Feasibility Study on the Biogas Production Potential in the Textile Industry in Bangladesh

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DEUTSCHE ZUSAMMENARBEIT

Implemented by:
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

In cooperation with
গণপ্রজাতন্ত্রী বাংলাদেশ সরকার

Published by the
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

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As at

January 2025

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On behalf of the
German Federal Ministry for Economic Cooperation and Development (BMZ)

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Abbreviations and Acronyms

AD	Anaerobic Digestion
ANG	Adsorbent Natural Gas
AVE	Average
BCR	Benefit-Cost-Ratio
BGMEA	Bangladesh Garment Manufacturers and Exporters Association
BKMEA	Bangladesh Knitwear Manufacturers and Exporters Association
BMP	Biomethane Potential
BMZ	German Federal Ministry for Economic Cooperation and Development
BOD	Biological Oxygen Demand
BTMA	Bangladesh Textile Mills Association
CDM	Clean Development Mechanisms
CETP	Common Effluent Treatment Plants
CH_4	Methane
CHP	Combined Heat and Power
C/N	Carbon/Nitrogen
C:N:P:S	Carbon:Nitrogen:Phosphorus:Sulfur
CO_2	Carbon Dioxide
OLR	Organic Loading Rate
CAPEX	Capital Expenditures
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DM	Dry Matter
EPR	Extended Producer Responsibility
ETP	Effluent Treatment Plant
ESG	Environmental, Social, and Governance
ESIA	Environmental and Social Impact Assessments
GHG	Greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GmbH	Limited Company (original: Gesellschaft mit beschränkter Haftung)
GS	Gold Standard
GWP	Global Warming Potential
ha	Hectare
IDCOL	Infrastructure Development Company Limited
IFC	International Finance Corporation
INTEGRATION	INTEGRATION Umwelt & Energie GmbH
IRR	Internal Rate of Return
kg	Kilogram
kWh	Kilowatt hour
LEED	Leadership in Energy and Environmental
LPG	Liquified Petroleum Gas
m^3	Cubic meter
MFA	Multi Fibre Arrangement
MRF	Materials Recovery Facility

NPV	Net Present Value
O&M	Operation and Maintenance
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operational Expenditures
PaCT	Partnership for Cleaner Textile
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Printed Circuit Boards
PGF	Plug-Flow Reactor
PPP	Public-Private-Partnership
REP	Renewable Energy Policy
RMG	Ready-Made Garments
ROI	Return on Investment
RSC	RMG Sustainability Council
SCAIP	Skills for Self-Monitoring and Compliance with Clean and Fair Production in the Textile
SREDA	Sustainable and Renewable Energy Development Authority
UASB	Upflow Anaerobic Sludge Blanket
UPM	UPM Umwelt-Projekt-Management GmbH
VCS	Verified Carbon Standard
VCU	Verified Carbon Unit
VER	Verified Emission Reduction
VOC	Volatile Organic Compounds
VS	Volatile solids
WTE	Waste-to-Energy
WW	Wastewater

Executive Summary

Bangladesh's textile and garment industry is a cornerstone of the national economy, significantly contributing to earnings and employment. The production value chain encompasses fibre production and import, spinning, weaving and knitting, dyeing and finishing, garment manufacturing, and export. Each phase of the production process generates substantial organic waste, presenting opportunities for biogas production.

Many textile factories dispose of waste through landfilling or incineration, which leads to environmental pollution and greenhouse gas emissions. Some factories sell waste to third parties or use biodegradable waste for composting. For energy needs, the sector predominantly relies on fossil fuels, such as natural gas and diesel generators, which results in high energy costs.

The feasibility study on **Biogas Production in Bangladesh's Textile Industry** explores the potential of integrating biogas technology for waste and wastewater treatment and energy generation within the country's pivotal textile industry. The study identifies significant opportunities for improving waste management, reducing energy costs, and promoting environmental sustainability by implementing biogas systems. Key findings indicate that biogas production is both technically feasible and economically viable, offering considerable benefits in reducing greenhouse gas emissions and enhancing waste management practices, aligning with national and global sustainability goals. The study recommends leveraging available financing options, enhancing regulatory support, and fostering public-private partnerships to facilitate the widespread adoption of biogas systems in the textile sector.

1 Introduction

1.1 Project Background

Bangladesh is the world’s second-largest textile and clothing producer after China, with the European Union and the USA as its main buyers of textiles. The textile and garment industry are a cornerstone of the country's economy, contributing to export earnings and employment generation. The sector is key to Bangladesh’s economic growth, comprising 84.58% of total exports in 2024[1]. However, the industry faces significant environmental and social challenges, particularly in waste management, energy use, and safety and labour standards compliance.

The large volumes of organic waste generated by textile factories and the industry's high energy demands present an opportunity for biogas production as a sustainable solution. Biogas technology offers a way to address waste management issues and energy needs simultaneously. By converting organic waste into renewable energy and nutrient-rich digestate, biogas systems can help textile factories reduce their environmental footprint while potentially lowering energy costs.

Recently, a growing focus has been on improving sustainability and working conditions in Bangladesh's garment industry. In 2020, the Bangladesh Garment Manufacturers and Exporters Association (BGMEA) and the Accord on Fire and Building Safety (the Accord) in Bangladesh established the Ready-Made-Garment Sustainability Council (RSC) to monitor safety, labour, and environmental standards in the textile industry[2]. Inspected factories that comply with safety requirements under the accord receive a certification from the RSC. The International Accord for Health and Safety in the Garment and Textile Industry (International Accord) aims to ensure worker health and safety through legally binding agreements between garment brands and trade unions[3]. Bangladesh boasts the highest number of green factories, with over 200 LEED (Leadership in Energy and Environmental Design) Certified factories as of 2023, setting an example for global sustainability practices[4].

Additionally, the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH for the implementation of the Skills for self-monitoring and compliance with clean and fair production in the textile industry (SCAIP) project to strengthen the skills for self-monitoring and compliance with clean and fair production in the textile industry. This project, running from 2022 to 2026, aims to enhance the RSC's capacity to monitor and improve the sector's safety, labour, and environmental standards.[5]

Despite these initiatives, challenges remain. Many factories still struggle to comply with environmental standards. The industry faces issues such as violations of environmental legislation,

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[1] Asia News Network: https://asianews.network/bangladeshs-garment-exports-earned-a-record-47-38-billion-in-2023/, 7.11.2024

[2] RSC: https://rsc-bd.org/en, 7.11.2024

[3] International Accord: https://internationalaccord.org, 7.11.2024

[4] Light Castle: https://lightcastlepartners.com/insights/2024/02/aligning-bangladesh-apparel-with-global-sustainability-trends/#:~:text=Bangladesh%20boasts%20the%20highest%20number,fully%20integrating%20circular%20economy%20principles, 7.11.2024

[5] GIZ: https://www.giz.de/en/worldwide/124448.html, 7.22.2024

poor infrastructure, and inefficient use of natural resources. Implementing biogas technology in textile factories aligns with the overall sustainability efforts and could contribute to addressing both environmental concerns and energy needs in the sector. It represents an opportunity to improve the industry's environmental performance further while offering economic benefits through reduced energy costs and improved waste management.

However, there needs to be more knowledge regarding biodegradable waste streams and state-of-the-art biogas technologies tailored to the textile industry. To fully realise the potential of biogas in the textile industry, the Gesellschaft für Internationale Zusammenarbeit (GIZ) initiated a feasibility study as part of the SCAIP project.

1.2 Objective

GIZ assigned UPM Umwelt-Projekt-Management GmbH and INTEGRATION Umwelt & Energie GmbH to conduct an in-depth feasibility study to evaluate the technical and economic potential of biomass to biogas production in the textile sector in Bangladesh. Key focus areas are

- Technical feasibility: The assessment of the feasibility of implementing biogas production systems in Bangladesh's textile sector, focusing on the available feedstock from textile production processes, suitable biogas production technologies, and integration with existing factory infrastructure.
- Economic viability: The evaluation of the economic viability of biogas projects in the textile industry, including capital investment requirements, operational costs, and potential cost savings and return on investment.
- Policy and regulatory framework: Examination of the regulatory and policy landscape affecting biogas implementation in the textile sector.
- To identify key challenges and opportunities for biogas adoption in Bangladesh's textile factories.
- To provide recommendations for stakeholders on the potential implementation of biogas systems.

1.3 The Project Team: UPM Umwelt-Projekt-Management GmbH and INTEGRATION Umwelt & Energie GmbH

UPM Umwelt-Projekt-Management GmbH (UPM) elaborated the feasibility study in partnership with INTEGRATION Umwelt & Energie GmbH (INTEGRATION). The following experts realised the work in the name of UPM and INTEGRATION:

Heinz-Peter Mang (Team Lead and Key Expert 1), with over four decades of experience in wastewater treatment and biogas energy, led the team as team leader & biogas expert. His mastery of biogas and sanitation, along with an M.Eng. from the University of Applied Science in Giessen, Germany, and a stint as a visiting professor at the University of Science and Technology in Beijing

(USTB), underpin his role as a "waste-to-value" maestro. Mang's collaboration with global companies enhances his impact within Bangladesh and strengthens his position as an expert and Technical Director at UPM Environmental Engineering.

M. F. Shadekul Islam (Key Expert 2), the site selection and sector expert, is a national luminary with an M. Eng. from Flensburg, Germany, and a B.Sc. from RUET, Bangladesh. Influential development cooperation projects under GIZ have shaped his 18-year journey in renewable energy. Shadekul's expertise in waste management and biogas, complemented by his leadership in various projects in Bangladesh, demonstrates his ability to drive energy solutions and policy development. His multilingual and IT skills further enhance his project implementation and stakeholder communication.

Prof Dr Humayun Kabir (Key Expert 3a), the cost-benefit expert, is a respected figure in agricultural economics with a PhD from the University of Giessen, Germany. His expertise includes biogas technology and sustainable energy management. Kabir's affiliations with prestigious organisations and his mastery of data analysis tools enhance his research and teaching. His decade-long experience in energy projects across Bangladesh demonstrates his commitment to environmental and economic progress, reflected in his leadership in publications and training. He is joined by **Dr GNM Ilias (Key Expert 3b),** an environmental and business expert with a PhD in mycology and plant pathology and extensive experience in investment finance. He has been involved in wood technology and organic waste management for over three decades. His entrepreneurial flair has been instrumental in driving sustainable projects on a global scale, with a particular focus on renewable energy and waste-to-value.

MD. Osman Goni (Key Expert 4), the legal expert, advocates for the Supreme Court of Bangladesh and has extensive experience with prestigious law firms and IDCOL. His legal practice, anchored by LL.M. from Chattogram, has been integral to the energy sector, advising on solar projects and waste-to-energy conversion. Goni's legal guidance has been instrumental in shaping the legal infrastructure for major power projects, cementing his role as a key legal figure in the region.

Mrs. Stefanie Abulazm-Thieme, technical support, is an expert in biogas, sustainable sanitation and waste-to-value solutions. She has a master’s degree in decentralized energy systems and energy efficiency. She has worked for a biogas plant construction company conducting feasibility and design studies. For several years, Mrs. Abulazm-Thieme was responsible for the operation and maintenance of a large-scale biogas plant. She supported the team in the preparation of the site visits, analysis of data, reporting and realization of the conference and workshops.

