard because of their non-biodegradation [5]. Moreover, the rising population of businesses, commercial outlets, and service industries has generated huge amounts of waste, including paper, plastics, and packaging waste. The amount of waste that is produced in Gazipur is directly proportional to population increase and growth of industrial and economic activities. It is estimated that around 4,000 tons of solid waste are produced in the city every day, but only around 3,000 tons are actually picked up and processed. The other 1000 tons are either abandoned or dumped illegally. To environmental degradation and health hazards, dumpsites, open spaces, or drainage systems. Furthermore, the problem of poor waste management in the city is aggravated by the lack of waste segregation at the source, the lack of community awareness about waste minimization, and the unavailability of resources to process the waste properly. This situation is further aggravated by the lack of effective systems of recycling, composting, and waste-to-energy transformation. The organic wastes are huge and form a huge percentage of the total wastes produced, posing a threat [3],[5].

3.3 Existing Waste Management System and Challenges

The waste-management system in Gazipur is being put under severe pressure at the moment due to the accelerated demographic growth, the spread of the industrial activity, and a corresponding increase in the volumes of municipal waste. This is on Gazipur City Corporation (GCC), but the infrastructure is crippled by a lack of adequate resources, collection procedures, and limited infrastructure. As a result, the current practice of waste management is fundamentally traditional and must include waste collection, transportation, and disposal in landfills, processes that are rather manual and rely on a small number of vehicles and inefficient routes [3]. To date, waste management is still mostly based on the conventional triad of collection, transport, and landfill – a model where manual labor is the main factor, and the lack of vehicles and inefficient route optimization algorithms hinders its progress. Lack of up-to-date technological solutions and integrated information systems has led to enormous amounts of uncollected waste, thus creating unsanitary conditions in the city. The main weakness is the absence of source segregation, a deficiency which excludes the possibility of successful recycling and composting programmes. In addition, recyclable and organic streams must divert to landfill sites due to the lack of highly developed processing facilities, which are fast dwindling in capacity. With no systematic approach to the new locations, the municipality is still relying on uncontrolled open dumping, thus triggering soil and water pollution, methane release and the resultant health hazards to people. Further aggravating the situation, there is a lack of awareness of sustainable practices among the populace and a lack of incentive to reduce waste or recycle it, which only contributes to the problem [5]. The second significant obstacle is financial constraints because insufficient funding and lack of investment in state-of-the-art infrastructure and equipment will limit the capacity of GCC to address the increasing need for effective waste management.

Overall, the waste-management issues in Gazipur require a multi-purpose and prospective approach that is more focused on modern technologies, the creation of recycling and composting plants, more education among the population, and more funding, as it will lead to a stable and efficient waste-management system.

3.4 Data Sources

This paper will utilize both primary and secondary sources of data to create a complete picture of the waste management system in Gazipur City Corporation (GCC) and in order to map the waste composition. The overlapping of numerous data sources contributes to the increased validity of the research and supports a high-quality analysis to inform the choice of the appropriate Waste-to-Energy (WtE) technologies. Primary data were collected by the use of field-based methods such as sampling, sorting and laboratory tests, and secondary data were obtained from the GCC administrative records, government documents, peer-reviewed research, and internationally approved normative frameworks. A compilation of all these datasets provides a solid basis for evaluating the technical, environmental and economic viability of implementing WtE solutions in Gazipur.

3.4.1 Primary Data (sampling, sorting, lab tests)

Systematic sampling and sorting of municipal refuse were the major approaches used to collect primary data. To capture the general compositional picture of the waste stream of the city, a representative sample of 1 kg was taken in different micro-districts of Gazipur. The sample was carefully fractionated into discrete categories: organic (food and green waste), paper, plastic, textiles and wood, metals, leather and rubber, glass and miscellaneous materials. The proportional weight of each fraction was determined in order to achieve its fractional mass of the total mass, and the process was done repeatedly with multiple specimens to ensure accuracy and representativeness. **Table 6** shows the results of the waste composition analysis:

Table 6: Waste Composition of Gazipur City Corporation (GCC)

Waste Category	Percentage (%)	Quantity (tons/day)
Organic (food/green)	~74	2,220
Paper	~9	270
Plastic	~3.5	105
Textile & Wood	~1.9	57
Metal	~1.5	45
Leather & Rubber	~0.8	24
Glass	~0.8	24
Other Waste	~8	240

The composition profile highlights how organic wastes are dominant in the municipal waste stream of Gazipur, followed by paper and plastics, with other categories having a minimal contribution. Such quantitative observations play an important role in determining the most appropriate waste treatment and energy recovery modalities. Determinants of calorific value were made to determine the thermal potential of waste in Gazipur. The heat yield of the various selected fractions, that is, paper, wood, and leaves, was measured by a bomb calorimeter under standard conditions The analysis shows that paper and wood tend to have a high calorific value compared to plastics or organic material. The findings are useful in the evaluation of the viability of using separate waste fractions in thermal WtE processes such as incineration and gasification

3.4.2 Secondary Data (GCC records, govt reports, published studies, standards)

The secondary data were used to supplement and put the primary data into perspective by giving information on the waste management trends, policies, and regulatory frameworks. The Gazipur City Corporation records provided key information on historical waste collection rates and disposal rates, the modalities of waste collection and the difficulties encountered by the municipality. These reports highlighted the gap between the amount of waste produced and the percentage of waste that was managed. The policy context provided were government reports and policies mainly of the Ministry of Environment and Forests (MOEF) and the Department of Environment (DoE). They set national policies on how waste infrastructure, recycling, and increasing the amount of renewable energy can be improved. The other issues raised in these reports were the difficulties linked with policy implementation, as well as waste-to-energy (WtE) solutions becoming part of the national sustainability agenda. Local and international published literature was reviewed to compare the waste stream in Gazipur to a similar urban center. These papers confirmed the primary data and outlined best practices and instructive lessons that have been learnt by other regions, which have been effective in adopting WtE technologies. Comparative knowledge on the structure of waste and the functionality of different WtE techniques in different conditions was particularly helpful to determine the most appropriate technologies to be used in Gazipur. The analysis was also guided by the national and international standards that provided environmental and technical standards. The sources were referenced to International Solid Waste Association (ISWA), the World Health Organization (WHO) and the Bangladesh

Environmental Conservation Rules (ECR). These norms preconditioned the fact that the assessment of the WtE technologies was made in accordance with the accepted environmental standards and the requirements of regulations, in the aspects of emissions and the efficiency of the waste treatment process.

Chapter 4 Methodology

4.1 Research Design and Workflow

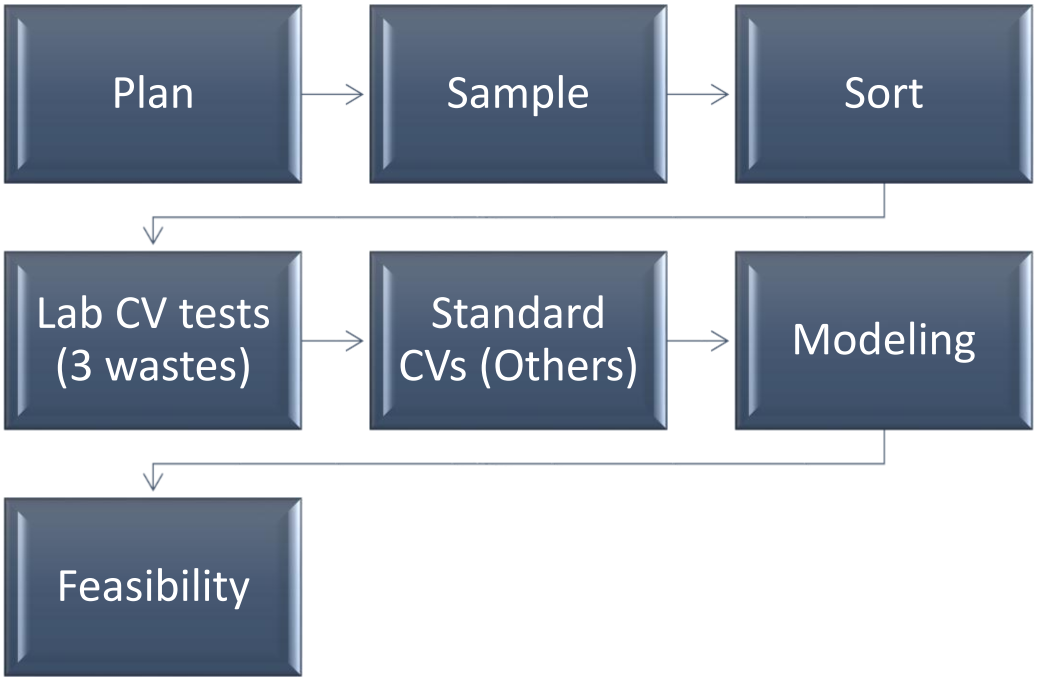

Figure 5: Methodology flowchart.

The methodological flow was in line with the research protocol and was conceptualized to determine the viability of the conversion of municipal solid waste into energy within the confines of Gazipur City Corporation, as shown in **Figure 5**.The first stage involved intensive planning that included formalization of the objectives of the study; selection of sampling sites was done judiciously, and the methodology framework of the entire study was outlined. Thereafter, a systematic sampling plan was followed to obtain representative waste samples of pre-identified precincts in the city, thus ensuring that the dataset was a true reflection of the current compositional picture of the solid waste stream of Gazipur. The material harvested was then carefully sorted into the major fractions – i.e., food waste, paper, plastic, and other relevant categories – which were followed by the subsequent analysis. Sorting provided the necessary baseline for both experimental analysis and data modeling. Following sorting, laboratory calorific value (CV) tests were conducted on three selected waste categories that represent the dominant portions of the waste stream. These experimental tests determined the actual energy content of these fractions. For the remaining waste types that were not tested experimentally, standard calorific values from established references were applied to complete the dataset. Once the calorific values of all waste categories were determined, the results were integrated into a modeling phase, where the total energy potential of Gazipur's waste stream was estimated. Finally, the outcomes of the modeling were subjected to a feasibility assessment, covering technical, economic, and environmental considerations to determine the practicality of implementing a waste-to-energy system in the city.

4.2 Sampling Strategy and Sample Size

This study adopted a focused sampling design that reflects the typical mixed municipal solid waste (MSW) handled by Gazipur City Corporation (GCC) while aligning with the analytical capacity of the laboratory bomb calorimeter. A single sampling campaign was conducted (i.e., no seasonal stratification). A composite grab sample of approximately 1 kg of mixed MSW was collected from an active GCC collection point receiving routine municipal loads. The bulk sample was thoroughly mixed and reduced by quartering to obtain a workable subsample for fraction-wise sorting. Because the bomb calorimeter available in the laboratory can process only three solid waste fractions reliably, the study targeted wood, leaf, and paper for direct calorific value (CV) measurement.

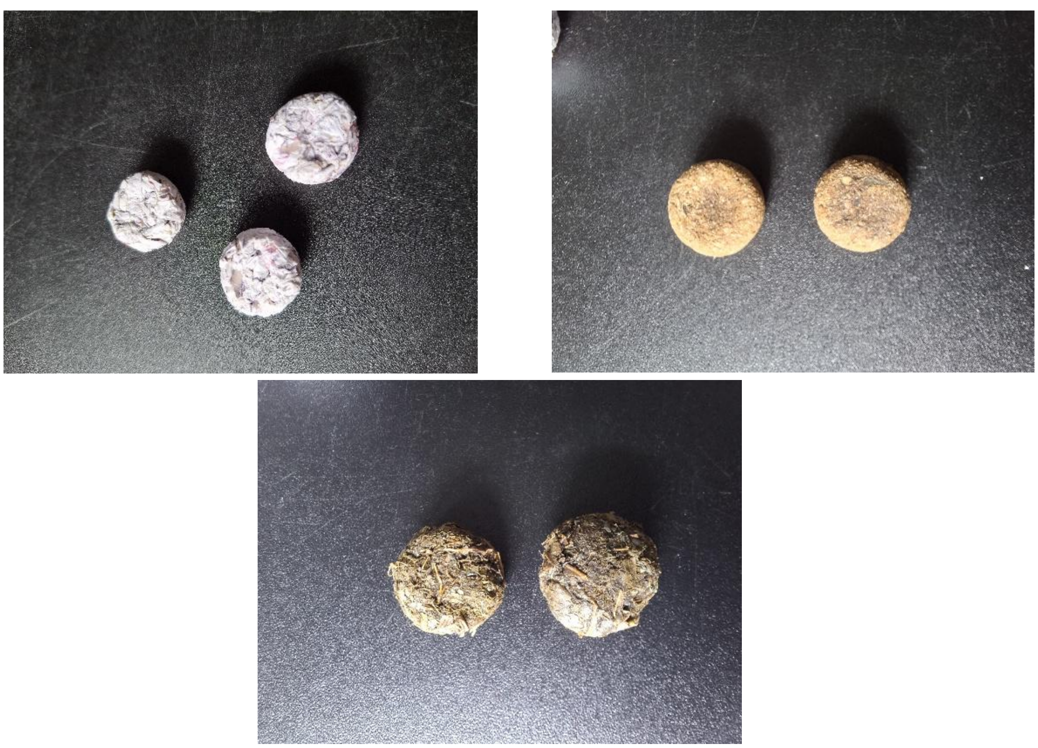

Figure 6: Waste Sample (paper, wood &leaf)

Figure 6 shows the waste samples of **paper**, **wood**, and **leaf**. These samples represent different types of waste materials, which are typically incinerated in Waste-to-Energy (WTE) plants to generate electricity. The image illustrates the physical forms of these waste types before processing. All other fractions were recorded during sorting for composition analysis and subsequently assigned standard CV values. For calorimetry, each of the three targeted fractions was tested in duplicate runs (total n = 6). The as-run masses for each bomb-calorimeter charge were recorded to support energy-per-mass normalization and QA checks. The wood fraction was tested at 0.692 g and 0.710 g; the leaf fraction at 0.799 g and 0.608 g; and the paper fraction at 0.918 g and 0.648 g. Scales were tared before each weighing, and moisture at receipt was noted when feasible to aid interpretation of HHV/LHV differences(see **Table 7**). Field notes documented any deviations from plan. Representativeness was addressed by (i) sampling from the routine mixed MSW stream rather than a single source-specific generator, (ii) thorough homogenization and quartering before sorting, and (iii) replicate calorimetry within each tested fraction. In downstream analysis, city-level energy estimates combine measured CVs (wood, leaf, paper) with standard CVs (other fractions), weighted by observed composition shares. Where GCC daily tonnage is available, results can be scaled to daily energy potential. The principal limitations single-campaign design, modest bulk mass (≈1 kg), and CV testing restricted to three fractions are explicitly addressed in the uncertainty and sensitivity analyses.

Table 7: Sampling plan and calorimeter runs

Item	Description
Sampling frame	Mixed MSW at routine GCC collection point (see Appendix A)
Campaigns / seasons	Single campaign; no seasonal stratification
Frequency per site	One visit; one composite sample
Bulk composite mass	≈ 1 kg (mixed; reduced by quartering prior to sorting)
Fractions analyzed for CV	Wood, Leaf, Paper (others: composition only; CV from standards)
Bomb-calorimeter replication	2 runs per fraction (total n = 6)
Wood run masses (g)	0.692, 0.710
Leaf run masses (g)	0.799, 0.608

Paper run masses (g)	0.918, 0.648
Weighting for city-level estimates	Composition-share weighting; optional scale-up using GCC daily tonnage

4.3 Waste Sorting & Classification Protocol (fraction definitions)

The goal of the sorting and analysis process was not only to determine the proportionate contents of the major fractions in mixed municipal solid waste (MSW) of Gazipur but also to develop a weighting model by which the measured CVs of various materials, such as wood, leaf, and paper, would be added to the publicly available standard CVs of other fractions. This sorting was carried out manually on a fraction-based protocol, and all the necessary health and safety precautions were followed. The preparation entailed carrying out the labour on a clean and washable tarp that was located in a well-ventilated place. Staff were fitted with personal protective gear (PPE) of masks or respirators, gloves, safety glasses, aprons and closed shoes. All the tools, such as trays, scoops, bins and scales, were washed and tared before they were used. Sharps and biological waste were sorted out into identified containers instantly. The sample of one kilogram of composite waste was homogenized to reduce the chances of clumping, and then it was subsampled through the quartering technique to maintain representativeness. The fraction identification was done, and items that are oversized and those that are visibly free liquids were added back in. Waste materials were sorted into fixed categories, and as can be seen in **Table 8** (Fractions and Codes Used in Manual Sorting), they were classified into organic waste, paper, wood, leaves, plastics, textiles, metals, glass, rubber/leather, fines and composite materials. The classification system had the aim of isolating the three fractions that are being tested in terms of calorific value (wood, leaves, and paper) and clustering the rest of the fractions in standard MSW categories where literature-based data on the CV are readily available.

A calibrated digital scale was used to weigh each fraction, and the mass of a wet fraction was noted to the nearest gram. To ensure quality, a mass balance check was used, which the sum of the fractions is added up and compared with the total weight of the sample; this value should be acceptable at a range of 3 to 5 per cent. In the case of the CV-tested fractions, re-running the bomb calorimeter was done because of the small bulk mass available, and the remainder was placed in sealed and labelled containers that would be stored in a traceable manner. All the procedures and findings were entered on standard field sheets so that there is consistency. The calculated fraction shares (wt) were achieved by dividing the mass of each category by the mass of the sample. Where mass balance was no longer within the range of closure, bins and scales were rechecked, and abnormal conditions (like excess moisture) were noted to be tested again in sensitivity. This guaranteed that the information used to calculate weighted calorific values and evaluate energy potential was of high quality control.

Table 8: Fractions and codes used in manual sorting

Code	Fraction (description)	Notes
ORG	Food/putrescible and fines adhering organics	High moisture; CV from standards
PAP	Paper & cardboard	CV measured (bomb calorimeter)
WOD	Wood (clean pieces, sticks)	CV measured
LEF	Leaves/yard trimmings	CV measured
PLA	Plastics (films and rigid combined)*	CV from standards
TXL	Textiles	CV from standards
MET	Metals (ferrous and non-ferrous)	Negligible CV; recorded for completeness
GLS	Glass/ceramics	No CV; inert
RBL	Rubber/leather	CV from standards
FIN	Fines (<10 mm)	Typically high moisture; CV from standards
OTH	Other/Composite (e.g., multilayer)	Assign CV per closest analogue

4.4 Calorific Value Determination

4.4.1 Experimental Method for Three Major Waste Types (specify your 3 types)

Sample preparation. After sorting the waste fractions (Section 4.3), the wood, leaves, and paper fractions were air-dried to remove free surface moisture, followed by size reduction using cutting and shredding techniques. The final particle size was approximately 1–3 mm to enhance homogeneity and ensure uniform combustion. Each prepared test portion was pelletized and weighed on a calibrated, tared digital balance to record the sample mass. Instrument and operating conditions. The Higher Heating Value (HHV) of each sample was determined using an isoperibol bomb calorimeter, charged with high-purity oxygen at ~30 bar. This calorimeter functions by combusting the fuel sample in a high-pressure oxygen atmosphere and measuring the heat released by the sample. The energy released is absorbed by a known mass of water in the calorimeter, and the resulting temperature rise is recorded. The energy equivalent of the calorimeter was verified at the start of the testing day using a certified standard (e.g., benzoic acid). Fuse-wire and acid corrections were done along the guidelines of the manufacturer in order to consider the heat transfer to the calorimeter and unique reactions of bomb combustion on the side walls.

The gross calorific value (GCV) is calculated using the following formula:

$$\text{Calorific Value}= \frac{(m_1+m_2)\ .\ (T_2-T_1)\ .\ c_w}{m_f}$$

Where:

- m_1 = Mass of water in the calorimeter (kg)
- m_2 = Water equivalent of the bomb calorimeter (kg)
- T_1 = Initial temperature of water (°C)
- T_2 = Final temperature of water (°C)
- c_w = Specific heat capacity of water (kJ/kg°C)
- m_f= Mass of the fuel sample (g)

The calorific value is determined by multiplying the total mass of the water and its equivalent energy of the calorimeter by the increase in temperature and then dividing it by the fuel sample mass. Energy emitted at the combustion point is now then transferred to the surrounding water, and the subsequent temperature increase is then used to ascertain the energy emitted with respect to the unit mass of fuel. Replicates performed. Two independent bomb calorimeter runs were completed for each of the three fractions, yielding a total of n = 6 runs. The recorded as-run masses were:

- Wood: 0.692 g and 0.710 g
- Leaves: 0.799 g and 0.608 g
- Paper: 0.918 g and 0.648 g

These measurements are recorded in **Table 7**. The results were evaluated for repeatability, and only those within the pre-set tolerance were accepted for further analysis. QA/QC and reporting basis. To ensure the accuracy and reliability of the calorimeter readings, daily calibration burns were conducted with a certified reference material (e.g., benzoic acid) to verify the calorimeter's energy equivalent. Additionally, fuse-wire and acid corrections (if applicable) were applied. Stable temperature-rise curves and visual checks for complete combustion were conducted as quality control checks. The replicate relative standard deviation (RSD) was targeted to be ≤ 1–2 % for each fraction. Because no seasonal variation was considered in this study, the reported HHVs are based on an air-dry test basis achieved by pre-drying the samples. For comparisons with literature values based on a dry basis (0% moisture), basis harmonization is performed, as detailed in Section 4.7. The reporting of HHV for the MSW fractions and subsequent conversion to lower heating value (LHV) follows common practices in thermochemical characterization of solid waste, ensuring consistency with established standards.

4.4.2 Standard Reference Values for Remaining Fractions (sources/standards to be cited)

In the case of waste fractions, which were not tested experimentally, namely plastics (PE, PP, PS, PVC, PET), textiles, rubber/leather, food and putrescibles, fines, metals and glass/ceramics, the standard component-level higher heating values (HHVs) were obtained in peer-reviewed literature and in the existing databases. This approach guarantees consistency of all fractions and ease of comparison with other Waste-to-Energy (WtE) feasibility studies [27]. The paper provided the main reference values; it stated commonly used HHVs of paper, wood/biomass, textiles, plastics, and rubber. Under the conditions of the presence of several datasets, the mean or median values were used preferentially to reduce the effect of the outliers. These literature values were later compared with elaborate meta-analyses of municipal solid waste thermochemical characteristics, especially that of paper, textile, plastics, wood, and rubber, to verify plausibility and to establish variation domains to be used in sensitivity analyses.

As the majority of literature values are reported on a dry basis, whereas the Gazipur samples were analyzed under air-dry conditions, harmonization of the data was necessary. The last protocol retained HHVs literature on the basis specified, varying them where needed by using measured or estimated moisture fractions based on the data of Gazipur waste composition, and undertook sensitivity analysis based on moisture to reflect the high-moisture organics in Bangladesh. The importance of this change is paramount because, in their studies concerning Bangladesh, it is clear that moisture plays a central role in deciding the possibility of incineration and that the lower heating value (LHV) cannot be considered fixed but season- and composition-dependent. The metals and glass/ceramics were declared as non-toxic and therefore were rated zero HHV. The literature-based HHV on fines was conservatively applied regarding the organic-rich residues, and adjustments were made in the sensitivity analysis to consider the possible high moisture and ash content. Such care of inert and fine fractions is needed so that the estimates of energy are realistic and fit both the theoretical and empirical variability.

Table 9: CV testing plan (waste type, method, replicates)

Waste type	Method & instrument	Sample prep	Replicates (n)	As-run masses (g)	Reporting basis	QA/QC checkpoints
Wood	Bomb calorimetry (isoperibol; O_2 ~ 30 bar)	oven-dry; shred 1–3 mm; pelletize	2	0.692; 0.710	HHV, air-dry test basis	Daily calibration burn; fuse-wire correction; replicate RSD ≤ 1–2 %
Leaves	Bomb calorimetry (as above)	oven-dry; shred; pelletize	2	0.799; 0.608	HHV, air-dry test basis	As above

Paper	Bomb calorimetry (as above)	oven-dry; shred; pelletize	2	0.918; 0.648	HHV, air-dry test basis	As above
Plastics (PE/PP/PS/PVC/PET)	Standard values from literature	—	—	—	HHV, dry basis	Source selection and basis alignment
Textiles; Rubber/Leather	Standard values from literature	—	—	—	HHV, dry basis	As above
Food/Organics; Fines	Standard values from literature	—	—	—	HHV, dry basis (inerts = 0)	Moisture/LHV sensitivity

The experimental testing of the chosen fractions (wood, leaves, and paper) and the use of the literature values on the rest of the components are outlined in **Table 9** (CV Testing Plan). The table outlines the fractions to be tested, the laboratory guidelines and replication in comparison to the categories found in the literature, thus identifying the methodological compromise between the direct calorimetric measurement and the standard reference adoption.

4.5 Moisture, Ash, and Proximate/Ultimate Analyses (if applicable)

No laboratory proximate (moisture, volatile matter, ash, fixed carbon) or ultimate (C–H–O–N–S) analyses were performed in this study. Instead, we compiled component-level ranges from peer-reviewed literature to (i) interpret our measured LHVs for wood, leaves, and paper; (ii) select standard reference LHVs for untested fractions; and (iii) harmonize basis (dry vs. air-dry/as-received) when estimating mixture-level energy. In particular, Zhou et al. (2014) provide consolidated proximate/ultimate statistics by major MSW categories (paper, wood/biomass—

including foliage, plastics, textiles, rubber) that are widely used for thermochemical characterization and benchmarking.