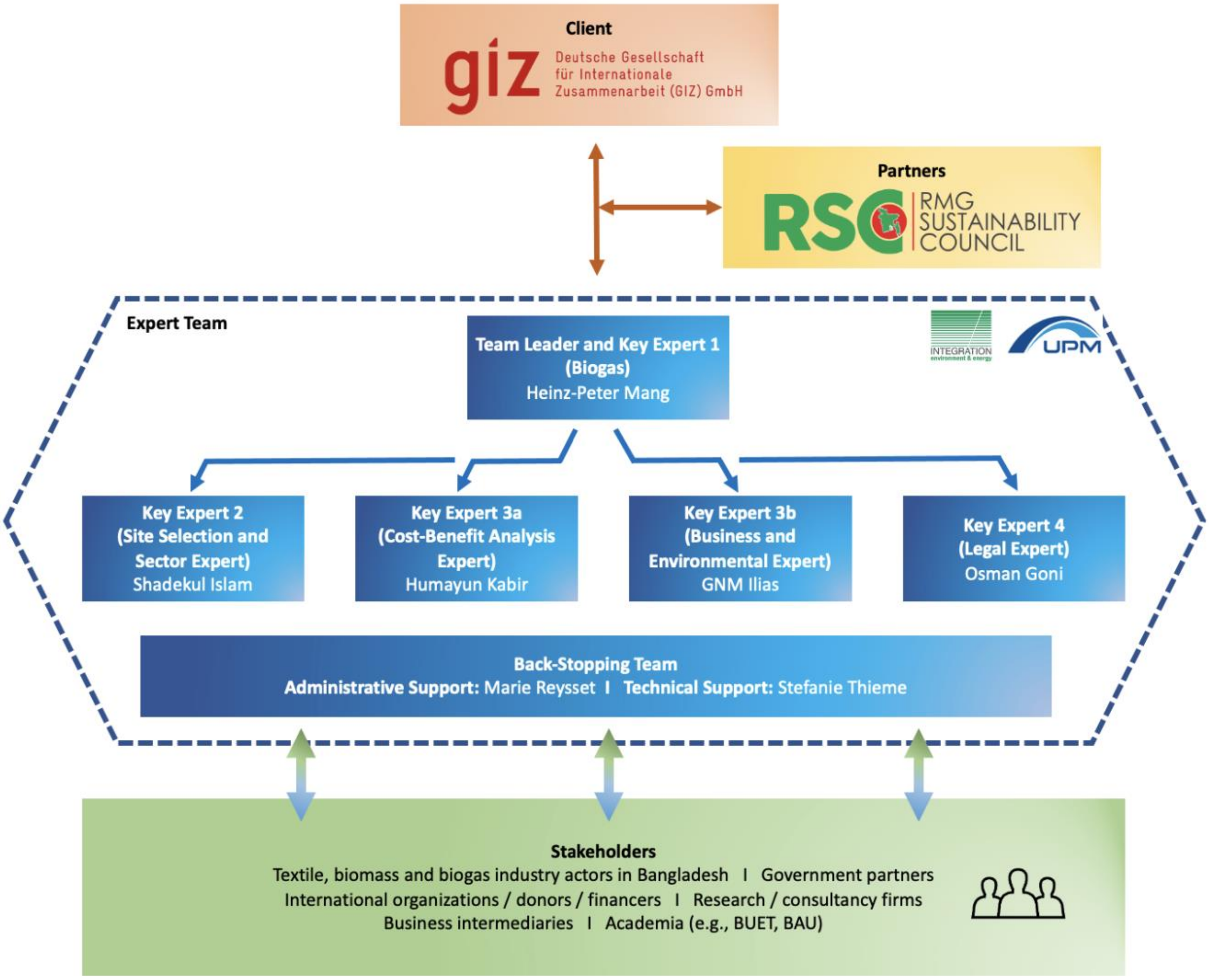

Figure 1: UPM and INTEGRATION Project Team for the Conduct of the Feasibility Study[6]

1.4 Approach

This feasibility study employed a multifaceted approach to capture a detailed and accurate picture of Bangladesh's current waste management practices and the potential for integrating biogas technology into the textile industry.

The following activities have been completed as part of the data collection and analysis process:

- Desk Research: A literature review of existing research and case studies on biogas production within the textile industry occurred. Since there are limited experiences with biogas in Bangladesh’s textile industry, international experiences were reviewed and assessed regarding their applicability to Bangladesh’s context.

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[6] UPM

- Field Surveys and Site Visits: Representative textile factories in Bangladesh were visited to collect first-hand data on organic waste generation, energy usage, and waste management practices.

- Stakeholder Consultations: The insights and feedback of factory owners, industry associations, and government officials were incorporated through interviews during site visits, industry-wide conferences, and two workshops. Expert panels further reviewed interim and final results.

- Data Analysis: Industry data and statistics were analysed. The results of the field surveys, site visits and stakeholder consultations complemented the analysis and allowed realistic and tailored conclusions and recommendations for Bangladesh’s textile industry.

- Technical and Economic Modelling: Based on preceding activities, technical variations for potential biogas systems were developed considering the different framework conditions of textile factories. Additionally, detailed financial models were developed to assess the economic implications of biogas projects, including investment requirements, operational costs, potential savings, and revenue generation opportunities.

2 Bangladesh's Ready-Made-Garment Industry and Its Waste and Energy Management System

2.1 Background of Bangladesh's Textile and RMG Industry

Bangladesh's textile and garment industry is a cornerstone of the country's economy, playing a crucial role in export earnings and employment generation. The industry's roots can be traced back almost 500 years, making I tone the world's oldest and most successful textile sectors. However, its path to becoming a global powerhouse began in the late 1970s and early 1980s.

Bangladesh is currently the second-largest clothing exporter in the world, behind China. This achievement is underpinned by a network of factories and a well-developed supply chain. According to the Bangladesh Investment Development Authority, the Ready-Made Garment (RMG) industry comprises over 4,000 factories. Around 4,000 garment factories are also registered under the Bangladesh Garment Manufacturers and Exporters Association (BGMEA), one of the most significant trade associations in the country. The BGMEA represents the woven garments, knitwear, and sweater subsectors equally.

The growth of Bangladesh's textile and RMG industry can be attributed to several factors:

- Abundant labour force: With its large population, the country provides a significant pool of workers.
- Government support: Favourable government policies, including export-oriented industrialisation strategies and establishing export processing zones, have significantly contributed to this.
- Global market conditions: The Multi Fibre Arrangement (MFA) quota system (1974 – 2005) and preferential market access to European markets initially helped Bangladesh establish its position in the global textile trade.
- Adaptation to globalisation: The industry has shown remarkable resilience and adaptability in changing global market conditions.

The textile production supply chain consists of several key stages, each contributing to transforming raw materials into finished garments. The supply chain begins with raw material sourcing, where Bangladesh imports most of its raw materials. Cotton is a primary raw material, often imported from India and the United States. The next step is yarn production, where cotton or synthetic fibres are spun into yarn. The yarn is then transformed into fabric through knitting or weaving processes. The primary textile sector in Bangladesh meets approximately 85 – 90% of the yarn demand for knit Ready-Made garments (RMG) and about 35 – 40% for woven RMG[7]. Once the fabric is produced, it undergoes dyeing, printing, and finishing. After dyeing and finishing, the fabric is cut according to patterns and sewn into garments. Accessory demand for buttons, zippers, and tags is met locally by

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[7] BTMA: https://www.btmadhaka.com/wp-content/uploads/2021/04/Basic-Data-of-BTMA-2020.pdf, 29.01.2025

about 80%. After quality checks and packaging, the products are shipped to international buyers. The following figure summarises the supply chain of the textile industry.

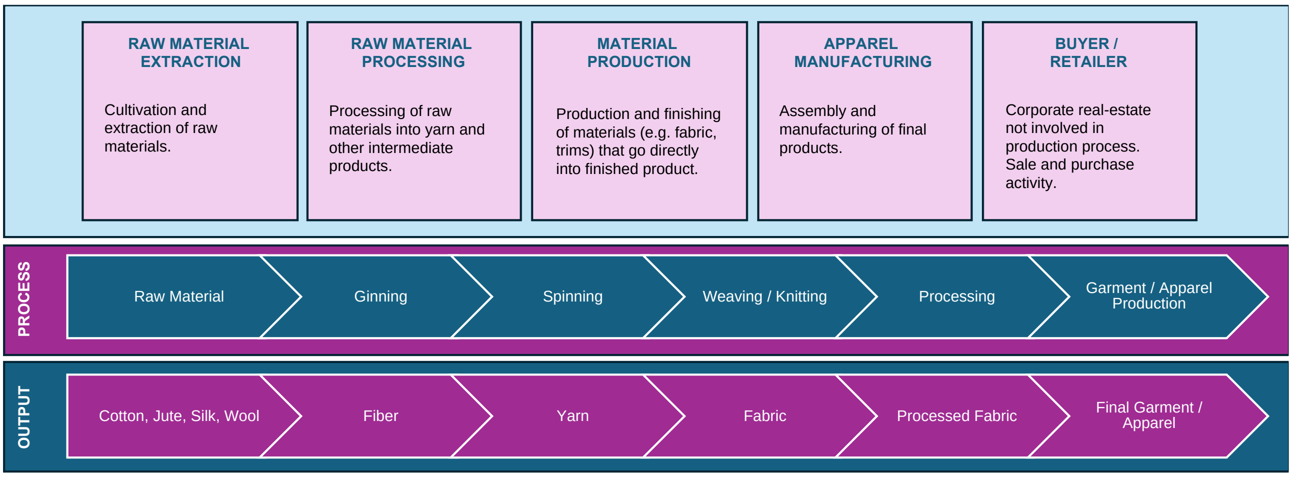

Figure 2: Supply Chain of Textile Industry[8]

2.2 Waste Along the RMG Supply Chain

Each stage of the textile industry's supply chain generates various types of waste. Bangladesh produces approximately 500,000 to 700,000 tonnes of textile and RMG pre-consumer waste annually[9]. The industry experiences a material loss of about 30% throughout the process[10]. This pre-consumer waste includes yarn, fabric scraps, roll ends, rejected pieces, and other production leftovers. The following table presents the various types of waste in the different production stages.

Table 1: Wastes along the Textile Production Process

Process	Input Products	Output Products	Type of Waste
Raw Material Processing	Fibres	Yarn	- Unusable fibre wastes - Yarn wastes, defective yarn - Excess yarn
Material Production	Yarns	Finished Fabric	- Excess input yarn - Yarn cone ends, broken yarns, defective fabric panels - Defected or shaded fabrics, excess fabrics
Apparel Manufacturing	Finished fabric	Garment articles	- Fabric rolls ends, excess fabrics - Fabric cut pieces, defective panels, waste from sewing floors - Excess garments, defective garments

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[8] UPM based on https://de.slideshare.net/slideshow/textile-supply-chainpptx/251596841#2, 29.01.2025
[9] Textile Insights: https://textileinsights.in/textile-waste-mismanagement-costs-bangladesh-billions/, 29.01.2025
[10] WE-TEAM: https://hb.diva-portal.org/smash/get/diva2:1892343/FULLTEXT01.pdf, 29.01.2025

Additionally, specific factories produce effluent from wet processing, which includes dyeing, printing, and finishing.