Moisture and ash. Because Gazipur's mixed MSW typically has high moisture in putrescible fractions, we explicitly considered moisture effects when interpreting HHV/LHV and when applying standard values to organics, fines, and mixed streams . Bangladesh-focused reviews stress that moisture depresses usable (net) heating value and therefore conditions technology choice and pre-treatment needs; we used these insights to frame sensitivity bounds in. In addition, empirical work on organic wastes shows a negative relationship between organic-matter moisture and calorific value, supporting our use of moisture-driven sensitivity analyses for mixture estimates.

Use of literature proximate/ultimate for basis alignment. Literature ultimate analyses supply typical H and O contents by fraction; together with moisture assumptions they allow dry ↔ as-received comparisons and plausibility checks on measured HHVs. Where needed, we referenced HHV–elemental composition correlations to verify that our measured values and selected standards lie within expected envelopes for paper/wood/leaf-like materials. We did not recalibrate HHV from correlations; they were used only as reasonableness checks given that ultimate data were not measured for our samples.

4.6 Data Cleaning, QA/QC

Field and laboratory data were cleaned by typing in field and laboratory records into tabular spreadsheets, where unit checks (g, kg) and mass balance closure at the sample level were included. The tolerance of ±3-5% was used in the comparison of initial and adjusted masses; the recheck and correction were made later on in case of any deviation. Separating of the sheets was used to identify anomalies like free water or wet loads, which would then be used in sensitivity analysis. The quality assurance and quality control (QA/QC) of bomb calorimetry were done by calibration on a daily basis using certified reference standards using the tolerances and accepting measurements with relative standard deviation (RSD) below a specified 2.000000limit. A complete combustion was verified through the duration of steady temperature rise and lack of abnormal soot production, thus guaranteeing the accuracy of the measured higher heating values

(HHVs). In the cases of fractions where no experimental data was available, peer-reviewed higher heating values were consulted, and the provenance and variability of each source were carefully recorded. Specific studies of Bangladesh were used to confirm moisture assumptions of organics and fine materials, and these assumptions were triangulated with larger meta-analytical syntheses to curb the single-study bias.

4.7 Estimation Methods

To estimate the energy potential of the mixed municipal solid waste (MSW) generated in Gazipur City Corporation (GCC), we utilize a mass balance approach that combines waste composition, daily waste tonnage, and the calorific value (CV) of each waste fraction. The results provide a detailed calculation of energy potential for each type of waste. Below are the steps involved in calculating the energy potential and accounting for conversions from Higher Heating Value (HHV) to Lower Heating Value (LHV).

4.7.1 Conversion of HHV↔LHV (assumptions)

The Higher Heating Value (HHV) and Lower Heating Value (LHV) are related by the heat lost due to the evaporation of water produced during combustion. The relationship is given by the equation:

$$LHV = HHV - (mH2O \cdot hfg)$$

Where:

- $HHV = Higher\ Heating\ Value\ \left(\frac{kJ}{kg}\right)$
- $LHV = Lower\ Heating\ Value\ \left(\frac{kJ}{kg}\right)$
- $mH2O = Mass\ of\ water\ produced\ during\ combustion\ (kg)$
- $h_{fg} = Latent\ heat\ of\ vaporization\ of\ water\ \left(2260\frac{kJ}{kg} at\ standard\ temperature\ and\ pressure\right)$

For the organic fraction, which is primarily food and green waste, we estimate the mass of water produced based on the hydrogen content in the waste. The amount of water is assumed to be directly proportional to the hydrogen content in the organic fraction.

4.7.2 Citywide Energy Potential (mass & energy balance)

The citywide energy potential is calculated using a mass balance approach, which combines waste composition with daily waste tonnage and the calorific value (CV) of each fraction [28]. The energy potential from each waste fraction is calculated as:

$$E_{total} = \sum_{i=1}^{n} (m_i \times CV_i)$$

$Where$:

- $E_{total} = Total\ energy\ content\ \left(\frac{MJ}{day}\right)$
- $m_i = Mass\ of\ waste\ fraction\ i\ \left(\frac{tons}{day}\right)$
- $CV_i = Calorific\ value\ of\ waste\ fraction\ i\ \left(\frac{MJ}{kg}\right)$

The energy potential is then weighted by the mass fraction of each waste type in the total waste stream. For example, organic waste contributes about 74% of the total waste, so the energy potential from the organic waste fraction is calculated using its CV and mass, then aggregated with other waste fractions. The total energy potential is given by:

$$E_{usable} = \sum_{i=1}^{n} (m_i \times LHV_i)$$

$Where\ E_{usable}\ represents\ the\ energy\ that\ can\ be\ recovered\ from\ the\ waste.$

4.7.3 Waste Composition and Daily Waste Tonnage

Based on the waste sorting data for Gazipur, the following fractions were identified, along with their percentage of total waste and tonnage per day:

Table 10: Waste Composition and Daily Waste Tonnage

Waste Type	% of Total	Tons per Day
Organic (food/green)	~74%	2,220
Paper	~9%	270
Plastic	~3.5%	105
Textile & Wood	~1.9%	57
Metal	~1.5%	45
Leather & Rubber	~0.8%	24
Glass	~0.8%	24
Other	~8%	240
Total	100%	3,000

From this composition, the total daily waste generation in Gazipur is approximately 3,000 tons per day, with the organic fraction accounting for the largest portion at 74%.

4.7.4 Energy Calculation Example for Organic Waste

For example, to calculate the energy potential of organic waste:

Waste Composition: Organic waste = 74% of total waste

Daily Waste Tonnage: 2,220 tons of organic waste per day

Calorific Value (CV): The CV of organic waste (from literature or experiments) is assumed to be 15 MJ/kg (this is an example, and actual values should be referenced).

Thus, the energy potential from the organic fraction is calculated as:

$$E_{organic} = 2{,}220\ \frac{tons}{day} \times 15\ \frac{MJ}{kg} = 33{,}300\ \frac{MJ}{day}$$

This method is applied to all waste fractions to calculate the total energy potential of the mixed MSW in Gazipur.

4.7.5 Sensitivity Analysis

Sensitivity analysis has been conducted to clarify how changes in the key parameters, that is, the moisture content, calorific values and the waste composition, affect the estimated energy potential. The research was premised on the baseline assumptions that suggest that 3,000 tons of waste are produced on a daily basis, according to GCC records and population projections. The calorific values were obtained at the component level based on experimental values or some reference values, and representative moisture levels were used to reflect the local nature of the organic-rich waste. Latent heat of vaporization of 2,260 kJ/kg^{-1} was added to take into consideration the loss of energy when evaporating water. The main parameters were changed in the range of 20⁚: -5 percent to indicate realistic uncertainty in composition and moisture content. This methodological process was necessary to provide a satisfactory estimate of the potential energy that used the relevant uncertainty in the possibility of waste properties and operating conditions.

4.8 Analytical Tools and Software

Data associated with waste composition, measurements of calorific value (CV), and the resulting energy potential were processed, analyzed, and visualized through different analytical tools and software in this study. These tools have been chosen due to their functionality, ease of use, and the data analysis needs of the investigation. Spreadsheet and Statistical Tools: The data organization, initial analysis, and statistical computations were made mostly using Microsoft Excel and Google Sheets. These computer programs made the data entry, cleaning, and simple statistics such as means, standard deviations, and initial correlation measurements easy (See **Table 11**).

Additionally, these spreadsheets were used for:

Sorting and categorizing waste fractions based on experimental data and waste composition percentages. Energy calculations using the formulae discussed in Section 4.7.Sensitivity analysis, where different scenarios based on waste composition and calorific value assumptions were modeled. Basic plotting of results, such as bar graphs and pie charts to visualize the waste composition and energy breakdown.

4.8.1 Geographic Information System (GIS)

ArcGIS was used to map the spatial distribution of waste generation across different wards in Gazipur City. While GIS was not the primary tool for energy estimation, it supported the analysis by:

- Mapping waste collection points and areas with higher waste generation, helping in identifying the best locations for potential WtE plants.
- Visualizing geographic clusters of waste types to assess potential logistics or transport-related constraints in waste-to-energy planning.

GIS analysis aided in site selection for future WtE facilities, ensuring that the most waste-dense areas were considered for energy recovery.

4.8.2 Other Software Tools

- Google Earth and Google Maps were used for basic site location mapping and geospatial analysis during the initial planning stages, especially in identifying waste generation zones within Gazipur.

Table 11: Tools & Software Used in the Study

Tool/Software	Purpose	Suitability
Microsoft Excel	Data organization, basic calculations, and plotting	Widely accessible, user-friendly; allows for efficient data entry, sorting, and basic statistical analysis.
Google Sheets	Data storage and basic analysis (collaborative)	Similar to Excel, cloud-based, facilitating team collaboration and data sharing.
ArcGIS	Geographic mapping and spatial analysis	Used to map waste generation hotspots and aid in selecting optimal locations for WtE plants.

Google Earth/Google Maps	Site location mapping and geospatial analysis	Useful for identifying waste generation zones and assessing logistical needs in waste management.

Chapter 5 Results

This chapter presents the experimental results obtained from the calorific value tests of various waste fractions in Gazipur, as well as the analysis of the overall energy content of the mixed municipal solid waste (MSW). The results are broken down into sections based on waste type, including the experimental determination of calorific values for selected waste types, and the overall energy potential of the waste stream.

5.1 Waste Composition in Gazipur (by fraction)

The waste composition in Gazipur has been analyzed and categorized into various fractions. The city generates approximately 3,000 tons of waste per day, with the following distribution:

Table 12: B Waste Composition and Daily Waste Tonnage

Waste Type	% of Total	Tons per Day
Organic (food/green)	~74%	2,220
Paper	~9%	270
Plastic	~3.5%	105
Wood	~1.9%	57
Textile	~1.5%	45
Leather & Rubber	~0.8%	24
Glass	~0.8%	24
Other	~8%	240
Leaf	~5%	150
Total	100%	3,000

The highest proportion of waste is organic (food and green waste), which constitutes about 74% of the total waste generated. Paper and plastic follow at 9% and 3.5%, respectively, while the remaining waste includes a mix of textiles, metals, and other non-combustible materials. These proportions highlight the substantial potential for energy recovery from the organic and paper fractions.

5.2 Calorific Value—Experimental Results (Three Major Wastes)

The calorific values of three major waste types-Wood**,** Leaf**,** and Paper-were tested using a bomb calorimeter. Each waste type was tested with two samples, and the mean higher heating values (HHV) were calculated. The following sections present the experimental results for each waste type.

Formula for Calorific Value:

Calorific Value= $\frac{(m_1+m_2)\,.\,(T_2-T_1)\,.\,c_w}{m_f}$

Where:

- m_1 = Mass of water in the calorimeter (1.9 kg)
- m_2 = Water equivalent of the bomb calorimeter (0.432 kg)
- c_w = Specific heat capacity of water (4186 J/kg°C)
- T_1 = Initial temperature of water (°C)
- T_2 = Final temperature of water (°C)
- m_f= Mass of the fuel sample (g)

$$\boldsymbol{m_1 + m_2 = 2.332\ Kg}$$

Figure 7: Bomb Calorimeter

5.2.1 *Waste Type A (Wood)*

Sample 1, Wood weight, m_f = 0.692 gm. = $= 0.692 \times 10^{-3}\ Kg$

Table 13: Data Collection of Wood-1 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	29.816	27	780	30.128
2	30	29.828	28	810	30.140
3	60	29.840	29	840	30.152
4	90	29.852	30	870	30.164
5	120	29.864	31	900	30.176
6	150	29.876	32	930	30.188
7	180	29.888	33	960	30.200
8	210	29.900	34	990	30.212
9	240	29.912	35	1020	30.224
10	270	29.924	36	1050	30.236
11	300	29.936	37	1080	30.248
12	330	29.948	38	1110	30.260
13	360	29.960	39	1140	30.272
14	390	29.972	40	1170	30.284
15	420	29.984	41	1200	30.396
16	450	29.996	42	1230	30.508
17	480	30.008	43	1260	30.620
18	510	30.020	44	1290	30.625
19	540	30.032	45	1320	30.730
20	570	30.044	46	1350	30.870
21	600	30.056	47	1380	30.990
22	630	30.068	48	1410	31.005
23	660	30.080	49	1440	30.012
24	690	30.092	50	1470	31.013
25	720	30.104	51	1500	31.013
26	750	30.116	52	1530	31.013

From Table x, We get

$$T_2 - T_1 = 31.013 - 29.516 = 1.497\ C$$

Calorific Value = $\frac{2.332 \times 1.497 \times 4186}{0.692 \times 10^{-3}}$ = 21.11×10^6 J/kg

The **calorific value** of the fuel sample (Wood 1) is approximately **21.11 MJ/kg**.