The approach for waste handling depends on the type of waste. Bangladesh has an extensive, albeit informal, textile waste management system with approximately 20,000 – 22,000 traders. However, the informal nature of this system poses challenges to transparency and governance. Furthermore, Bangladesh recycles only 5 – 25% of its textile waste (5 – 7% of 100% cotton and cotton-elastane waste[11], 5 – 25% for all textile waste ranges depending on the source and type of material[12]).

Proper environmental regulations specific to the textile sector only apply to effluent. The Department of Environment (DoE) enforces effluent discharge standards and promotes using Effluent Treatment Plants (ETPs) to address water pollution.

Bangladesh still needs to work on managing its textile waste effectively. Some of the consequences of insufficient waste handling are as follows:

1. Air Pollution: Uncontrolled incinerating synthetic textile processing wastes release toxic emissions, such as dioxins, furans, particulate matter, and volatile organic compounds (VOCs). Synthetic fibres generally produce more harmful emissions than natural fibres.
2. Resource Depletion: Improper management of textile scraps represents a significant resource loss, as virgin materials are continually required for new production.
3. Chemical Leaching: Textile industry processing waste often contains chemicals, such as dyes and finishing agents, that can leach into soil and water supplies when disposed of in landfills. These chemicals include azo dyes, chlorinated compounds, and heavy metals, which can contaminate ecosystems and water supplies.
4. Landfill Issues: When textile processing waste is disposed of in landfills, it undergoes decomposition, releasing hazardous chemicals that leach into soil and groundwater. This poses environmental and health risks.
5. Long-term Environmental Consequences: The leaching of chemicals can cause significant environmental harm, including bioaccumulation of heavy metals in the food chain and pollution of soil and groundwater.

A survey was conducted as part of the feasibility study to determine the wastes arising from production and factory operation. The chapter on technical feasibility describes the waste types, quantities, handling practices, and challenges.

2.3 Energy Use in the Textile Industry

Bangladesh's textile and garment industry is one of the most energy-intensive sectors, accounting for a significant portion of the country's total industrial energy consumption. This industry is highly

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[11] GIZ: https://asiagarmenthub.net/resources/2024/internal-stile-jhut-sector-project-preliminary-doc-06-june-24-1final-3-pdf.pdf, 29.01.2025

[12] WE-TEAM: https://hb.diva-portal.org/smash/get/diva2:1892343/FULLTEXT01.pdf, 29.01.2025

reliant on natural gas, comprising 98% of total consumption in fabric production. However, Bangladesh has faced a natural gas shortage in recent years, which has affected the textile industry.

Due to the natural gas shortage, many textile factories are forced to switch to alternative energy sources such as diesel generators, coal, and liquefied petroleum gas (LPG). There's a growing trend in the textile sector toward adopting renewable energy sources. Some factories are installing solar rooftop panels to supplement their energy needs and reduce dependency on the national grid.

Electricity consumption is also significant. For instance, 270 textile dyeing industries consumed 647 GWh of electricity in 2015[13]. At the same time, the national electricity grid coverage has improved, but reliability and voltage fluctuations persist, affecting textile factory production. Further, this substantial electricity use contributes to the industry's overall energy footprint. Around 15,000 kg of carbon dioxide is emitted per ton of fabric produced annually[14].

The textile sector is increasingly focused on sustainable energy practices, driven by cost considerations and pressure from international buyers to produce more environmentally friendly products. Rising energy costs, mainly due to the shift from natural gas to more expensive alternatives, pressure Bangladesh's textile industry's competitiveness.

Nonetheless, the potential for improving energy efficiency in the garment and textile sector is estimated at 25 – 31%[15]. This increase in industrial gas consumption efficiency could result in significant annual savings.

Recognising these opportunities, the Bangladesh government has initiated the "Energy Efficiency and Conversation Master Plan up to 2030". This plan presents a strong business case for deploying energy-efficient technologies in the textile industry. The industry also faces pressure to meet global clients' increasing environmental, social, and governance (ESG) requirements. In response, the Bangladesh Garment Manufacturers and Exporters Association (BGMEA) has committed to a 30% reduction in GHG emissions by 2030. Furthermore, the Partnership for Cleaner Textile (PaCT) program, supported by the International Finance Corporation (IFC), has been working with textile factories to improve energy efficiency.

Another approach is to implement biogas technology. This approach addresses the issue of waste disposal and generates valuable energy resources. Textile factories could reduce their dependence on fossil fuels. This shift would lower operational costs in the long run and decrease the sector's carbon footprint, aligning with global sustainability trends and meeting the environmental demands of international clients.

Additionally, recent research and pilot projects in Bangladesh have demonstrated the potential of biogas solutions for textile wastewater treatment:

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[13] Worldbank: https://documents1.worldbank.org/curated/ar/845631543398730054/pdf/132544-Bangladesh-Demand-Side-Energy-Efficiency-FINAL.pdf, 29.01.2025
[14] RUET: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4859374, 29.01.2025
[15] IEEFA: https://ieefa.org/resources/industrial-energy-efficiency-offers-multitude-benefits-bangladesh, 29.01.2025

- A study conducted at textile processing factories in Gazipur and Shofipur, Dhaka, implemented a cost-effective biological treatment process using Up-flow Anaerobic Sludge Blanket (UASB) technology (https://cas.iubat.edu/prof-dr-md-shohidullah-miah-textile-wastewater-treatment/).
- The UASB system offers advantages such as high organic removal efficiency, low excess sludge production, and biogas generation (https://cas.iubat.edu/prof-dr-md-shohidullah-miah-textile-wastewater-treatment/).
- Anaerobic digestion of textile sludge has been identified as a sustainable and eco-friendly sludge management method. This method produces biogas as a valuable byproduct (https://www.textiletoday.com.bd/production-of-bio-gas-from-textile-sludge-by-anaerobic-digestion-a-sustainable-eco-friendly-sludge-management-method).

The potential will be further assessed in the technical and economic feasibility chapters.

2.4 Current Policies Affecting Energy and Waste Management of Textile Factories

Bangladesh has implemented several policies and regulations that impact waste management and energy use in the textile sector:

1. Solid Waste Management Rules 2021:

    - Issued under the Environment Conservation Act 1995
    - Provides directives for extended producer responsibility (EPR)
    - Details on how to process solid waste, including incineration standards and landfill information
    - Specific formats for waste deposit and processing are included

2. National 3R Strategy for Waste Management 2010:

    - Focuses on reducing, reusing, and recycling waste

3. Bangladesh Penal Code 1860 and Code of Criminal Procedures 1898:

    - Address offences affecting public health, safety, and environmental concerns

4. Industrial Policy 2022:

    - Includes a definition of informal enterprises for the first time, though it lacks specifics for waste collection and recycling needs

5. Air Pollution Control Rules 2022:

    - To obtain necessary environmental clearances. Key considerations include:

        a. Emission Controls: Implementing advanced emission control systems to meet local and international standards, particularly for incineration technologies.

    b. ESIA Requirements: Conduct thorough Environmental and Social Impact Assessments (ESIA) to mitigate risks related to air quality, groundwater contamination, and social displacement.

6. Energy Efficiency and Conservation Master Plan:

    - Developed by SREDA and the Power Division
    - Provides a roadmap for improving energy efficiency by 2030

7. Renewable Energy Policy (REP) 2008:

    - Encourages the use of renewable energy and investment in renewable energy projects

8. Bangladesh Standards and Guidelines for Sludge Management 2015:

    - Relevant for the textile industry in several ways. The document provides classification and management guidelines for different types of sludge, including industrial sludge from textile processing. It categorises sludge into three classes:

        a. Category A: Municipal sludge, including comparable sludge

        b. Category B: Sludge from the industry, including sludge from Common Effluent Treatment Plants (CETP)

        c. Category C: Hazardous sludge from industry, including sludge from CETP

      Textile industry sludge falls under Category B or C depending on its characteristics and origin.

    - The document outlines management options for industrial sludge, including Anaerobic digestion, Controlled landfill, Thermal incineration, Land application, and Recycling of construction materials.
    - It provides specific guidance on managing sludge from the textile industry, including treatment options for textile wastewater and sludge, recycling possibilities for textile sludge, and disposal requirements for hazardous textile sludge.
    - The guidelines set standards for sludge analysis, classification, treatment, and disposal for textile industry sludge.
    - There are sections on the best textile industry wastewater and sludge management techniques.

3 Basics of Biogas Technology

3.1 Principles of Biogas Technology

A basic understanding of microbiology and the factors influencing anaerobic digestion is essential for designing biogas plants. The following sections describe anaerobic digestion and explain the principles of biogas technology.

3.1.1 Anaerobic Digestion

Anaerobic digestion (AD) is a chemical process with four steps. In it, groups of co-dependent bacteria break down complex biodegradable organic matter without free oxygen to form methane and carbon dioxide, the final product of which is biogas. Different bacteria and enzymes are involved in each of these steps: hydrolysis, acidogenesis (acidification), acetogenesis (acetic acid formation), and methanogenesis (methane formation). Digestion is completed once the substrate has undergone all four stages.

Figure 3 illustrates those four stages with the intermediate products between each stage until biogas is produced during methanogenesis. The bacteria of this fourth and final stage demand the absence of oxygen. Compared to aerobe processes, the energy yield of substrate degradation is smaller, and the generation time of anaerobic organisms is longer. Therefore, these bacteria give the speed for the entire single-stage process. In addition, desirable conditions for the methanogenesis stage, such as pH value and temperature, differ slightly from the optimum conditions in previous stages.

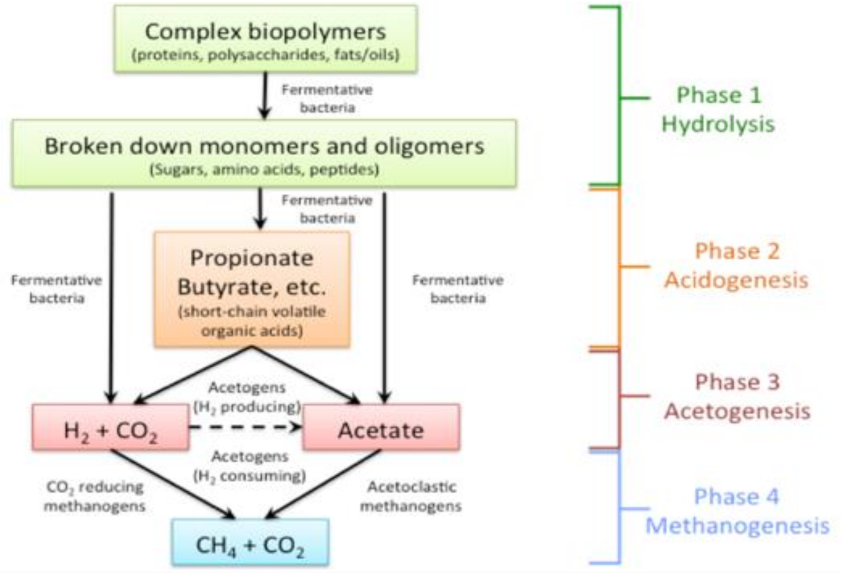

Figure 3: Schematic of 4 Phases of Biogas Production[16]

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[16] E-Education: https://www.e-education.psu.edu/egee439/node/727, 25.01.2025

Continuously operated AD is particularly appropriate for liquidised organic waste due to the ease with which bacterial colonies can move and expand within a mixed fluid medium and the simplicity of systems for storing and transferring liquid wastes. Several factors within the digester affect the physical environment and, thus, the rate of digestion and biogas production. Facility managers must monitor and maintain the following parameters within acceptable ranges: pH, temperature, C/N ratio, hydraulic and solid retention times, organic loading rate (OLR), bacterial competition, nutrient content, toxicants, and total solids content.

Industrial-sized anaerobic digestion is a proven technology but a complex process. It requires storage space for the raw (feedstock) and treated (digestate) material, dosing pumps, a gas-tight reactor with insulation, a heating system to stabilise day-night temperature variations to guarantee mesophilic conditions, mixing facilities, facilities to store the biogas, a boiler and/or internal combustion engine with a power generator, and a safety flare for excess biogas.

Biogas yields and valorisation must be maximised to sustain anaerobic processes as an economical and cost-effective alternative to other treatment technologies, including a reasonable payback period. Nevertheless, environmental and health targets on the substrate side are more critical when sanitising sludge than selling electricity, heat/cold conversion and digestate valorisation.

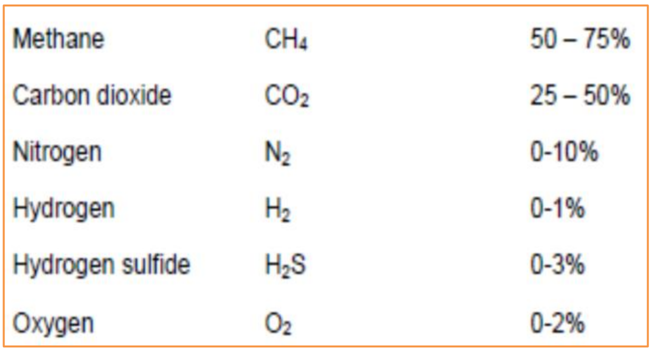
Table 2: Advantages vs disadvantages of anaerobic digestion

Advantages	Disadvantages
Effective destruction of a wide range of pathogenic and faecal microorganisms	Specialized technical input and maintenance control
Odor and a range of environmental impacts can be effectively reduced	Lower biogas production than other digester systems if not good stirred
Surplus biogas can be used to generate electricity, or distributed as cooking gas	Interlinked sensible biochemical processes: plant operation requires trained specialists
Excess of heat/cold conversion can be sold for industrial heating or cooling purposes	Neither reduction of waste volume nor of nitrogen content
Reduction of climate endangering methane emissions from stored or on land applied organic waste	Integration into external energy and heat consumer networks required.
Stabilization of organic matter, and hence reduction of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD)	
Increased immediate availability of nutrients by converting available organic nitrogen to ammoniac nitrogen	
Decreasing C/N ratio by converting carbonaceous compounds to carbon dioxide gas	

3.1.2 Co-Digestion

Co-digestion refers to using one feedstock for AD and mixing several biodegradable input materials. Additional co-feedstock improves digestion if the correct material composition, C/N ratio, and volume mix are considered. To boost hydrolysis, other materials rich in lipids and proteins can be added as the hydrolysis bacteria transform lipids and proteins more easily than cellulose, resulting in a faster process. Therefore, sorted organic waste from households or the food industry is a good co-digestion material, as is slaughterhouse waste with high protein content.

It is recommended that a laboratory analysis and biomethane potential test (BMP) be carried out to determine the biochemical composition (dry matter (DM), volatile solids (VS), and carbon-nitrogen ratio (C/N)). The analysis must include parameters such as methane production potential, feedstock mixture ratio, and acceptable organic load for the final design of the selected co-substrate. Evaluating co-substrates includes seasonal availability, purchase price, transport cost, and other typical logistics constraints.



Methane	CH_4	50 – 75%
Carbon dioxide	CO_2	25 – 50%
Nitrogen	N_2	0-10%
Hydrogen	H_2	0-1%
Hydrogen sulfide	H_2S	0-3%
Oxygen	O_2	0-2%

Figure 4: Biogas Composition

Figure 4 shows the resulting composition of methane (50 to 75%), carbon dioxide (25 to 50%), and small quantities of hydrogen, hydrogen sulphide, ammonia, and other trace gases. Substrate material, the digestion process, and the plant's technical design decisions are the main determining factors for the gas mixture.

3.1.3 Factors Affecting Anaerobic Digestion

A wide variety of factors impact the digestion process. Various parameters must be considered, especially the needs of the methanogenic bacteria, which must be fulfilled with care since they are susceptible to environmental factors and have a low growth rate[17,18]. The most important parameters are listed in the following table.

Table 3: Digestion Influencing Factors

<table>
<tr><th>Factor</th><th colspan="2">Description</th></tr>
<tr><td>Oxygen</td><td colspan="2">Absence of O2 to establish anaerobic environment (required by methanogenic archaea)</td></tr>
<tr><td>Temperature</td><td colspan="2">Three Groups:
1) Psychrophilic: <20°C
2) Mesophilic: ~20 to 40°C
3) Thermophilic: ~40 to 60°C
Fluid transition, but to maintain microorganisms, temperature fluctuations are to be avoided.
With higher temperatures, higher biogas production rate, but also more instability in case of environment changes.</td></tr>
<tr><td>pH value</td><td colspan="2">Optimum varies between digestion stages:
- Hydrolysing/acid-forming bacteria: pH 5.2 to 6.3
- Acetic acids/methanogenic archaea: pH 6.5 to 8.0
Single-stage digesters are operated at pH 6.5 to 8.0 to ensure gas production.</td></tr>
<tr><td>Feedstock composition</td><td colspan="2">Methane production depends on composition of proteins, fats and carbohydrates contained in substrate material.
Desirable C:N ratio ranges between 10 to 30:1.
Desirable C:N:P:S ratio is 600:15:5:3.</td></tr>
<tr><td rowspan="8">Inhibitors</td><td colspan="2">Can cause slow-down to complete stop of digestion processes[19].</td></tr>
<tr><td>Inhibitor</td><td>Inhibitory Concentration</td></tr>
<tr><td>Oxygen O_2</td><td>>0.1 mg/l</td></tr>
<tr><td>Hydrogen Sulphide H_2S</td><td>>50 mg/l</td></tr>
<tr><td>Volatile Fatty Acids</td><td>>2,000 mg/l</td></tr>
<tr><td>Ammoniacal Nitrogen NH</td><td>>3,500 mg/l</td></tr>
<tr><td>Heavy Metals</td><td>Cu >50 mg/l
Zn >150 mg/l
Cr >100 mg/l</td></tr>
<tr><td>Disinfectants, Antibiotics</td><td>n.s.</td></tr>
<tr><td>Total Solid Concentration</td><td colspan="2">Solids left after evaporation of substrate and its subsequent drying.
Distinguishing indicator between wet and dry fermentation.
Wet fermentation: <12 %
Dry fermentation: >15 %</td></tr>
</table>

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[17] Weiland: https://link.springer.com/article/10.1007/S00253-009-2246-7, 29.01.2025
[18] Ward et al.: https://www.sciencedirect.com/science/article/abs/pii/S0960852408001880?via%3Dihub, 29.01.2025
[19] FNR: https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf, 29.01.2025

3.2 Biogas Plant Set-up

The technological process of anaerobic digestion consists of three main phases: pretreatment of feedstock and co-substrate material, anaerobic digestion, and post-treatment of digestate and biogas.

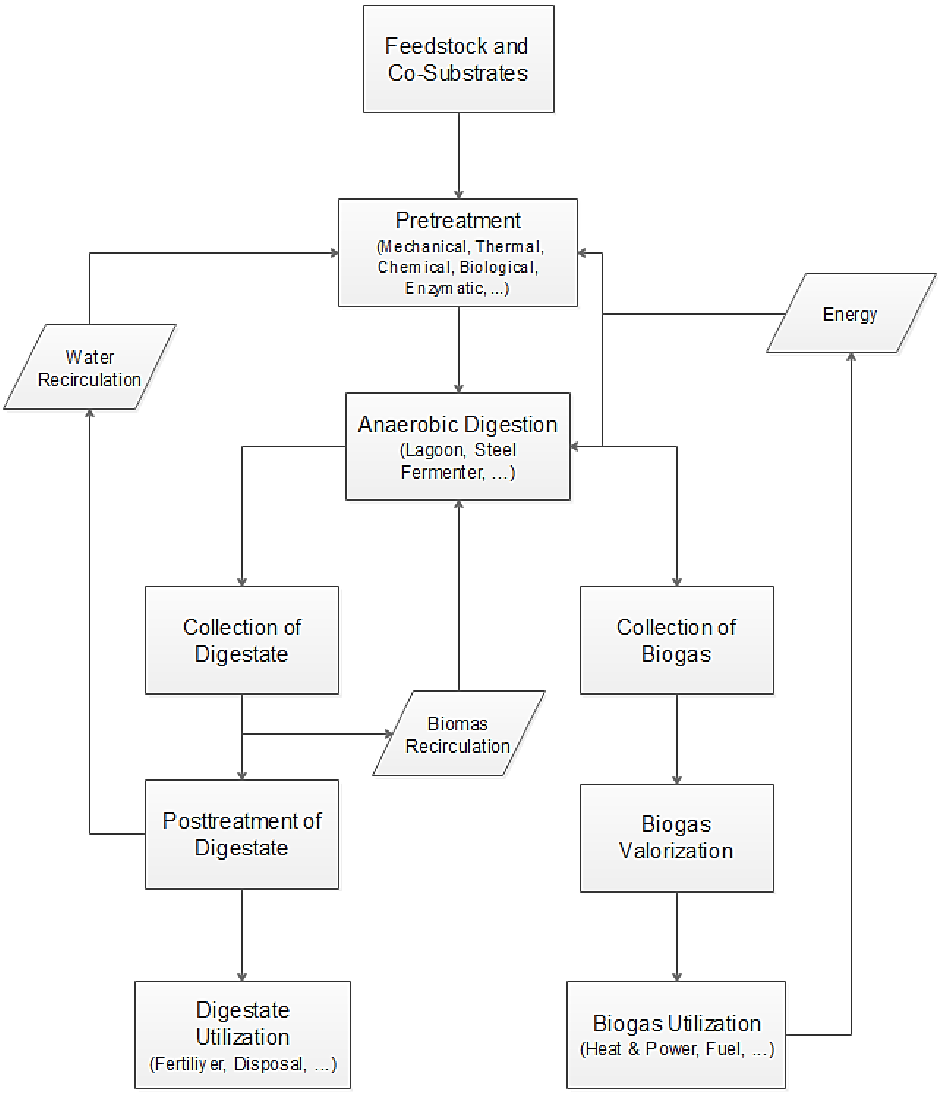

Figure 5: General Process Flow of Biogas Production[20]

3.2.1 Pre-Treatment

The content and concentration of substrates need to match the selected digestion process. Anaerobic treatment of organic waste needs a suitable concentration of dry solids between 0.1 to 15%. However, organic waste can contain impurities and inert elements such as soil, sand, skin and other inorganic material. These impurities need to be separated from the potential biogas production

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[20] UPM

substrate. The presence of impurities can otherwise lead to increased complexity in the pretreatment's operating process, which can further cause clogging, layer formation, and decreased digestion efficiency. Inorganic substances generally do not contribute to biogas production and must be excluded. Organic material can be physically, chemically, thermally or enzymatically pre-treated. Physical pretreatment is the most common. It includes methods such as grinding and mincing.