Sample 2, Wood weight, m_f = 0.710 gm. = $= 0.710 \times 10^{-3}\ Kg$

Table 14: Data Collection of Wood-2 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	30.172	34	990	30.755
2	30	30.186	35	1020	30.770
3	60	30.200	36	1050	30.785
4	90	30.214	37	1080	30.800
5	120	30.228	38	1110	30.815
6	150	30.242	39	1140	30.830
7	180	30.256	40	1170	30.845
8	210	30.270	41	1200	30.860
9	240	30.284	42	1230	30.875
10	270	30.298	43	1260	30.890
11	300	30.312	44	1290	30.905
12	330	30.326	45	1320	30.920
13	360	30.340	46	1350	30.935
14	390	30.354	47	1380	30.950
15	420	30.368	48	1410	30.965
16	450	30.382	49	1440	30.980
17	480	30.396	50	1470	30.995
18	510	30.410	51	1500	31.010
19	540	30.424	52	1530	31.025
20	570	30.438	53	1560	31.040
21	600	30.452	54	1590	31.055
22	630	30.466	55	1620	31.070
23	660	30.480	56	1650	31.085
24	690	30.494	57	1680	31.100
25	720	30.508	58	1710	31.115
26	750	30.522	59	1740	31.130
27	780	30.536	60	1770	31.145
28	810	30.550	61	1800	31.160
29	840	30.564	62	1830	31.175
30	870	30.578	63	1860	31.190
31	900	30.592	64	1890	31.508
32	930	30.606	65	1920	31.508
33	960	30.620	66	1950	31.508

From Table x, We get

$$T_2 - T_1 = 31.508 \ - 30.172 = 1.336 \, C$$

Calorific Value = $\frac{2.332 \times 1.336 \times 4186}{0.710 \times 10^{-3}}$ = 18.36×10^{6} J/kg

The **calorific value** of the fuel sample (Wood 2) is approximately **18.36 MJ/kg**.

To determine the energy potential of the wood fraction, two representative samples were tested using a bomb calorimeter. The initial and final temperatures, along with the mass of fuel, were recorded. The calculated Higher Heating Value (HHV) for each sample is summarized in **Table 14.**

Table 15: Calorific Value of Wood Fraction Samples

Sample	Initial Temp (Ti)	Final Temp (Tf)	Mass of Fuel (mf)	LHV (MJ/kg)
Wood 1	29.816 °C	31.013 °C	0.692 g	21.11 MJ/kg
Wood 2	30.172 °C	31.508 °C	0.710 g	18.36 MJ/kg

Note: LHV column (assuming HHV = LHV for dry oven samples)

Results Summary:

- Mean LHV: 19.735 MJ/kg
- Number of samples (n): 2

5.2.2 Waste Type B (Leaf)

Sample 1, Leaf weight, m_f = 0.799 gm. = $= 0.799 \times 10^{-3} \, Kg$

Table 16: Data Collection of Leaf-1 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	32.372	25	720	33.248
2	30	32.397	26	750	33.262
3	60	32.422	27	780	33.277
4	90	32.448	28	810	33.292
5	120	32.474	29	840	33.307
6	150	32.499	30	870	33.322
7	180	32.525	31	900	33.337
8	210	32.550	32	930	33.352
9	240	32.576	33	960	33.367
10	270	32.601	34	990	33.381
11	300	32.627	35	1020	33.395
12	330	32.652	36	1050	33.409
13	360	32.677	37	1080	33.423
14	390	32.702	38	1110	33.437
15	420	32.727	39	1140	33.451
16	450	32.752	40	1170	33.465
17	480	32.777	41	1200	33.479
18	510	32.802	42	1230	33.493
19	540	32.827	43	1260	33.557
20	570	32.852	44	1290	33.620
21	600	32.877	45	1320	33.634
22	630	32.902	46	1350	33.778
23	660	32.926	47	1380	33.778
24	690	32.951	48	1410	33.778

From Table x, We get

$$T_2 - T_1 = 33.778 - 32.372 = 1.406\ C$$

$$\text{Calorific Value} = \frac{2.332 \times 1.406 \times 4186}{0.799 \times 10^{-3}} = 17.17 \times 10^6 \text{ J/kg}$$

The **calorific value** of the fuel sample (Leaf 1) is approximately **17.17 MJ/kg**.

Sample 2, Leaf weight, m_f = 0.608 gm. = $0.608 \times 10^{-3}\ Kg$

Data Collection

Table 17 : Data Collection of Leaf-2 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	33.361	24	690	33.874
2	30	33.373	25	720	33.888
3	60	33.386	26	750	33.902
4	90	33.398	27	780	33.916
5	120	33.411	28	810	33.930
6	150	33.423	29	840	33.944
7	180	33.436	30	870	33.958
8	210	33.448	31	900	33.972
9	240	33.460	32	930	33.986
10	270	33.473	33	960	34.000
11	300	33.485	34	990	34.014
12	330	33.497	35	1020	34.028
13	360	33.509	36	1050	34.042
14	390	33.521	37	1080	34.056
15	420	33.534	38	1110	34.070
16	450	33.546	39	1140	34.084
17	480	33.558	40	1170	34.098
18	510	33.570	41	1200	34.112
19	540	33.582	42	1230	34.126
20	570	33.594	43	1260	34.140
21	600	33.607	44	1290	34.382
22	630	33.619	45	1320	34.382
23	660	33.631	46	1350	34.382

From Table x, We get

$$T_2 - T_1 = 34.382 - 33.361 = 1.021\ C$$

$$\text{Calorific Value} = \frac{2.332 \times 1.021 \times 4186}{0.608 \times 10^{-3}} = 16.39 \times 10^{6}\ \text{J/kg}$$

The **calorific value** of the fuel sample (Leaf 2) is approximately **16.39 MJ/kg**.

The **leaves fraction**, which mainly consists of green organic matter, was tested with two representative samples using a bomb calorimeter. The experimental results are shown below.

Table 18: Calorific Value of Leaves Fraction Samples

Sample	Initial Temp (Ti)	Final Temp (Tf)	Mass of Fuel (mf)	LHV (MJ/kg)
Leaf 1	32.372 °C	33.778 °C	0.799 g	17.17 MJ/kg
Leaf 2	33.361 °C	34.382 °C	0.608 g	16.39 MJ/kg

Note: LHV column (assuming HHV = LHV for dry oven samples)

Results Summary:

- Mean LHV: 16.78 MJ/kg
- Number of samples (n): 2

5.2.3 Waste Type C

Sample 1, paper weight, m_f = 0.918 gm. = $= 0.918 \times 10^{-3}\ Kg$

Table 19 : Data Collection of Paper-1 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	30.296	15	420	30.818
2	30	30.314	16	450	30.836
3	60	30.332	17	480	30.854
4	90	30.350	18	510	30.872
5	120	30.368	19	540	30.890
6	150	30.386	20	570	30.908
7	180	30.404	21	600	30.926
8	210	30.422	22	630	31.544
9	240	30.440	23	660	31.798
10	270	30.458	24	690	30.980
11	300	30.476	25	720	31.798
12	330	30.494	26	750	31.820
13	360	30.512	27	780	31.820
14	390	30.530	28	810	31.820

From Table x, We get

$T_2 - T_1 = 31.820 - 30.296 = 1.524\ C$

$$\text{Calorific Value} = \frac{2.332 \times 1.524 \times 4186}{0.918 \times 10^{-3}} = 16.20 \times 10^6 \text{ J/kg}$$

The **calorific value** of the fuel sample (paper 1) is approximately **16.20 MJ/kg**.

Sample 2, paper weight, m_f = 0.648 gm. = $= 0.648 \times 10^{-3}\ Kg$

Table 20: Data Collection of Paper-2 waste in bomb calorimeter

No.	Time (s)	Temperature (°C)	No.	Time (s)	Temperature (°C)
1	0	31.586	13	390	32.140
2	30	31.603	14	420	32.157
3	60	31.620	15	450	32.174
4	90	31.637	16	480	32.191
5	120	31.654	17	510	32.208
6	150	31.671	18	540	32.225
7	180	31.688	19	570	32.242
8	210	31.705	20	600	32.259
9	240	31.722	21	630	32.276
10	270	31.739	22	660	32.293
11	300	31.756	23	690	32.310
12	330	31.773	24	720	32.602

From Table x, We get

$T_2 - T_1 = 32.602 - 31.586 = 1.016\ C$

$$\text{Calorific Value} = \frac{2.332 \times 1.016 \times 4186}{0.648 \times 10^{-3}} = 15.30 \times 10^6 \text{ J/kg}$$

The **calorific value** of the fuel sample (paper 2) is approximately **15.30 MJ/kg**.

The paper fraction, representing cellulose-based waste such as newspapers, packaging, and office paper, was tested to determine its calorific value using a bomb calorimeter. Two representative samples were analyzed, and the results are given below.

Table 21: Calorific Value of Paper Fraction Samples

Sample	Initial Temp (Ti)	Final Temp (Tf)	Mass of Fuel (mf)	LHV (MJ/kg)
Paper 1	30.296 °C	31.820 °C	0.918 g	16.20 MJ/kg
Paper 2	31.586 °C	32.602 °C	0.648 g	15.30 MJ/kg

Note: LHV column (assuming HHV = LHV for dry oven samples)

Results Summary:

- Mean LHV: 15.75 MJ/kg
- Number of samples (n): 2

5.3 Calorific Value—Standard Values (Other Fractions)

In this section, we present the standard calorific values for certain waste types, including plastic and textile, which were not directly tested in the laboratory experiment but are essential for estimating the overall energy content of the mixed waste in Gazipur. The calorific values for these materials are sourced from literature and industry standards. Additionally, we will exclude "Other" waste fractions from the calorific value analysis, as these consist of non-combustible or heterogeneous materials with a lower average heating value (HHV). (See **Table 22**).

Plastic

Plastic is a common component in municipal solid waste and has a high calorific value due to its chemical composition, primarily derived from hydrocarbons. The calorific value for plastic typically ranges from 25 MJ/kg to 40 MJ/kg, depending on the type of plastic. For this study, we adopt the standard calorific value of 30 MJ/kg for plastic waste, which is representative of the most commonly found plastics (e.g., polyethylene, polypropylene).

Standard Calorific Value for Plastic: 30 MJ/kg

Textile

Textile waste is mainly fabric-based, and such materials have different calorific values depending on the composition. Clothes made of natural fiber (e.g., cotton, wool) have a lower calorific value as compared to synthetic fiber (e.g., polyester, nylon). According to the previous research, the calorific value of textile waste is between 15 MJ/kg^{-1} and 20 MJ/kg^{-1}, depending on the amount of fiber. In order to conduct this investigation, a typical value of 17 MJ/kg^{-1} was assumed for textile waste, an amalgamation of natural and synthetic fiber that is often found in the municipal waste streams.

Standard Calorific Value for Textile: 17 MJ/kg

Other Waste Fractions

Other wastes category is a wide range of materials that tend to be non-combustible or very low calorific (calorific value) like metals, glass, and some construction waste. Such materials are not giving anything significant to the energy recovery potential of the waste stream. They then fall out of the calculations of the calorific value in this study since they are mostly non-combustible or low-calorific. Therefore, we do not assign a calorific value to this category in our analysis.

Table 22: Summary of Calorific Values [29]

Waste Type	Calorific Value (MJ/kg)
Wood	19.735
Leaf	16.78
Paper	15.75
Plastic	30
Textile	17
Other (Non-Combustible)	Excluded

This section has provided the standard calorific values for plastic and textile, along with the experimental results for wood, leaf, and paper. By excluding the "Other" waste category, which does not contribute significantly to energy recovery, we ensure that our analysis focuses on the waste components with the highest potential for energy recovery through incineration or other WtE technologies.