3.2.2 Biogas Post-Treatment

The steps for purifying raw biogas into pure biogas include dehydration and desulphurisation. Dehydration removes water from biogas, which is required to increase desulphurisation efficiency and avoid corrosion and damage to engine components. The amount of water or vapour that biogas can assimilate depends on the gas temperature. Inside the digester, biogas has a relative humidity of 100%. Dehydration can be achieved by condensation, adsorption, and absorption drying or cooling.

Hydrogen sulphide is toxic and forms sulfuric acid in conjunction with water vapour. The chemical compound damages engine components and decreases the performance of subsequent cleaning stages. Desulphurisation can be categorised into biological, chemical, and physical procedures. Depending on the application, rough or fine desulphurisation is necessary.

Further steps such as methane enrichment, CO_2 separation and recovery, and fine cleaning may be required depending on the biogas utilisation purposes and their requirements.

3.2.3 Biogas Valorisation

The biogas produced can be used for:

- Electricity generation through combined heat and power (CHP) units,
- Direct use as a fuel for industrial processes (e.g., boilers, dryers),
- Use as cooking gas to replace LPG or natural gas,
- Upgrading to biomethane for injection into the natural gas grid or use as vehicle fuel.

Biogas consists mainly of methane and carbon dioxide. With an increasing share of CO_2, the caloric value of biogas decreases. At the same time, methane has a caloric value of about 10 kWh/m^3, the value for biogas ranges, depending on the CH_4 content, between 5 and 7.5 kWh/m^3. Removing carbon dioxide is only necessary if upgrading to natural gas quality is intended or if CO_2 can be commercially recovered.

Several methods can be used to produce biogas. These options depend on local conditions and the product's end-use or demand. Figure 7 gives an overview of the options and the steps necessary to precondition the biogas according to the end-user.

Biogas is purified through dehydration and desulphurisation. Dehydration is commonly conducted by cooling the gas. When the temperature of the gas stream is lowered below the dew point, the condensate can be separated, and only dry biogas continues to flow towards the desulphurisation unit.

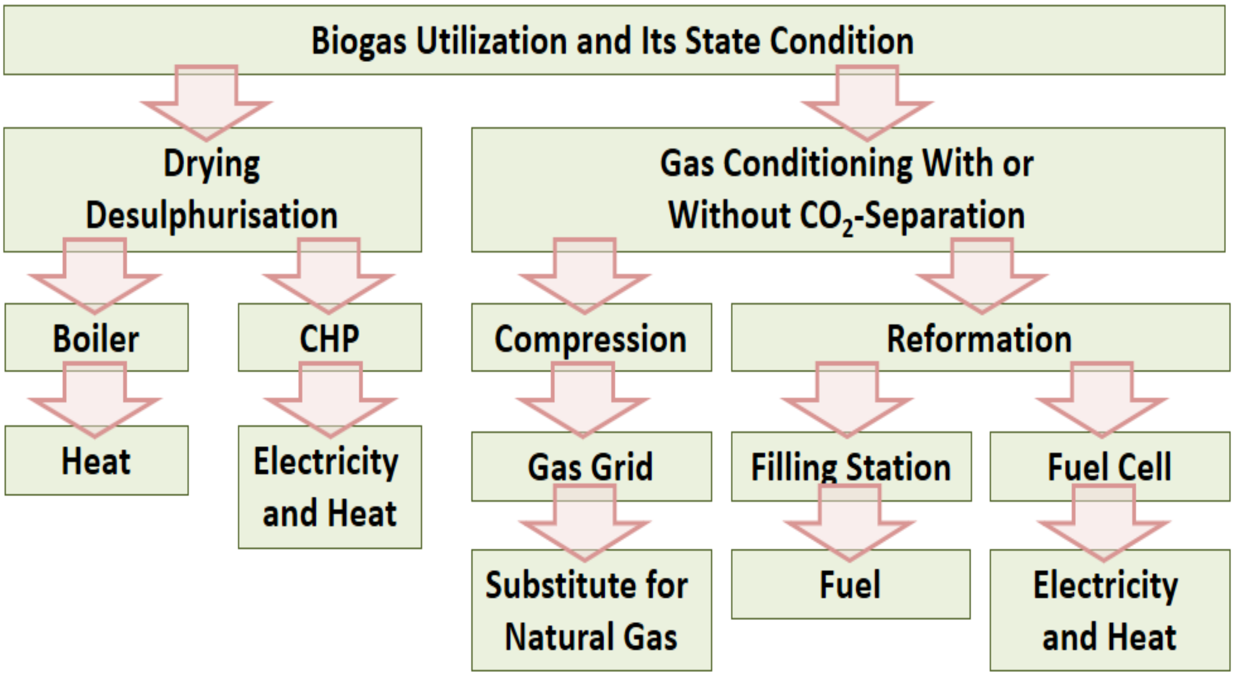

Figure 6: Possibilities for Biogas Utilization[21]

After pre-conditioning, the biogas can supply gas directly to households via the gas pipe network, gas bottling, electricity generation via a Combined Heat and Power (CHP) unit, and supply to the power grid.

Commercial boilers or burners (cookers) are used for the thermal utilisation of biogas. Due to biogas's low ignition speed compared to natural gas, special burner nozzles are required. Atmospheric burners are applied for lower heating, with capacities of up to 30kW, whereas blast burners are exclusively used for higher heat capacities. The low pressure predominantly used in free-bubbling biogas digesters is insufficient for operating boilers, so a biogas blower equipped with a pressure regulator is necessary.

Since the electrical feed-in grid connection of a CHP unit often cannot be guaranteed for a biogas plant ("state grid monopole"), and as the world market price for liquefied petrol gas (LPG) as cooking gas increases and exceeds, alternative possibilities for biogas use were investigated.

Special trucks (compressed gas trailers) can transport the biomethane upgraded from biogas to the bottling station, filling it in proper bottles. Biogas can also be fed into a cooking gas network. However, this requires pre-treatment of the biogas to achieve the quality of customarily used domestic gas. The methane content of biogas for household use or transport fuel must be at most 80%. This reduces the cost of the biomethane upgrading installation.

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[21] UPM

No upgrading is necessary for mixing up to 5% of biogas in low pressure (up to 17-20 bar) with natural gas. It is enough to purify the gas from condensed water and screen the raw biogas's Sulphur content before mixing. When bottling for cooking gas mixture, biogas upgrading to higher methane content is requested, as carbon dioxide (CO_2) has a different specific weight and non-combustible CO_2 will settle down if the gas bottle is left without rattling, as the biomethane (CH_4) part will float on top of the bottle.

Alternatives and innovations include ANG bottles since bio-methane plants produce methane gas at low pressures (40 bar). Adsorbent Natural Gas (ANG) is a perfect fit for storing this gas. Biogas was upgraded to biomethane and distributed in ANG bottles in 2014 in Thailand. The captured and cleaned biogas in these ANG tanks replace LPG usage. A Thai farm in Sri Beau barn Village in Lamphoon, near Chang Mai, Thailand, delivers bottled biogas to 180 homes, which is used for cooking to help their community be energy independent.

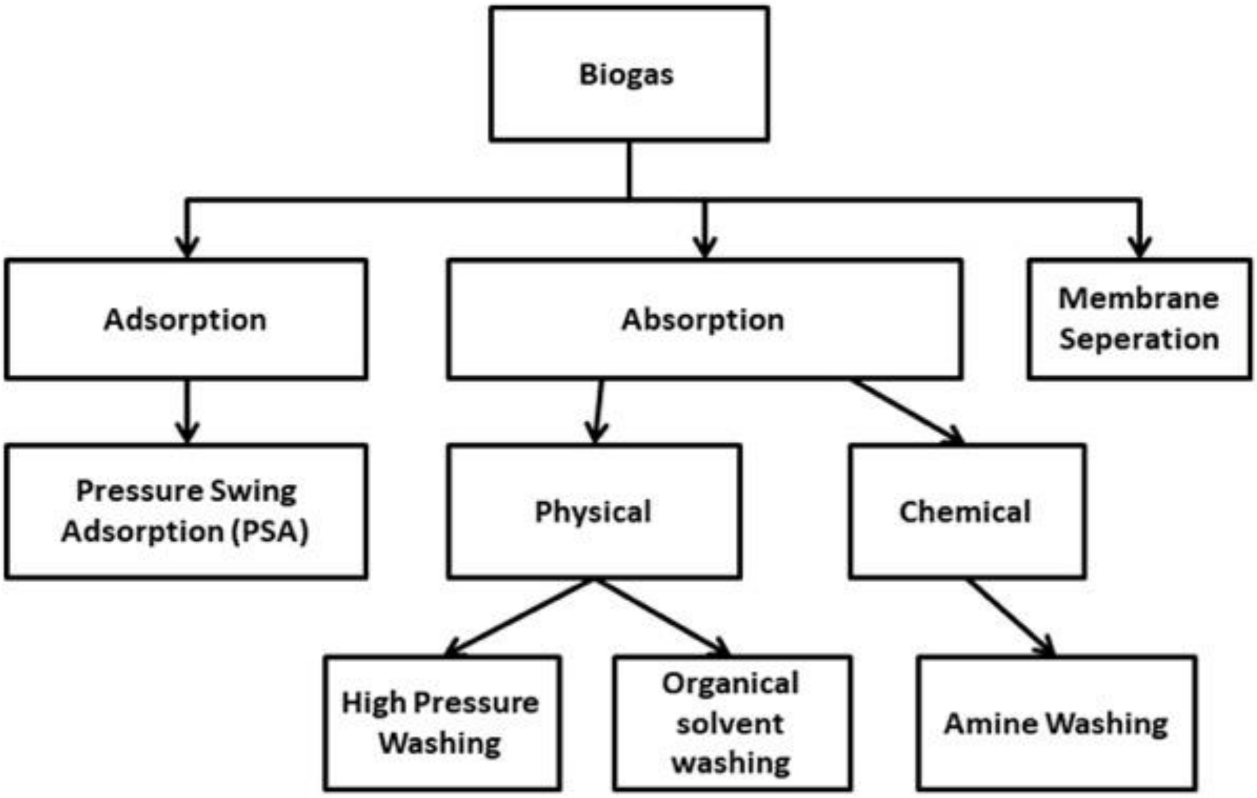

Figure 7: Biogas Upgrading Technologies

3.2.4 Digestate Post-Treatment

The digested substrate usually requires additional treatment before discharge or utilisation. Depending on the purpose of utilisation, it could be applied in a liquid or solid state.

Solid substrate requires mechanical dewatering by leaching bed (here recommended as brick filter platform), belt press or centrifuge without chemical additives before it could be used as fertiliser; it could also be stabilised by composting or dried as feedstock for biochar production. Sterilisation by heating (steaming or controlled composting) the substrate up to a certain degree for a specific time (see WHO or national standards) may be required before marketing as a soil improver by the regulations to fulfil the standards.