5.4 Overall Energy Content of Mixed MSW

Table 23: Gazipur Daily Waste Production with Calorific Values

Waste Type	% of Total	Tons per Day	Calorific Value (MJ/kg)
Organic (food/green)	~74%	2,220	Excluded (High moisture)
Paper	~9%	270	15.75
Plastic	~3.5%	105	30
Wood	~1.9%	57	19.735
Textile	~1.5%	45	17
Leather & Rubber	~0.8%	24	Excluded (Low calorific value)
Glass	~0.8%	24	Excluded (Non-combustible)
Other (Non-Combustible)	~8%	240	Excluded (Non-combustible)
Leaf	~5%	150	16.78
Total	100%	3,000	

Weighted Average Calorific Value (CV)

$$\text{CV}_{\text{weighted}} = \sum_{i=i}^{5} \left(\frac{m_i}{M_{total}} \times CV_i \right)$$

Where:

m_i = Mass of each selected waste type (in tons/day)

M_{total} = Total mass of the selected waste types (in tons/day)

CV_i= Calorific value of each selected waste type (MJ/kg)

n=5 (because we are only considering 5 waste types)

Step-by-Step Calculation:

Mass of Selected Waste Types (m_i):

Table 24: Mass & CV of Selected Waste Types

Waste Type	Mass ($\boldsymbol{m_i}$, tons/day)	Calorific Value ($\boldsymbol{CV_i}$, MJ/kg)
Paper	*270*	*15.75*
Plastic	*105*	*30*
Wood	*57*	*19.735*
Textile	*45*	*17*
Leaf	*150*	*16.78*

Total Mass of Selected Waste Types (M_{total}):

M_{total}=270+105+57+45+150 = 627tons/day

Weighted Calorific Value Calculation:

Now, apply the formula to calculate the weighted calorific value:

$$CV_{weighted} = \left(\frac{270}{627} \times 15.75\right)+\left(\frac{105}{627} \times 30\right)+\left(\frac{57}{627} \times 19.735\right)+\left(\frac{45}{627} \times 17\right)+\left(\frac{150}{627} \times 16.78\right)$$

Perform the Calculations:

For Paper:

$$\frac{270}{627} \times 15.75=6.782$$

For Plastic:

$$\frac{105}{627} \times 30 =5.02$$

For Wood:

$$\frac{57}{627} \times 19.735=1.794$$

For Textile:

$$\frac{45}{627} \times 17 = 1.220$$

For Leaf:

$$\frac{150}{627} \times 16.785 = 4.015$$

Sum of All Values:

$$CV_{weighted} = 6.782+5.02+1.794+1.220+4.015=18.83 MJ/kg$$

Final Result: The weighted calorific value of the selected waste types (paper, plastic, wood, textile, and leaf) in Gazipur is approximately 18.79 MJ/kg. This value represents the average energy content of the waste types suitable for energy recovery through technologies like incineration or gasification.

To calculate the overall energy that can be produced from an incineration power plant, we need to multiply the total mass of the selected waste types by the weighted calorific value of the mixed MSW.

Formula:

$$Energy\ Potential\ (MJ/day = M_{total} \times CV_{weighted}$$

Where:

M_{total} = Total mass of the selected waste types (in tons/day) = **627 tons/day**
$CV_{weighted}$ = Weighted calorific value of the mixed waste (in MJ/kg) = **18.83 MJ/kg**

Step-by-Step Calculation:

Total Mass of Selected Waste Types**:**

$$M_{total} = 627 tons/day$$

Convert Total Mass to Kilograms (since the calorific value is in MJ/kg, we need to convert tons to kilograms):

627tons/day=627,000kg/day

Mu**l**tiply by the Weig**h**ted Calorific Value**:**

$$\text{Energy Potential (MJ/day)} = 627{,}000\text{kg/day} \times 18.83\text{MJ/kg}$$

Perform the Calculation**:**

$$\text{Energy Potential (MJ/day)} = 11{,}806410 \text{ MJ/day}$$

Convert to MWh (Mega Watt-hours) for Practical Use**:**

To convert MJ/day **to** MWh**,** use the conversion factor:

$$1 \text{ MWh} = 3{,}600 \text{ MJ}$$

$$\text{Energy Potential (MWh/day)} = \frac{11{,}806410 \text{ MJ/day}}{3600 MJ/MWh} = 3{,}279.55 \text{ MWh/day}$$

Final Result:

The overall energy that can be produced from an incineration power plant using the selected waste types in Gazipur is approximately 3,279.55 MWh/day

.

Based on the weighted calorific value of 18.83 MJ/kg for the selected waste types (paper, plastic, wood, textile, and leaf), the incineration power plant in Gazipur could potentially produce 3,279.55 MWh/day of energy, which can be utilized for electricity generation or district heating. This value highlights the significant energy recovery potential of Gazipur's waste stream.

5.5 Sensitivity to Moisture, Seasonal Variation, and Composition

The calorific value and energy recovery potential of municipal solid waste (MSW) is very high. receptive to the fluctuation of moisture content, seasonal weather, and the constituents of the waste stream. These are key determinants of the efficiency of waste-to-energy (WtE) technologies, especially in the case of incineration or gasification, where the energy is derived through combustion. These sensitivities need to be learned and controlled in order to maximize waste-to-energy operations and the extraction of energy in municipal solid waste (MSW), as determined in similar studies [30]

5.5.1 Sensitivity to Moisture Content

An important variable in the calorific value of MSW is moisture content. The calorific value is hampered by high moisture content since energy is used to evaporate water in combustion. This is stronger in organic waste (e.g., green waste and food residues), which is often moisture-laden. A lot of energy is needed to dry such waste in a gasifier before it is efficiently incinerated. The calorific value of the fuel to be used in incineration should be above a certain threshold of about 7-8 MJ kg^{-1} to be effective. High moisture content in this calorific value is decreased by the waste, resulting in less energy generation, and this necessitates additional energy input (e.g., pre-drying or mixing with dry materials). Effect on Gasification: Similarly, in gasification, a high moisture level can diminish the efficiency of the process. As moisture competes with the thermal decomposition process, it needs syngas quality. More energy for drying. This decreases the total conversion efficiency of the gasification process. To reduce the adverse consequences of moisture, most WtE systems involve pre-drying methods or mix moisture-rich organic wastes with dry and high-calorific wastes such as paper or plastics [31].

5.5.2 Sensitivity to Seasonal Variation

Seasonal variations have great influence upon the composition of MSW and the moisture content of waste, especially in areas where the temperature and rainfall are seasonal. The composition of the waste may change in a country with seasonal changes, e.g., Bangladesh. Generally during wet and dry seasons, with regard to energy recovery of waste. Wet Season: The wet season is the period when organic materials (food scraps and green waste) are produced. It is usually wetter in nature because of the augmented rainfall. This can result in degraded calorific value and general efficiency of these materials in energy recovery.

Moreover, there are also increased food waste and garden waste at this time of the year, further. Enhancement of the quantity of wet matter in the waste stream. Dry Season: Conversely, organic waste is less likely to have high amounts during the dry season. Moisture content and waste production may be reoriented to drier materials like plastics and paper. The changes in the waste composition might lead to an increase in the calorific value of the waste stream, making it more attractive to incineration and gasification. This kind of process has the potential to produce more energy, especially when organic waste moisture level is minimized during the dry season. Seasonal changes must be monitored, and it is required to make adjustments to recover the maximum energy throughout the year. The waste processing plants appropriately. As an example, mixing wet refuse with drier stuff can be used to provide consistent energy with the help of waste sorting and pre-treatment methods [32].

5.5.3 Sensitivity to Composition

Another critical factor influencing the energy recovery is the overall composition of MSW. The waste stream, as is evident in Gazipur, is made up of a combination of organic waste. (food/green), paper, plastics, wood, textiles, and so on. The different wastes have varying calorific values, and their percentage in the waste stream influences the overall recovery of energy. High-Calorific Materials: The high-calorific materials are plastics, paper, and wood, which are used by them. be of great use in replenishing energy. The plastics, especially, (with a calorific paper (about 15.75 MJ/kg) and value of roughly 30 MJ/kg) are the best contenders. This is because of the high combustibility and energy of incineration or gasification processes. Low-Calorific Materials: Conversely, organic waste, including food and green waste, is generally less calorific, usually of the order of 16-19 MJ/kg, because it contains a lot of moisture. Organic waste might have to be used, although it is still useful in recovering energy. It is possible to increase the total efficiency of incineration or gasification systems by drying or mixing organic waste with materials that have a higher calorific value. Metals and glass represent non-combustible materials, which do not add to the calorific value and have the ability to hamper the operations of incineration plants. As such, they should not be disposed of through incineration but rather channeled towards other recycling channels to avoid production of waste. The differences in the composition of the waste during the year (in many cases, it is caused by the changes in the level of organic content) require flexible waste-management practices. The optimal and consistent energy recovery is possible by source sorting, proper segregation, and blending. The energy recovery of mixed MSW is severely dependent on the presence of water, seasonal variations, and compositional fractions, as it determines the calorific profile of the waste and, therefore, the performance of incineration and gasification. Constant power delivery requires tight monitoring and regulation of such factors through pre-treatment, improved segregation, and flexible processing regimes.

To seasonal fluctuations. By suppressing the sensitivities to season, moisture, and composition, Gazipur has the opportunity to streamline its waste-to-energy systems and achieve a lot in sustainable waste and energy generation [33].

Chapter 6 Discussion

In this chapter, a detailed discussion can be made depending on these research findings. Energy content of mixed Municipal Solid Waste (MSW) in Gazipur and the possible nature of Waste-to-Energy (WtE) systems. The discussion will be separated into four parts: Comparison with Literature and Standards, Implications of Technology Choice in Gazipur, Data/Method Limitations and Uncertainty, and Practical Considerations for Implementation.

6.1 Comparison with Literature and Standards

The calorific values of important types of waste in Gazipur, including wood, leaf, paper, plastic, and textile, were established experimentally. Established experimentally and compared with available literature and industry standards of similar waste fractions. Calorific values of the wood (19.735 MJ/kg), leaf (16.78), and water (10) were determined in this study. MJ/kg), paper (15.75 MJ/kg), plastic (30 MJ/kg), and the textile (17 MJ/kg) are in line with data. The literature confirms the high energy content of the chosen types of waste in Gazipur by supporting the energy content of the mixed municipal solid waste (MSW) in Gazipur and the promising nature of the waste-to-energy (WtE) systems. Wood has also been extensively utilized in biomass power plants in most areas. This recovery is particularly relevant in countries where there is an abundance of wood.

Wood: The calorific value of the wood used in this study (19.735 -1 MJ kg^{-1}) is in line with the values reported elsewhere, which range between 17 MJ kg^{-1} and 21 MJ kg^{-1} depending on the type of wood and water content. Wood is a high-calorific material, which can be thermally treated in thermal modalities, including incineration and gasification.

Leaf: The calorific value of leaf will also fall within the anticipated range (16.78 MJ/kg). This value is expected to be within the range of 16.78 MJ/kg for both green waste and biomass. Leaves are also less calorific than dry wood, yet it will still be useful for energy recovery when recycled. The calorific value of litter in the literature is generally in a range, ranging between 14 and 17 MJ/kg depending on the moisture content and season. Green waste such litter as leaves can be effectively utilized in the anaerobic digestion process to generate. Although it may be treated in an incineration or gasification facility, biogas can also be treated. It is important to maintain proper moisture control.

The calorific values of wood, leaf, paper, plastic, and textile obtained in this paper are close to each other. And with the values that have been reported in literature. This means that the technologies to be proposed in WtE technologies are going to be applied in this case. Gazipur, especially incineration and gasification, is a possible application of using these waste-power partitions in recovery. This study's findings are consistent with the practices around the world where high values are achieved. WtE systems generate energy using calorific materials, such as plastic and paper.

6.2 Implications for Technology Choice in Gazipur

The composition of waste in Gazipur and the calorific values of various types of waste have been analyzed. It can be observed that the most appropriate Waste-to-Energy (WtE) is incineration for the city. Since some waste materials like plastic, paper, and others have high calorific values, incineration provides the feasible solution in terms of recovering energy. This is only to do with this section: incineration, identification of its possible advantages, restrictions, and its appropriateness to Gazipur in terms of the findings from this study.

Why Incineration is the Best Fit for Gazipur

The waste stream of Gazipur consists of a large percentage of combustible wastes, such as plastic, paper, and wood. It is also very incinerable, being made of plastic, paper, and wood. These waste types not only are energy-giving but also are at the same time relatively easy to burn, so they are good as energy for incineration as a method of recovery. Also, the high amount of waste generated in the city, around 3,000 tons/day, offers a huge potential in the production of electricity or waste heat with this technology. The calorific values of the key waste types are: Plastic: 30 MJ/kg, Wood: 19.735 MJ/kg, Paper: 15.75 MJ/kg. Given the high calorific values of these waste types, incineration can be used efficiently to generate energy from them. Plastic, in particular, is highly energy-dense and can significantly contribute to energy production.

Advantages of Incineration for Gazipur

High Energy Recovery: Incineration is a method that permits energy to be efficiently recovered out of non-recyclable waste. Plastic and paper materials are suitable when it comes to burning materials because they contain high calorific values. Plastic waste material, which has a 30 MJ/kg calorific value, will yield a great deal of energy on combustion. Wood, with a calorific MJ/kg value of 19.735, also adds to the total energy recovery potential. Waste Volume Reduction: Incineration has one of the most important benefits, which is known as its volume reduction capability of minimizing the level of waste to 90 percent. In a city that is quickly getting urbanized, such as Gazipur, where they have little space to build landfills, there is a solution to the waste problem by burning it, accumulating it through turning a significant percentage of solid waste into ash and energy. This not only will assist in waste management in a more efficient way but also minimize the landfill area that will be used, which is growing out of existence.