The liquid substrate could dilute water for the new input substrate. Still, caution must be given to nutrient or salt build-up and possible inhibition in the anaerobic digestion. Constructed wetlands could be installed to purify the liquid digestate before the final discharge. Optional ozonation or chlorination disinfection may be required to meet national standards. Although Chloride is an essential micronutrient and all crops require Chloride in small quantities, Chloride, at high concentrations, is toxic to many crops and contributes to the overall salinity.

Filtered digestate could be commercialised as BIOL, a biologically active hormone-containing substance applied as a leaf or seed fertiliser.

Within the scope of this Feasibility Study, an innovative concept is converting treated sludge to (bio)char that can be used for various purposes. The International Biochar Initiative (IBI) has defined biochar as a stable and solid carbon-rich material obtained from the thermochemical conversion of biomass in an oxygen-limited environment[22].

Practical Applications

Biogas plant + Pyrolysis: A biogas plant produces biogas from organic waste. The solid digestate can be treated through pyrolysis to recover additional energy and produce biochar. The syngas produced during pyrolysis can be used in combined heat and power (CHP) systems to generate electricity and heat.

Biogas plant + Composting: After anaerobic digestion, part of the digestate (the solid fraction) can be composted to produce a stable soil improver. While this doesn't generate energy, it enhances the value of the digestate by making it agriculturally beneficial.

Char is created by the thermochemical conversion of organic materials, called pyrolysis. Pyrolysis converts organic compounds into three fractions—one that comprises poly-condensed aromatic rings (char), which can be stored in the long term in soil (biochar); another that can be used for energy generation: a liquid bio-oil; and a third fraction, a gas (syngas), which can also be used for the synthesis of organic molecules.

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[22] Biochar: https://biochar-international.org, 2025.01.27

Figure 8: Sludge Pyrolysis Unit for Char Production

The advantage of the pyrolysis process is the effective reduction of volume and mass of the dewatered sludge and vaporisation of organic toxic agents from the sludge (e.g. PCB, PAH) into harmless substances in the combustion chamber. Mercury and its compounds are thermos-decomposed and vaporised as well.

Pyrolysis also achieves energy recovery. The target is that no supplementary fuel supply is required for standard operations, only for the start-ups, leading to significant running cost reductions. Self-contained pyrolysis sludge treatment facility of the dewatered digestate or sludge with a 60-80% moisture content reduces sludge to 10~12% of the initial amount. Proper mechanical sludge dewatering (25-30% moisture) followed by a dryer and the pyrolysis process can simultaneously dispose of waste and generate considerable energy.

Table 4: Advantages vs Disadvantages of Biochar Technology

Advantages	Disadvantages
Increases the available nutrients for plant growth, water retention capability of the soil, and reduces the amount of fertilizer by preventing the leaching of nutrients out of the soil.	Batch manufacturing of biochar is simple, continuous charring needs more engineering skills.
Reduces methane and nitrous oxide emissions from soil, thus further reducing GHGs emissions.	Applications sometimes disturb the physical and chemical balances of nutrients in the rhizosphere.
Can be utilized in many applications as a replacement for other biomass energy systems.	Generally, helps the growth of undesirable weeds.
Can be used as a soil amendment to increase plant growth yield.	

Co-pyrolysis refers to using not only one feedstock but the mixing of several char-able input materials. Co-feedstock inputs improve the pyrolysis process if the correct material composition, the dry matter ratio, and the volume mix are incorporated. Sorted organic or non-organic but carbon-rich waste from the textile industry is an excellent co-pyrolysis material. Evaluation of co-substrates includes their seasonal availability over the year, price of purchase and transport, logistic challenges and other potential constraints should also be considered.

Figure 9: Filling Process of Biochar from Co-Pyrolysis of Various Biomasses

3.2.5 Char Valorisation

The digestate sludge char can be marketed directly as raw material for the fertiliser industry. It is highly valued for its purity and the high plant availability of recycled phosphorus.

Other co-feedstock (from other non-digestible textile wastes) can be converted to high-quality char in the reactor. In this case, the structure of the carbon contained in the mineralised material is similar to charcoal. Bound in the char, the carbon is no longer released as climate-hazardous and flammable carbon dioxide, and – used as a soil additive – it remains in the soil. It serves as a soil improver and reservoir for micronutrients and water.

The Christian Commission for Development in Bangladesh (CCDB) reported that village 'Biochar Enterprise Groups' pay around 50 Tk/kg for biochar. Biochar prices in Bangladesh appear to be variable.

The following overview is sourced from the publications of the Switzerland-based Ithaka Institute, directed by Hans-Peter Schmidt, Ancienne Eglise 9, CH-1974 Arbaz.

Table 5: Overview of Application Possibilities for Biochar

Category	Application Possibilities
Animal farming	- Silage agent - Feed additive / supplement - Litter additive - Slurry treatment - Manure composting - Water treatment in fish farming
Soil conditioner	- Carbon fertilizer - Compost additive - Substitute for peat in potting soil - Plant protection - Compensatory fertiliser for trace elements
Building sector	- Insulation - Air decontamination - Decontamination of earth foundations - Humidity regulation - Protection against electromagnetic radiation (“electro-smog”)
Decontamination	- Soil additive for soil remediation – particularly on former mine works, military bases and landfill sites - Soil substrates used in cleaning wastewater; particularly urban wastewater contaminated by heavy metals. - A barrier preventing pesticides from getting into surface water - Treating pond and lake water
Biogas production	- Biomass additive - Biogas slurry treatment
Wastewater treatment	- Alternative to active carbon filter - Pre-rinsing additive - Soil substrate for organic plant beds - Composting toilets
Water treatment	- Micro-filters

	- Macro-filters in developing countries
Other industrial uses	- Exhaust filters: controlling emissions, room air filters - Industrial materials: carbon fibres, plastics - Electronics: semiconductors, batteries - Metallurgy: metal reduction - Cosmetics: soaps, skin cream, therapeutic bath additives - Paints and colouring: food colourants, industrial paints - Energy production: pellets, substitute for lignite
Medicines	- Detoxification - Carrier for active pharmaceutical ingredients - Cataplasm for insect bites, abscesses and eczema
Textiles	- Fabrice additive for functional underwear - Thermal insulation for functional clothing - Deodorant for shoe soles
Wellness	- Filling for mattresses - Filling for pillows
Food conservation	- Odour and humidity control - Additive for packaging material

3.2.6 Combining Biogas (Anaerobic Digestion) and Pyrolysis

Anaerobic digestion and pyrolysis can be combined to enhance the Waste-to-Energy (WTE) process. Combining these technologies can offer complementary benefits, optimising energy recovery and waste management. By integrating AD and pyrolysis, the organic waste components are first treated to produce biogas, and the residuals, especially those with lower biodegradability and higher calorific value, are further processed through pyrolysis to extract additional energy forms.

- Anaerobic Digestion (AD) converts the organic fraction into biogas, primarily methane, which can be used for electricity generation or heating.
- Pyrolysis thermally decomposes the remaining non-organic and low-moisture waste fractions (digestate from the anaerobic digestion process that has undergone further treatment) in an oxygen-limited environment to produce pyrolysis oil, syngas (mixture of gases including hydrogen, methane, carbon monoxide, carbon dioxide, and other hydrocarbons), and (bio-)char.
- Pyrolysis can achieve substantial reductions in both waste volume (80 – 90%) and weight (70 – 80%).

This dual approach can lead to more significant waste volume reduction than using either technology alone. However, certain considerations need to be kept in mind:

- Sequential Processing: Implementing AD followed by pyrolysis allows for the utilisation of biogas generated from the digestate, potentially powering the pyrolysis process itself.
- Feedstock Preparation/Digestate Post-Treatment: The effluent from AD may require drying or stabilisation before pyrolysis to ensure optimal performance and energy efficiency.
- Resource Recovery: The integration facilitates the recovery of multiple energy streams, including biogas, pyrolysis oil, and potentially high-quality char, which can be used as soil amendments or fuel additives.

- Technical Complexity: Combining AD and pyrolysis increases the complexity of the WTE facility, requiring more sophisticated control systems and operational expertise.
- Capital Investment: The initial investment may be higher due to the need for additional equipment and infrastructure to support both technologies.
- Economic Viability: Ensuring that the combined systems are economically feasible requires careful assessment of energy yields, operational costs, and potential revenue streams from multiple energy products. Pyrolysis in a biogas-to-power plant set-up creates a circular system that opens new markets for the subproducts.

Fertilizer	**Biochar**					**Special Applications**
	Digestate	Agriculture	Forestry	Municipal Waste	Production Waste	
Sewage Sludge	Silage	Grain and Grain Waste	Wood Chips	Bush and Tree Cuttings	Nutshells	Fly Ash
Flotation Slimes	Renewable Biomass	Husks	Sawdust	Green Waste	Fruitstones	Plastics, Rubber
Liquid Manure	Foodwaste	Dung, Droppings, Manure	Wood Pellets	Landscaping Materials	Old Bread	Alu Flakes
	Organic Waste Collection Bin	Slaughterhouse Waste	Wood from Short Rotation Forestry	Screened Compost	Malt and Roasting Residues	Rinsing Slurry
		Silage waste		Organic Waste Collection Bin	Rape, Draff	Oil Contaminated Iron Slurry
		Hay, Straw	Sawn Timber		Residues from Extraction	
					Okara, Carrots	

Figure 10: Suitable Biomass for Pyrolysis[23]

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[23] PYREG

4 Technical Feasibility

4.1 Basis for Feasibility Assessment

As part of a field survey, eleven specific textile production factories and industrial zones were visited from March to July 2024. The survey that guided these visits covered the following topics:

- Waste sources and management practices: This section determined the occurring waste types and quantities. Further, it explored current disposal management practices and challenges that factories are faced with.
- Energy use and sources: This sector collected data on primary sources of energy currently used, monthly energy consumption and associated costs.
- Biogas solution perspectives: This section was used to determine the awareness of biogas solutions as well as the benefits and concerns related to this technology.
- Sustainability initiatives: This section discussed existing sustainability practices as well as goals and ambition related to environmental sustainability that factories follow.

Additionally, to the factories itself, the surrounding areas of the factories was evaluated. The results and conclusions from these factory surveys will be presented in the following chapters.

4.2 Available Feedstock for Biogas Production in Textile Production Factories

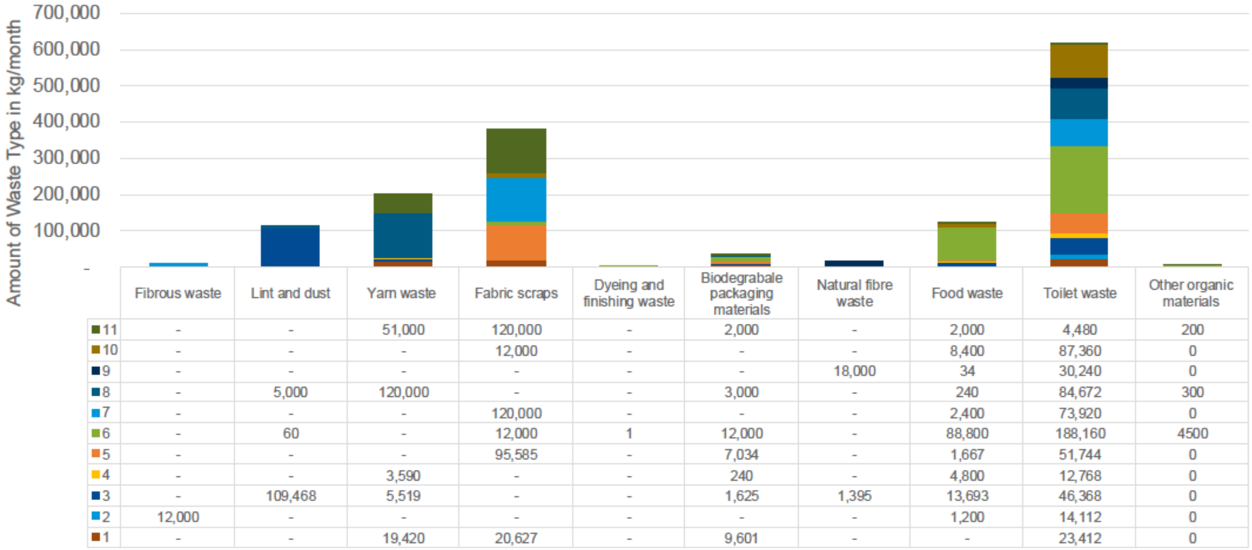
Waste streams were collected from eleven textile factories with 49,542 employees. The quantity and composition of waste streams varies depending on the size and type of textile factory. The following table lists the different waste types that were surveyed at the factories.

Table 6: Waste Types Surveyed at the 11 Textile Factories

Waste Type	Description	Recommended Treatment Method
Fibrous Waste	Waste materials consisting of natural or synthetic fibres. This can include off-cuts, trimmings, and discarded fibres from spinning, weaving, or knitting operations.	- Combustion in boilers to generate heat and steam - Recycling (depending on the fibre type and market demand)
Lint and Dust	Fine particulate matter composed of loose fibres and small debris generated during manufacturing, particularly in spinning and weaving processes.	- Combustion in boiler to generate energy - Landfill
Yarn Waste	Discarded or unused yarn from spinning, winding and weaving processes.	- Combustion in boiler to generate energy - Recycling (if clean and sorted)
Fabric Scraps	Unused or discarded pieces of fabric resulting from cutting and other manufacturing processes.	- Combustion - Recycling (depending on type of fabric)
Dyeing and Finishing Waste	Liquid and solid waste generated from textile dyeing and finishing processes. This includes spent dye baths, chemical residues, and sludge from wastewater treatment.	- Hazardous waste disposal
Biodegradable Packaging Materials	Packaging materials designed to decompose naturally through biological processes. These may include materials such as paper, cardboard, or bioplastics.	- Anaerobic digestion - Composting
Natural Fibre Waste	Waste composed of plant-based or animal-based fibres, such as cotton, wool, silk, or line, generated during various stages of the textile production.	- Combustion - Recycling (depending on fibre quality and contamination levels)
Food and Kitchen Waste	Organic waste derived from food preparation and consumption activities.	- Anaerobic digestion
Toilet Waste (faecal sludge from septic tanks)	Human excreta and associated wastewater collected in septic systems.	- Anaerobic digestion
Cleaning Agents	Cleaning products used in industrial cleaning processes.	- Anaerobic digestion (if cleaning agent is biodegradable and organic) - Chemical treatment

In addition to typical textile production waste, waste related to factory operations was to be observed. This includes food and kitchen waste that arises from the meal preparation and consumption by factory workers as well as toilet waste. The quantities for these waste types correlates with the number of factory employees.

The following figure shows the different waste types that were observed at the factories as well as the quantities of each waste type. All factories have several waste sources that need to be managed.



	Fibrous waste	Lint and dust	Yarn waste	Fabric scraps	Dyeing and finishing waste	Biodegrabale packaging materials	Natural fibre waste	Food waste	Toilet waste	Other organic materials
11	-	-	51,000	120,000	-	2,000	-	2,000	4,480	200
10	-	-	-	12,000	-	-	-	8,400	87,360	0
9	-	-	-	-	-	-	18,000	34	30,240	0
8	-	5,000	120,000	-	-	3,000	-	240	84,672	300
7	-	-	-	120,000	-	-	-	2,400	73,920	0
6	-	60	-	12,000	1	12,000	-	88,800	188,160	4500
5	-	-	-	95,585	-	7,034	-	1,667	51,744	0
4	-	-	3,590	-	-	240	-	4,800	12,768	0
3	-	109,468	5,519	-	-	1,625	1,395	13,693	46,368	0
2	12,000	-	-	-	-	-	-	1,200	14,112	0
1	-	-	19,420	20,627	-	9,601	-	-	23,412	0

Figure 11: Types and Quantities of Waste from 11 Surveyed Textile Factories

In addition, at three of the factory sites visited, essential amounts of other waste types were identified, such as soft waste from landscaping (tree leaves, grass cuttings) and manure from livestock.

While all waste types were determined, the focus are biodegradable and organic waste types that are suitable for biogas production. Based on the site visits conducted, the main types of biodegradable waste include:

(1) Cotton textile waste: Fabric scraps, yarn waste, dust, and other textile production residues,
(2) Faecal Sludge / Septic sludge from desludging septic tanks,
(3) Food waste from factory canteens and cafeterias,
(4) Landscaping waste from maintaining green areas,
(5) Packaging waste, such as cardboard, paper, and other biodegradable packaging materials,
(6) Sludge from effluent treatment plants (ETPs).
(7) Jhut encompasses fabric scraps, yarn, and additional residues from textile production processes. However, as Jhut refers to various types of textile production waste, with biodegradability depending on the specific fibre composition, only the pure natural Jhut would be biodegradable. In contrast, synthetic or mixed fibre Jhut would have limited or no biodegradability. It is classified into different categories, including:
    a. Cotton Jhut (from pure cotton fabric production)
    b. Woven Jhut (scraps from woven fabric production)
    c. Knit Jhut (waste from knit fabric manufacturing)
    d. Denim Jhut (from denim production)
    e. Mixed Jhut (mixture of various fabric scraps)

On average, 0.5 kg of organic waste per day and employees are available in these factories, mainly composed of kitchen and food waste (20%) and blackwater from the toilets (80%).

Waste stream data from surrounding areas were also collected, but after the interviews with sector stakeholders, they were not considered potential complementary sources. The service and required logistics need to fit the core business of textile factories.

4.3 Current Waste Handling Practices

Just as every factory has several different waste sources, each factory has a different waste handling strategy. The following figure shows the different disposal practices that the surveyed factories applied.

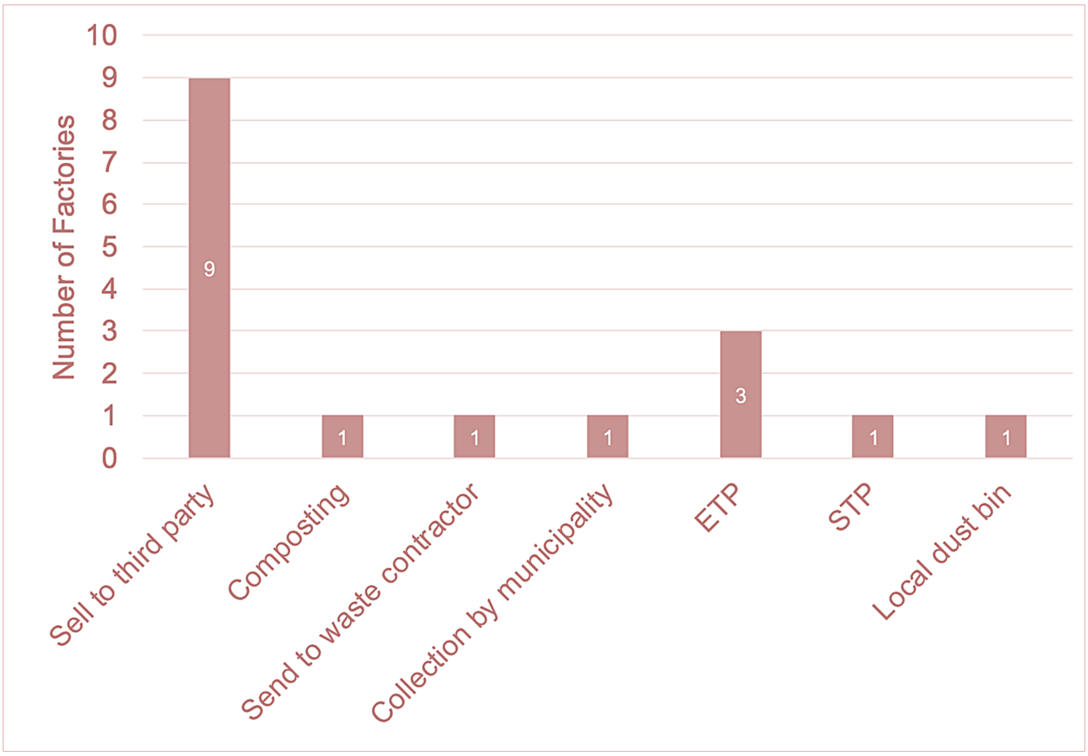


Figure 12: Disposal Practices of Surveyed Factories

Regarding wastewater, some factories utilize Effluent Treatment Plants (ETPs) to process textile production wastewater. For human wastewater (toilet waste), all factories are equipped with septic tanks for collection and pre-treatment of the toilet wastewater. These on-site sanitation systems are required to be mechanically emptied on a regular basis.

Cotton waste is recycled 20 – 30% on-site by vertically integrated factories. The remaining cotton waste is sold to partner recycling facilities or local vendors. Some sustainable partnerships exist for mechanical recycling of cleaned and segregated waste.

The informal sector is significantly involved in waste handling. For example, local businesses, often affiliated with community groups, purchase Jhut (a broader textile scrape category) from factories at minimal prices. They clean, segregate by colour and composition, and aggregate the waste before reselling to local and international buyers.