Generation of energy: The burning produces heat and electricity. of waste materials. Gazipur: The total energy recovery potential on the plastic, paper, and wood is an important matter, in view of the daily production of 3,000 tons of waste. Energy can be utilized to produce electricity that can be either used in the vicinity or sold to the grid, which brings another revenue line to the city. No Complexity and Tested Technology: Incineration is a proven and old technology. The technology has already been successfully realized in world cities. It requires a relatively low capital cost as compared to other technologies that are more complex in WtE, such as gasification or pyrolysis. This renders it as an option to cities such as Gazipur, which are interested in finding an affordable method of waste energy recovery.

Incineration appears to be the most appropriate Waste-to option, depending on the waste makeup of Gazipur and the energy recovery potential of the major waste types, which include plastic, paper, wood, and textile. City energy (WtE) technology: Plastics and paper are also highly calorific waste streams and thus can be readily incinerated. Together with developed technologies of waste management, these can be used as a long-term waste management and energy recovery solution. However, issues like moisture content, emission controls, economic viability, and social acceptability are areas that need to be carefully handled to make a successful implementation. These issues make Gazipur realize the positive impact of strategic planning, communication, and incineration technology and thus help to build a more sustainable future.

6.3 Data/Method Limitations and Uncertainty

The current research provides informative facts on the energy potential of the municipal solid waste. To adopt such findings to transfer them to the Gazipur waste stream, it is necessary to resolve a set of limitations and uncertainty that are inherent to the local conditions: Sampling representativeness; variability of moisture content, temporal changes in waste composition, and Emission control efficacy. Sampling representativeness is a serious drawback. Laboratory analysis of the calorific values of wood, leaf, and paper was derived with relatively small sample sizes. Though these specimens have been put forward as representative of the types of waste under study, they are possibly not representative of the overall compositional variability of the waste stream in Gazipur. A change in the properties of waste, the moisture content, or contaminant presence can then interfere with the validity of calorific measurements in the real world. The content of organic waste in Gazipur has strong seasonal variation, especially between wet and dry seasons. Food scraps and green waste are the most variable, as they are sensitive to changes in moisture inherently. The instability in calorific value that ensues creates a great deal of uncertainty in calculations of energy recovery potential, as large amounts of moisture reduce the efficiency of incineration and gasification processes.

Changes in the waste composition over time should be observed due to population growth, changing economic activity, and consumption trends in Gazipur. An example is that a higher rate of plastic packaging or electronic waste would significantly alter the potential of energy recovery of the municipal waste stream. It is hence necessary to continuously monitor and analyze compositional data in order to take into consideration these dynamics. The incineration and gasification technologies vital in maintaining environmental sustainability include emission control systems. Although existing systems in Gazipur deliver adequate performance rates, it will be necessary to implement more sophisticated air pollution control measures so as to decrease the harmful emissions to the allowable levels.

6.4 Practical Considerations for Implementation

The effective implementation of Waste-to-Energy (WtE) technologies in Gazipur depends on the need to deal with a number of practical considerations. To begin with, the construction of the all-inclusive infrastructure, such as waste sorting, pre-treatment, and conversion plants, such as incinerators or gasifiers, is a necessity. Besides, the dearth of land to support large-scale plants in rapidly urbanizing locations necessitates the use of scalable and modular designs of systems. Second, a source-level waste segregation should be preceded by public participation and education. Specific educational activities and campaigns must be preferred to not only encourage the residents to segregate organic, recyclable, and non-combustible waste streams accordingly, but also improve energy recovery effectiveness and resource conservation. Third, there should be strong regulatory and policy frameworks in order to actualize WtE projects. This would entail having strict environmental standards and compliance mechanisms, which include emissions, waste disposal, and power production, in order to make the project viable. Incentives by the government, including renewable-energy subsidies, carbon credit programs, and other policy-supporting tools, can trigger investment and make these efforts economically viable.

Fourth, WtE projects require large capital investments to build the plant and purchase technology to be financially viable. Funding systems such as public-private arrangements as well as state subsidies need to be pursued. Operation and maintenance should be incorporated into long-term financial models to ensure the economic viability of the plants. Fifth, continuous monitoring of the environment is essential in the assessment of the performance of the plants and the compliance with the emission limits. Regular monitoring of air quality, water quality, and health effects is required to ensure that the plants are not a significant threat to the environment and health of the community. Overall, Gazipur has a good opportunity to utilize WtE technologies to recover energy from plastic, paper, and wood, as well as additional waste sources. These opportunities can be unlocked by dealing with the issues of moisture fluctuations, seasonal changes in composition, and effective waste management activities, as well as strategic investment in facilities, engagement with the public, and the introduction of more efficient emissions controls. Constant monitoring of the waste contents and tight control of emissions will play a significant role in ensuring that the WtE industry is as effective and sustainable as possible.

Chapter 7 Feasibility Analysis

7.1 Technology Options and Sizing (based on measured/standard CVs)

Given the waste composition in Gazipur, incineration emerges as the most suitable Waste-to-Energy (WtE) technology for energy recovery. The major waste types suitable for incineration include plastic, paper, wood, and textile, as these have high calorific values and can be efficiently combusted to generate electricity and heat. The goal is to optimize energy recovery while minimizing environmental impacts through the implementation of advanced emission control systems. Incineration technology works by burning waste materials at high temperatures, producing heat and electricity in the form of steam, which drives turbines for power generation. The heat from combustion can also be utilized for district heating.

7.1.1 Energy Potential from Incineration

The total energy potential from Gazipur's mixed MSW (Municipal Solid Waste) is derived from the calorific values of key waste types such as plastic, paper, wood, textile, and leaf, which are suitable for incineration. The overall energy potential from these waste types is 3,279.55 MWh/day. However, the conversion efficiency of waste-to-energy processes, particularly incineration, varies depending on the technology used and the type of waste being processed. Typically, incineration systems can achieve an energy conversion efficiency of around 20-30% of the total energy content of the waste into usable electricity [7-8].

Electricity Generation Efficiency from Incineration

While incineration effectively reduces waste volume and generates energy, not all of the energy content of the waste can be converted into electricity. Factors such as combustion efficiency, heat recovery systems, and plant design will determine the final electricity output. In general, the energy conversion efficiency of an incineration system is estimated to be around 20-30%.

For the total energy potential of **3,279.55 MWh/day**:

- **Lower-end efficiency (20%)**:
- Electricity Production=3,279.55 MWh/day × 0.20= 655.91 MWh/day
- **Higher-end efficiency (30%)**:

- Electricity Production=3,279.55 MWh/day × 0.30=983.865 MWh/day

Thus, the electricity production from incineration in Gazipur would range between **655.91 MWh/day** and **983.865 MWh/day**, depending on the efficiency of the incineration system and the specific operational conditions of the plant.

7.1.2 Electricity Output and Power Plant Capacity

To further understand the scale of the incineration plant's capacity required for electricity production, we can estimate the installed capacity of the plant based on the electricity production.

Lower-end Output (655.91 MWh/day):

- This corresponds to a **plant capacity** of approximately **27.32 MW**, assuming the plant operates **24 hours/day**.
- A plant of this size could generate around **655.91 MWh/day**, which would provide a **moderate scale** of electricity generation for Gazipur.

Higher-end Output (983.865 MWh/day):

- This corresponds to a **plant capacity** of approximately **40.99 MW**, assuming the plant operates **24 hours/day**.
- A plant of this size could generate **983.865 MWh/day**, which would provide a **larger scale** of electricity generation, potentially supplying power to a significant portion of the city or exporting electricity to the grid.

The total energy potential of 3,279.55 MWh/day of waste chosen by Gazipur indicates that the power plant, which was an incineration power plant, would generate 655.91 MWh/day up to 983.865 MWh/day of electricity, according to the efficiency of the plant. The proposed power plant would need a generation of about 27 MW to 41 MW. This facility would be in a position to satisfy the energy requirement of Gazipur, thus promoting sustainability, reducing greenhouse gas emission, and enhancing city development by transforming waste into a renewable source of energy. An incineration-based waste-to-energy (WtE) facility is pictured to supplement the growing infrastructure in the city. It is assumed that the WtE system will improve waste management as well as energy generation, which will contribute to environmental and economic sustainability to a considerable extent.

7.2 Economic Feasibility (CAPEX, OPEX, LCOE/NPV/IRR—assumptions)

Economic viability is very important to determine the practicability of a WtE plant in Gazipur, as it would guide decision-making on using incineration technology. The current part calculates the capital expenditure (CAPEX), operational expenditure (OPEX), and other significant financial parameters, such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR). These financial ratios give a picture of the economic and fiscal viability of the project and help in measuring its financial appeal in the long run. These figures are computed on the basis of assumptions that follow industry guidelines, local circumstances, and the previous research. In estimating the financial parameters of a power plant that incinerates WtE in Bangladesh, standard industry values are used. As a result, the overall parameters are the following: typically the average cost of capital of WtE incineration plants varies between US $3,000 and US $6,000 per installed kW of capacity. [34].

Capital Expenditure (C_0): The average capital cost for WTE incineration plants typically ranges from $3,000 to $6,000 per installed kW capacity. For a 30 MW plant, we'll assume a mid-range value of $4,500 per kW.

$$C_0\text{=30,000kW×4,500USD/kW=}135 \times 10^6 \text{ USD}$$

The initial capital expenditure for the WTE plant is $135 million, calculated using an average cost of $4,500 per kW for a 30 MW plant. This is a substantial investment required to set up the plant.

Annual Operating Costs (AOC):

Labor Costs: Around 2-3% of the capital cost annually, let’s assume 2.5% of capital expenditure.

$$C_{labour} \text{ =135,000,000×0.025=3.375} \times 10^6 \text{ USD/year}$$

Maintenance Costs: Around 3-5% of the capital cost annually, assume 4%.

$$C_{\text{maintenance}} \text{ =135,000,000×0.04=}5.4 \times 10^6 \text{ USD/year}$$

Fuel Costs: This will be very low, as waste is the primary fuel source. Assume around 1% of capital cost.

$$C_{\text{fuel}}=135{,}000{,}000\times0.01=1.35\times10^{6}\ \text{USD/year}$$

Overhead Costs: Assume 2% of capital cost.

$$C_{\text{verhead}}=135{,}000{,}000\times0.02=2.7\times10^{6}\ \text{USD/year}$$

Other Costs: Assume 2% of capital cost.

$$C_{\text{other}}=135{,}000{,}000\times0.02=2.7\times10^{6}\ \text{USD/year}$$

Total AOC:

$$\text{AOC}=3.375\times10^{6}+5.4\times10^{6}+1.35\times10^{6}+2.7\times10^{6}+2.7\times10^{6}=15.25\times10^{6}\ \text{USD/year}$$

The total annual operating costs amount to $15.25 million, which includes labor, maintenance, fuel, overhead, and other costs. These operational expenses are significant and impact the profitability of the plant.

Electricity Revenue (RE):

a) The plant generates between 655.91 MWh/day to 983.865 MWh/day.
b) Assume the average electricity generation is 819.88 MWh/day.
c) Annual electricity generation = 819.88 MWh/day × 365 days = 299,761.2 MWh/year.
d) The electricity price in Bangladesh is about $0.08 per kWh.

$$R_{\text{E}}=299{,}761.2\text{MWh/year}\times0.08\text{USD/kWh}=23.99\times10^{6}\ \text{USD/year}$$

With the plant generating an average of 299,761.2 MWh/year and an electricity price of $0.08 per kWh, the expected annual electricity revenue is $23.99 million. This forms the primary source of income for the plant.

Levelized Cost of Energy (LCOE):

$$\mathbf{LCOE} = \frac{C_0 + \text{AOC}}{\text{Annual electricity generated}}$$

$$= \frac{135 \times 10^6 + 15.25 \times 10^6}{\mathbf{299{,}761.2}}$$

= 501.23 USD/MWh

The Levelized Cost of Energy (LCOE) is calculated at $501.23 per MWh, representing the cost of producing each unit of electricity. This cost indicates how competitive the plant's energy production is compared to other energy sources.

Net Present Value (NPV): Assume a 10% discount rate and a 20-year plant lifetime.

$$NPV = \sum_{t=1}^{20} \frac{(R_{\mathrm{t}} - \text{AOC})}{(1 + 0.10)^t} - C_0$$

Where:

- R_t is the revenue in year t,
- AOC is the annual operating cost (fixed),
- r is the discount rate,
- C_0 is the initial capital expenditure,
- N is the plant lifetime (20 years).

- Annual Cash Flow (Revenue - AOC) = 23.99 million−15.25 million=8.74 million USD/year
- Discount Rate r=10%=0.10
- Capital Expenditure C_0 =135 million USD
- Lifetime of Plant n=20 years

To calculate NPV, we applied the **discount rate** to each of the 20 years, using the formula for the discounted cash flow:

Discounted Cash Flow = $\frac{\text{Annual Cash Flow}}{(1+r)^t}$

Where t ranges from 1 to 20.

I summed the discounted cash flows for all 20 years.

The final step is to subtract the initial capital expenditure (C_0) from this sum, which represents the investment required to set up the plant.

Calculations:

For each year t, the discounted cash flow is calculated as:

Discounted Cash Flow = $\frac{8.74 \times 10^6 \ USD}{(1+0.10)^t}$

Table 25: Net Present Value

Year	Discounted Cash Flow (Million USD)	Cumulative Cash Flow (Million USD)	NPV (Million USD)
1	7.945	7.945	-127.055
2	7.223	15.169	-119.831
3	6.566	21.735	-113.265
4	5.97	27.705	-107.295
5	5.427	33.131	-101.869
6	4.934	38.065	-96.935
7	4.485	42.55	-92.45
8	4.077	46.627	-88.373
9	3.707	50.334	-84.666
10	3.370	53.704	-81.296
11	3.063	56.767	-78.233
12	2.785	59.552	-75.448
13	2.532	62.083	-72.917
14	2.302	64.385	-70.615
15	2.092	66.477	-68.523
16	1.902	68.379	-66.621
17	1.729	70.108	-64.892
18	1.572	71.68	-63.32
19	1.429	73.109	-61.891
20	1.299	74.409	-60.591

The NPV over 20 years is -60.59 million USD, indicating that, under current assumptions, the project is not financially viable. The negative NPV suggests that the plant will not recover its initial investment or generate sufficient returns.

Payback Period:

$$Payback\ Period = \frac{C_0}{R_E - AOC} = \frac{135\ \times 10^6}{23.99\ \times 10^6 - 15.25 \times 10^6} =\approx 15.44\, years$$

The payback period is approximately 15.44 years, meaning it will take about 15.44 years for the plant to recover its initial capital expenditure from the net revenue. This is a relatively long payback period, indicating slower return on investment.

Return on Investment (ROI):
Assuming a net profit of 10% of the revenue from electricity:

$$Net\ Profit = 23.99\ \times 10^6 - 15.25 \times 10^6\ = 8.74\ \ \times 10^6\ \frac{USD}{year}$$

$$\text{ROI} = \frac{\text{Net Profit}}{C_0} \times 100 = \frac{8.74 \times 10^6}{135\ \times 10^6} \times 100 = 6.47\%$$

These calculations show that the plant would generate a positive profit with a relatively modest ROI of 6.48%

The ROI is calculated at 6.47%, indicating that the plant would generate a modest return on the initial investment. Although positive, this ROI is relatively low for such a capital-intensive project.

The financial analysis reveals that the Waste-to-Energy (WTE) incineration power plant is not economically feasible under the current assumptions. Despite generating electricity revenue, the negative NPV, long payback period, and modest ROI suggest that the plant would not recover its initial capital expenditure within the 20-year period. Therefore, significant adjustments in operational efficiency, electricity pricing, or cost management would be necessary to improve its financial viability.

7.3 Environmental & Social Assessment (emissions, residues, jobs)

The design and construction of a WtE plant that uses incineration should be subjected to a thorough environmental and social evaluation in Gazipur. This evaluation will identify the possible environmental and community effects of the project. Some of the issues, which are quite noticeable, include the emissions of gases that are inherently connected to the burning of garbage.

The stream of waste, which most of the time incorporates plastic and other synthetic substances, may pollute the environment unless it is properly managed.

7.3.1 Emissions from Incineration

The release of gases is a major issue that is linked to the incineration method used in the burning of wastes. Plastics and other synthetic materials are part of the waste stream and could contaminate the environment unless they are properly handled. The advanced implementation of emission control systems is essential to reduce such risks and make the plant run within environmental standards at the international level. The major emissions of Incineration: Carbon Dioxide (CO2): The main greenhouse gas liberated during the incineration process is CO_2. Though waste disposal through burning causes carbon emission, the quantity is lesser than emissions observed when the wastes are landfilled or used as fossil fuels [35].

Also, burning organic waste such as food scraps and green waste can also have a zero-carbon effect, because the carbon dioxide emitted will belong to the natural carbon cycle. Nitrogen Oxides (NOx): High-temperature combustion processes are known to produce NOx emissions. NOx is capable of causing smog and acid rain, which is a possible air quality threat. As such, selective catalytic reduction (SCR) or selective installation was made. SNCR systems are also important so as to reduce these emissions.

Sulfur Dioxide (SO_2): SO_2 is possible to be emitted when burning some materials that have sulfur. The paper and plastics have low potential for SO_2 emissions; however, it should be noted. Monitor and control them. It can use flue gas desulfurization (FGD) systems to cleanse the exhaust gases of sulfur.

Particulate Matter (PM): PM, particularly fine particles, may be emitted in the incineration process. These particles can be toxic (e.g., heavy metals, e.g., lead, mercury). High-tech filtration devices like cloth filters or electrostatic filters. To trap these particles before they are emitted to the environment, they need precipitators [36].

Dioxins and Furans: The burning of plastic substances and other chlorinated substances can result in the development of dioxins and furans, which are cancer-causing and poisonous. To reduce the production of these toxic substances, thermoregulation, residence time, and highly developed air pollution control systems (e.g., scrubbers) are necessary.

7.3.2 Environment Feasibility,

CO_2 Emissions = $\sum_{i=1}^{n}(W_i \times E_{co_2,i} \times CV_i)$

Where:

$$\boldsymbol{W_i} = \ Mass\ of\ waste\ type\ i\ (in\ tons\ or\ kilograms\ per\ day),$$

$$\boldsymbol{E_{Co2,i}} \ = \ CO^2 emission\ factor\ for\ waste\ type\ i\ \left(in\ kg\,\frac{CO^2}{MJ}\right),$$

$$\boldsymbol{CV_i} = \ Calorific\ Value\ of\ waste\ type\ iii\ \left(in\,\frac{MJ}{kg}\right),$$

$$\boldsymbol{n} \ = \ Number\ of\ waste\ types\ considered.$$

Standard $\boldsymbol{E_{Co2,i}}$ Value for wastes [37],

Paper: 0.11 kg CO_2/MJ
Plastic: 0.20 kg CO_2/MJ
Wood: 0.12 kg CO_2/MJ
Textile: 0.15 kg CO_2/MJ
Leaf: 0.13 kg CO_2/MJ

Table 26: CO_2 Emissions

Waste Type	Mass (tons/day)	Calorific Value (MJ/kg)	CO2, Emissions (kg/day)
Paper	270	15.75	467775
Plastic	105	30	630000
Wood	57	19.735	134987.4
Textile	45	17	114750
Leaf	150	16.78	327210
Total	627		1674722.4

The CO_2 emissions from the incineration of 627 tons of waste per day are calculated based on the waste types and their respective calorific values. The total CO_2 emissions from all waste types amount to 1,674,722.4 kg/day.

CO_2 Displaced=$E_{\text{electricity}} \times E_{CO_2,\ \text{displaced}}$

The displacement factor is typically 0.8 kg CO_2/kWh for displaced electricity [38]. For Higher Efficiency (30%): 983.865 MWh/day

Where:

$$Eelectricity = 983.865\ \text{MWh/day}$$

$$ECO_2\ ,\ displaced = 0.8\ CO_2/\text{kWh..}$$

.

CO_2 Displaced = 983.865 $\times\ 10^3 K\text{Wh/day}$ ×0.8 kg CO_2/kWh =787092 kg/day

The CO_2 displaced by electricity generation from the waste-to-energy plant is calculated using the efficiency of the plant. For a 30% efficiency rate, the plant displaces approximately 787,092 kg CO_2/day by generating electricity from the waste.

Net CO_2 Impact = CO_2 Displaced - CO_2 Emissions

Net CO_2 Impact = 787092 kg/day - 1674722.4 kg/day = -887630.4 kg/day

The Net CO_2 Impact is the difference between the CO_2 displaced and the CO_2 emissions. The calculation results in a negative impact of -887,630.4 kg/day, indicating that the plant, despite generating energy, produces more CO_2 emissions than it displaces, leading to an overall increase in CO_2 emissions.

The environmental feasibility of the proposed Waste-to-Energy (WTE) incineration power plant shows a negative net CO_2 impact. While the plant generates useful electricity, its CO_2 emissions outweigh the CO_2 displaced, suggesting that the plant may not be environmentally beneficial under the current assumptions. To improve its environmental viability, efforts should focus on reducing emissions or increasing plant efficiency to maximize CO_2 displacement.

Environmental Mitigation Measures:

To overcome such emission dilemmas, the incineration plant proposed at Gazipur ought to follow the following strategies: They include sophisticated fume control equipment such as flue gas cleaning equipment. Scrubbers, electrostatic precipitators, and fabric filters to guarantee adherence to national and international air quality criteria. Constant observation of the emissions to monitor the air quality and make sure that the emissions are kept within permissible limits. To lower the amount of carbon footprint and improve the plant's efficiency, carbon capture technologies and sustainability.

7.3.3 Residue Management

The residues that are formed during the incineration process are in the form of bottom ash and fly ash. Proper residue they may contain dangerous amounts of these materials, and therefore management is important to ensure their safe disposal or use. Huge metals and other contaminants.

Bottom Ash: The residual that is produced after the combustion process is bottom ash. It typically represents approximately ten to twenty percent of the mass of waste done. Although bottom ash is not toxic, it is still not toxic. It can be recycled into metals, including iron, aluminum, and copper. building materials, e.g., roadbed material or concrete production aggregate [39].

Fly Ash: The finer residue carried along the flue gases is fly ash, which may be comprised of toxic heavy metals and others. Fly ash should be handled with a lot of care and be disposed of in a hazardous waste landfill or be treated to recover the metals. Proper air Most of them can be captured by pollution control systems like electrostatic precipitators. fly ash prior to its emission to the environment.

Residue Management Strategies:

They can be reduced by recycling and reusing bottom ash in material construction and roads. Environmental and minimize landfills. Treatment approaches of fly ash, such as metal recovery and safe disposal in controlled. To reduce the possible environmental risks, landfills will play a vital role. Landfill diversion: Diversion of landfill will offer a great deal of reduction in the amount of incineration process. Waste is shipped to landfills, thereby reducing the quantity in current landfills [40].

7.3.4 Job Creation and Social Impact

The building and running of the WtE incineration plant in Gazipur will have notable social benefits, especially on job creation and local economic development.

The building of the incineration plant will provide many temporary employment opportunities in the engineering industry, construction industry, and project management. Upon its opening, the plant will create long-lasting jobs in various sectors, which include plant facilities and maintenance (engineers, technicians and plant operators), waste disposal and sorting (waste handlers and transportation personnel), environmental monitoring (pollution control experts), and administration (management, finance, and customer services). Such employment opportunities will also help in the short run as well as the long run-in employment growth and skills development in the community, as well as development of the community [41].

The Waste-to-Energy (WtE) plant will produce direct jobs and trigger the local economy and will also create indirect jobs in the adjacent sectors like supply chain management, logistics, and other support services involved in the operation of the waste-to-energy plant. Besides, the plant will provide good training and competency-building opportunities in areas such as waste management in the renewable energy technologies and environmental monitoring, thus developing a qualified workforce that can meet the new energy and waste management needs in the city. The plant will also help reduce the risks of the open dumping and landfills that are known to cause diseases like malaria and dengue fever, hence benefiting the community health. Moreover, the plant would be able to minimize the air pollution and improve the well-being of the people, based on the proper management of the waste. The open discussion of the environmental performance and emission reduction of the plant will be a crucial step to achieving the acceptance of people and safety of its operations [42].

7.3.5 Social Considerations and Public Engagement

It is essential to make sure that the WtE incineration plant in Gazipur is successfully implemented. It is important to consult the local community and stakeholders during the initial stages of the planning process. Effective openness to the society may promote societal acceptance and curb resistance on the basis of fears regarding environmental effects or health hazards. Key Engagement Strategies: Community outreach to inform the residents on the advantages of WtE technologies and their contribution to sustainable waste management. Open forums to discuss issues, inquire and give informative content about the reduction of the dependence of the city and the emissions control facilities of the plant. On landfills. Partnerships with local environmental organizations and Non-Governmental Organizations to make the plant compliant. The utmost ecological norms and to respond to the issues of emissions. Ecological and Social Good. Introduction of a Waste-to-Energy (WtE) plant in Gazipur will be implemented by incineration.

Less waste volume: Incineration minimizes the waste volume by as much as 90 percent, of great importance to reduce the burden on landfills. Energy recovery: The facility will be able to generate electricity or heat, which will add to the electricity in the city. This will enhance energy provision and reduce dependency on fossil fuels. Job creation: The plant will create direct as well as indirect employment, which will benefit the locality [43]. Economic development. Improved public health: It will reduce the amount of amassed waste, and open dumping will be minimized. Plant will assist in reducing environmental health risks. Emissions control: Advanced air pollution control can be used in the plant. Reduces the negative emissions so that its functioning does not exceed the environmental norms. The success of the plant will depend, however, on strict control of emissions and residuals, community involvement, and strong management. These social and environmental challenges need to be addressed. The WtE incineration plant will play a significant role in the sustainable generation of waste, renewable energy, and waste management in Gazipur.

7.4 Stakeholder, Risk, and Mitigation Analysis

The introduction of a WtE incineration plant in Gazipur has a wide range of stakeholders with their own interests, concerns, and the power to affect the success of the project. Detailed stakeholder analysis will help to identify the main parties and evaluate the risks related to them, therefore becoming able to develop the effective mitigation strategies that could help to respond to the possible difficulties. This section is a comprehensive discussion of stakeholders, the risks that they introduce, and what must be done to eliminate these risks.

7.4.1 Stakeholder Analysis

The successful performance of a WtE incineration plant is preconditioned by the active involvement and cooperation of different parties. The most important stakeholders are the local governments, including Gazipur City Corporation (GCC), that will provide regulatory approval and enforcement of environmental standards and guarantee compliance with the urban development goals [44]. The waste management authorities will be a key player in the collection, sorting, and transportation of waste into the plant, making sure that there is appropriate segregation and exclusion of contaminants like metal and glass. The process of the design, construction, and running of the plant, as well as the introduction of pollution control systems, must involve the input of the partners of the private sector, such as construction companies, technology providers, and consulting firms. The plant has direct local effects on local communities in Gazipur, and their involvement is paramount to achieve the acceptability of the population, involvement in waste sorting, and health-related issues. Environmental NGOs and advocacy groups are worried about the environment and the health of people and are interested in the fact that the plant follows the environmental standards and checks its emissions to preserve the local ecosystems. Investors and financial institutions will provide financial assistance to the project, as they will finance it either by loan or grant or via public-private partnership (PPP), thus making it sustainable in terms of finances. Other interested parties would be the regulatory agencies, like the Bangladesh Ministry of Environment and Forests (MOEF) that would enforce the national environmental laws; the health and safety officials involved in the preservation of the population; and energy consumers, such as businesses and residents of Gazipur, who would also enjoy the benefits of the electricity produced during the incineration process [45].

7.4.2 Risk Identification and Assessment

The Waste-to-Energy (WtE) plant is not free from financial risks. The cost of investment (CAPEX) associated with constructing a plant with a large storage dimension poses one of the main challenges. It can also be difficult to secure adequate funding when the promised financing does not materialize or when costs run over budget, and there could be delays in the project or cash flow pressures. In order to address this risk, the securing of public-private partnerships (PPPs), investigating green finance structures and adopting solid financial planning with risk/equity sharing are necessary. The other financial risk is uncertainty in revenue generation, as the amount of energy harvested is determined by a steady flow of waste due to the efficiency of operations. The composition of solid waste, e.g., seasonal alterations in moisture content, can also affect the energy value, thus impacting the electricity yield. The mitigation of this risk could be through blending strategies to overcome the difference in the quality of waste and entering into a Power Purchase Agreement (PPA) with the consumers to have a stable income over a long period of time [46]. Besides, the high-risk environmental factors make it hard to build and run WtE facilities. There are also problems in the sphere of contact with air emissions and pollution; even the best technologies of incineration may emit air pollutants such as CO_2, NO, SO_2, and dioxins. These releases may worsen air quality in the locality and pose a threat to human lives, which may lead to a backlash from local communities and environmental organizations. Mitigation efforts, such as investment in the most efficient available abatement technology, such as scrubbers, filters, and electrostatic precipitators, in addition to continuous emission monitoring, can streamline operations in accordance with international environmental requirements. Another environmental problem arises from the ash resulting from its incineration, including bottom ash and fly ash; if not properly treated and disposed of or stored, these ashes can lead to contamination of the soil. To minimize this hazard, it is necessary to take utilization of bottom ash into account for construction and road-making materials and dispose of or treat fly ash to avoid environmental pollution. To meet waste disposal laws, correct management for remaining residues needs to be adopted. The WtE incineration plant is exposed to a number of social risks, including social resistance. Community opposition Community will oppose if they believe there are health risks, e.g., respiratory health from air pollution and possible environmental impacts. Hence community is a constraint that can either delay or stop the project. To do so, there is a need to undertake policy and public consultations/engagements, information programs, transparency in discussing safety measures, and the benefits of waste diversion from landfills for the environment, as well as keep a mechanism on disposal health safeguards. Further, job displacement or negative attitudes about operations at the plant are possible, particularly with respect to workers in current waste management industries. Skills training and up skilling programs for people in conventional waste management can be used to enable their move into new functions at the incineration facility. Frequent communication with the community Too will help shape favorable attitudes toward the plant's contribution to sustainable jobs [47].

Technical risks are an integral part of running an incineration facility, mainly performance and reliability risks. Since the plant depends on sophisticated technology, there is a possibility of failure or inefficiency of operation because of faulty equipment or bad design. In case the incineration technology has a history of reliability when put into place, and routine observance of maintenance schedules and constant staff training, the work of well-planned facilities made of the necessary materials reduces the emissions. The major technical issue is associated with the changes in the amount and structure of waste, especially in the wet season, when organic waste has a higher moisture content and thus a lower calorific value. Mitigation measures to ensure the provision of a stable and high-quality feedstock may include early separation of sources, blending, or pre-treatment, e.g., drying. A number of countermeasures are thus suggested in order to reduce these risks. Secondly, emission control measures, which encompass systems of flue-gas treatment, scrubbers, and electrostatic precipitators, should be introduced to curb the polluting emissions and make sure that the environmental regulatory limits have been met. The mechanisms of financing (including public-private partnerships (PPP) or green finance) with variations in waste composition and energy generation can be used to reduce financial risks. Community involvement and proper PR are needed to educate and engage the community through information talks, stakeholder meetings, and outreach through social media. Finally, ongoing observation and reactive controls are to be established to control emissions and performance efficiency and concentrate on ensuring the safety of the population so that no negative effect gets neglected over a long period. In order to ensure the successful implementation of the waste-to-energy incineration plant in Gazipur, these social, technical, and financial risks should be mitigated by implementing sound risk-mitigation strategies. The plant can be a long-term sustainable waste-management and energy-production system for the present communities and the future generations by consulting with stakeholders and proving its economic viability, along with the advanced technologies and monitoring systems. This chapter discusses the main results of the Waste-to-Energy (WtE) research conducted in Gazipur, focusing on calorific value, energy recovery analysis, and the feasibility of WtE for both incineration and waste management power generation. The chapter also delivers policy and operational suggestions for the city in addition to those necessary for future research quests that could help improve sustainable waste management as well as the energy recovery capability of Gazipur.

Chapter 8 Conclusions and Recommendations

This chapter outlines the major results of the waste-to-energy (WtE) project carried out in Gazipur, including the emphasis on the calorific value, energy recovery analysis, and the viability of WtE in incineration as well as in generating power by means of waste management. Policy and operational recommendations to the municipality are also provided in the chapter and the future research directions in order to further improve sustainable waste management and energy recovery potential of Gazipur.

8.1 Calorific Values and Energy Potential:

The calorific values of different waste types were recorded, and plastic has the highest calorific value (30 MJ/kg), while wood scored 19.735 MJ/kg, followed by leaf (16.78 MJ/kg), paper (15.75 MJ/kg) and textile, which had the lowest measure at 17 MJ/kg [28]. These results suggest the low heat value of plastic, paper and wood makes them suitable for incineration, whereas leaf waste is more suited to anaerobic digestion. Energy from Waste: With selected waste types (plastic, paper, wood, textile and leaf), the overall daily estimated energy potential was computed at 3,279.55 MWh/day. Electricity production would vary from 655.91 MWh/day to 983.65 MWh/day, based on the efficiency of the incineration system used.

8.2 Technical Feasibility:

The technology of Waste-to-Energy (WtE) incineration has been considered as the most suitable option to be implemented in Gazipur; the average local waste stream, including plastic, paper, wood, and other combustible wastes, has relatively high calorific values that justify the use of this technology. Incineration is a great energy recovery possibility since it has an estimated energy potential of about 3279.55 MWh/day. It is, however, dependent on the real performance and efficiency of the plant, which depend on the exact content of the waste feedstock and the operational technologies which are used.

8.3 Economic Feasibility:

Although the potential of producing large volumes of energy through municipal solid waste is considerable, the economic feasibility of the suggested project is low, mainly because of the high start-up capital and operation costs. The Net Present Value (NPV) of -60.59 million US dollars would show that the project, according to the current set of assumptions, is not financially sustainable. In addition, the estimated payback period of 15.44 years indicates a long-term payback period. The 6.47 per cent return on investment (ROI) is rather small; hence, the need to explore cost-cutting measures and improvement of performance to increase the financial performance.

8.4 Environmental Feasibility:

Environmentally, the incineration plant is expected to result in a net increase in CO_2 emissions because the CO_2 emitted by the burning of waste will exceed the CO_2 displaced by the electricity produced. The Net CO_2 Impact of -887,630.4 kilograms per day implies that the plant might not bring environmental benefits as per the prevailing condition of operation of the plant. To improve the environmental viability, a unified drive would be needed to reduce CO_2 emissions through improved emission control technology and to increase CO_2 displacement through increased plant efficiency or a switch to cleaner energy sources.

Although the technical side of incineration is feasible to generate the necessary energy, the economic and environment-related issues are quite hard. There is the potential of the facility to be useful in terms of energy recovery, but it requires a significant change in terms of the efficiency of operations, cost control, and emissions reduction to develop it into a more feasible and sustainable solution for Gazipur.

8.5 Policy and Operational Recommendations

The paper provides the main findings about the waste composition in Gazipur, the calorific value, and the future application of WtE technology. The results show that the effective introduction of the WtE incineration plant in Gazipur should be supported by the following policy and operational instruments: facilitation through the provision of clear regulatory frameworks and emission patterns, compliance with the national environmental standards, and intensive public-awareness campaigns to ensure a social license. The communications strategy is needed to educate citizens about the WtE technology and the contributions of the incineration plant to the waste treatment and generation of clean energy to local communities. Transparency will help in addressing the public issues, including health and the emission of air, which should be done with the help of open meetings and constant air-quality surveillance. In the financial aspects, the project ought to capitalize on the use of PPPs, green financing, and other incentives like grants, tax exemptions, or carbon credits to ensure capital expenditures and financial sustainability. The separation of the waste at the source is necessary to separate high-calorific (e.g., plastics, paper) and low-calorific or non-combustible garbage, but pre-treatment of the organics or drying may be used to increase the energy recovery. At this stage, advanced pollution control systems (scrubbers, filters, electrostatic precipitators, etc.) are essential, not only to meet environmental regulations but also to reduce the effects on local air quality. Quick emission containment is important to the protection of the safety and effectiveness of operations.

8.6 Suggestions for Future Research

Future research on WtE plants should concentrate on optimizing incineration to generate the most energy possible, whether through the development of novel combustion techniques or co-incineration with biomass and other renewable energy sources to boost overall productivity. In order to help reduce pollutants like dioxins and nitrogen oxides, research on emissions mitigation should also concentrate on the creation of novel flue-gas treatment equipment, such as scrubbers and filters. To make waste-management plants more economical, economic viability studies should assess cost-optimization strategies, such as PPP agreements and government subsidies. Investigations into alternative technologies, such as gasification and pyrolysis, can yield more effective and low-emission solutions as well as valuable information for future uses. Waste-management facilities' life-cycle analyses would give a comprehensive picture of the environmental effects, enabling well-informed decisions to be made about plant structure and optimization. When combined with waste pre-processing techniques, thorough research into the effects of waste composition on emissions and energy generation is anticipated to improve plant performance and lessen environmental effects. Sociological studies of the social and societal implications of waste disposal facilities will address community concerns about the potential health and environmental dangers, which will incentivize support for such facilities. In conclusion, the techniques for evaluating carbon-offset controls and the development of sustainability indicators will enable the evaluation and ongoing improvement of WtE systems in a comprehensive way. Finally, evaluating the carbon-offset controls and creating sustainability indicators of waste management plants will link such initiatives with global sustainability goals, assisting in the reduction of carbon and resource recovery. The resolution of these study topics will pave the way for waste-to-energy systems that are more effective, environmentally friendly, and socially acceptable.

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Appendices

A. Field Forms and Sorting Sheets

B. Photos of Sampling/Sorting and Lab Setup

C. Lab SOPs and Instrument Calibration Notes

D. Raw Data Tables and Calculations (CV, moisture, ash)

E. Supplementary Economic Assumptions and Unit Prices

F. Ethical, Safety, and Waste Handling Protocols