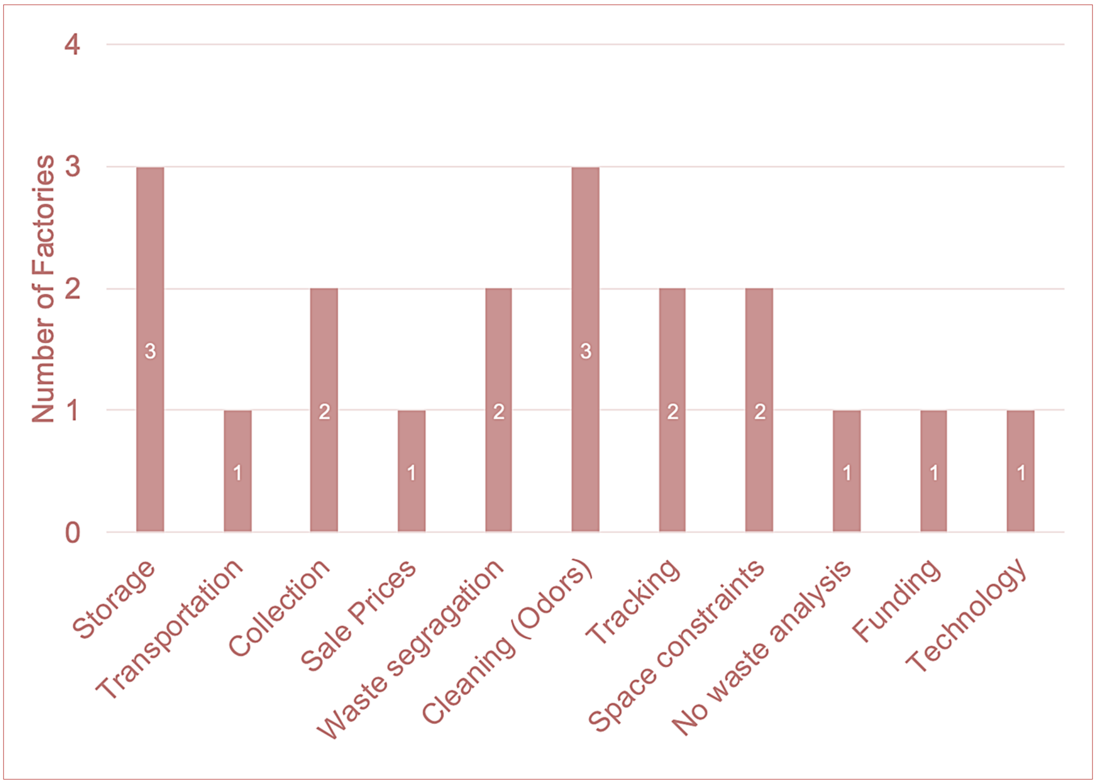


Figure 13: Challenges Identified by the Factories regarding Waste Management

A challenge that can be observed and was also named by some factories, is the common lack of preliminary sorting or segregation processes, shifting waste management responsibility to local businesses. Regarding printed and mixed fabric waste, recycling or selling is frequently not possible due to its composition and limited demand. Consequently, these scraps end up in landfills.

Biodegradable waste is used by some factories to generate compost. In other cases, it is simply discarded or remains unused.

Table 7: Management Practices for Different Waste Types

Waste Type	Management of these types of waste
Fibers and yarns from raw material processing	- Sell to local traders - Use them for cleaning
Yarns and finished fabric from material production	- Sell to local traders
Food waste	- Usually dump them in drainage - Handover to others for free or by paying them - Use for energy production
Faecal sludge	- Usually dump them in drainage - Handover to others for free or by paying them. - Use for energy production
ETP sludge	- Usually dump these in the landfill - Handover to HeidelbergCement Bangladesh Limited and pay them to deal with it

4.4 Current Energy Use and Practices

Textile production processes are energy intensive. Factories typically utilize a combination of energy sources to meet their power requirements. The primary energy sources are natural gas, electricity supplied from the power grid and diesel. Furthermore, solar energy as a renewable energy source is commonly used.

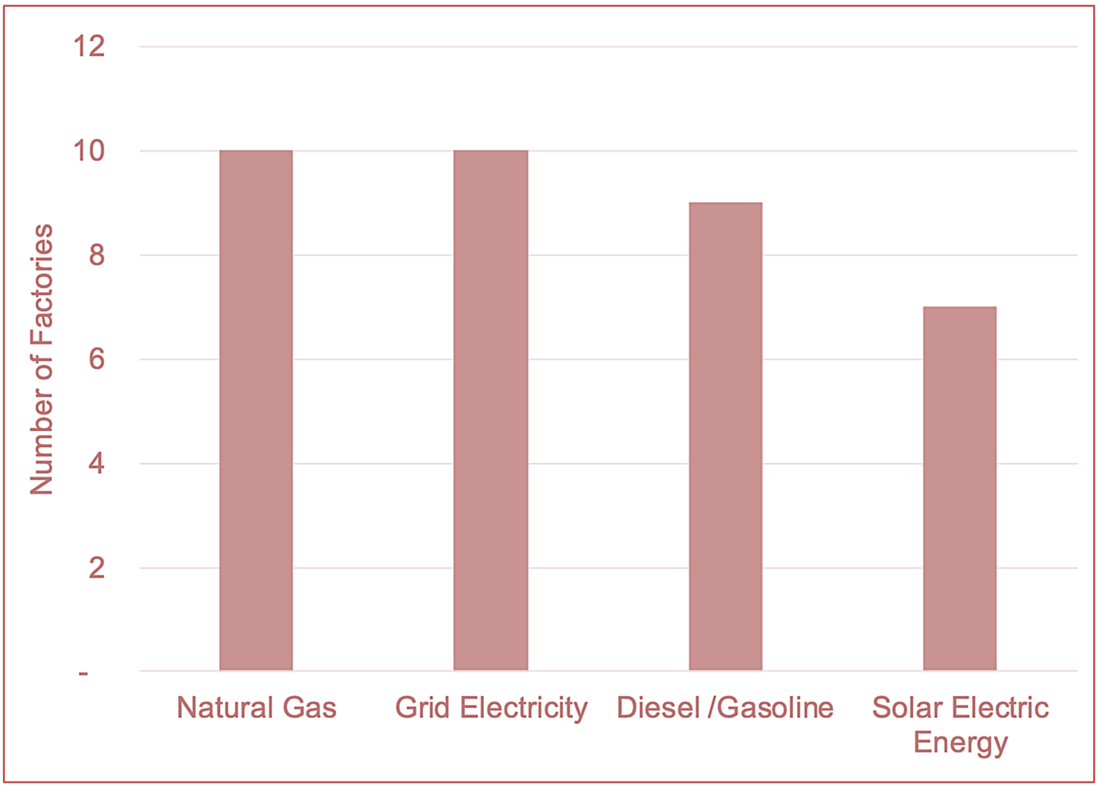


Figure 14: Energy Sources Used by the Surveyed Factories

Natural gas is particularly for processes that require heat generation. It is commonly employed in boilers for steam production, direct heating applications and drying processes. Electricity from the power grid is commonly powering machinery and equipment such as spinning machines and looms. Furthermore, it is required for lighting systems, air conditioning and ventilation as well as office equipment. Diesel fuel is used for backup generators during power outages, some types of industrial machinery, and transportation of materials and products.

Solar energy may supplement grid electricity, can power lighting systems and heat water for certain processes. Other renewable energy sources, such as biogas that can supplement natural gas as well as electricity are not yet established in Bangladesh's textile production factories.

Interestingly, the survey results indicate that the energy consumption in the questioned textile factories doesn't necessarily correlate directly with the size of the factory based on employee numbers. This suggest that smaller factories may sometimes have higher energy consumption, indicating potential inefficiencies or outdated equipment. On the other hand, larger factories might have implemented more energy-efficient technologies or processes. The type of textile products being manufactured, and the specific processes involved likely play a significant role in the energy consumption patterns.

4.5 Biogas Potential Based on Available Feedstock Sources

This list of waste types provides a holistic view of waste generation associated with the textile industry in Bangladesh. It encompasses direct manufacturing waste and waste from supporting activities and the surrounding environment. This comprehensive approach allows for a more thorough understanding of the environmental impact and potential for waste management in the context of Bangladesh's textile industry. The following table provides a general overview and comparison of the different feedstocks. Experimental tests on the actual substrates are recommended for specific applications, as local variations and specific characteristics can significantly impact the anaerobic digestion process and biogas yields. Please note that not all information is available for every feedstock, and some values are approximated or ranged based on typical values, as reported in the literature; see the attached literature analysis.

Table 8: Characteristics of Different Waste Types

Waste Type	C/N Ratio	Organic Content (% of DM)	Dry Matter Content (DM) (%)	Biogas Potential (L/kg VS) (depending on pretreatment)	Methane (%)	AVG Biogas Potential (l/kg feedstock)	AVG Biogas Potential (m^3/m^3 feedstock)	Specific weight (kg/m^3 feedstock)
Cotton Dust	32-40	52-90%	91-95%	230-500	50-77%	160	80	400-600
Cotton Yarn waste	32-42	80-83%	91-94%	280-1,500	50-62%	736	110	100-200
Cotton fabric scraps waste (*Jhut, Jhoot*)	41-43	82%	70%	240-1,000	50-62%	622	120	150-300
Cow Dung (100% grass-fed)	25	75-85%	15-18%	270-300	55-65%	40	40	1,000
Faecal Sludge sucked from septic tanks	6-10	65-75%	1-8%	250-460	60-65%	4	4	1,000
Food and Kitchen Waste	16 - 25	80-90%	20-30%	580-1,000	50-70%	146	80	500-600
Leaves and Grass Clippings	25	80-90%	20-40%	300-600	53-55%	115	40	300-400
OFMSW collected in separate Bins	20	75-80%	20-30%	270-630	55-60%	120	30	250
Waste Paper and Cardboard	130-300	85-95%	85-95%	200-600	50-60%	309	40	90-170
Sewage Sludge from a textile WW ETP	8	60-80%	2-8%	80-300	60-65%	8	8	1,000
Textile Wastewaters (treated in an UASB)	3-8	70-80%	0,5-2%	250	51-60%	2	2	1,000
Rice husk	70-110	80%	93-94%	17-27	50-53%	19	3	100-160

*OFMSW: Organic Fraction of Municipal Solid Waste I DM: Dry Matter I VS: Volatile Solids I C:N: Carbon-Nitrogen I UASB: Upflow Anaerobic Sludge Blanket I AVG: Average I WW: Wastewater

Please note:

1. The values indicated in the table are from literature. The references can be found in the attached literature analysis of this feasibility study.
2. The lowest range of the biogas potential is usually without pretreatment and a short hydraulic retention time (HRT).
3. These values should be considered approximations, as biogas production can vary significantly depending on specific conditions, co-digestion, and pre-treatments.
4. The C/N ratio for paper and cardboard is typically high, so it's often used in co-digestion to balance low C/N ratio substrates.
5. The biogas potential for cotton dust was calculated from a given laboratory study value of 180 cc per 100g. The biogas potential (m^3/m^3 feedstock) for cotton dust was calculated from the reported 200 L per 5 kg of cotton waste.
6. General cotton textile waste: One study found cumulative biogas production of 567.3 mL/g volatile solids and methane production of 244.1 mL/g volatile solids added from textile industry waste over 30 days of anaerobic digestion. Another study on cotton textile waste reported biogas yields of 147-268 mL/gVS, depending on pretreatment.
7. Textile wastewater significantly reduced Chemical Oxygen Demand (COD) by more than 85% during biogas production. The methane percentage for textile wastewater varies between studies, with one reporting 51% and another up to 60%.
8. The data on cotton dust suggests it has good potential for biogas production due to its high cellulose content and methane percentage.
9. The digestion conditions, pretreatment methods, and co-digestion strategies can significantly affect the biogas potential and methane content.

Adding rice husk to a biogas digester can improve the carbon-to-nitrogen (C/N) ratio and enhance biogas production. Here are some key points about using rice husk to optimise the C/N ratio in anaerobic digestion:

- Rice husk has a high carbon content, which can help balance out nitrogen-rich substrates like food waste or manure.
- It can improve the C/N ratio to the optimal range of 20-30, which is ideal for anaerobic digestion.
- Adding rice husk can increase biogas yields compared to digesting nitrogen-rich substrates alone.

The ideal C/N ratio for anaerobic digestion is typically between 20-30. A C/N ratio of 20-25 has been found to produce maximum biogas yields. Too low C/N ratio (<20) can lead to ammonia accumulation and inhibit methane production. Too high of a C/N ratio (>30) can result in lower methane yields due to nitrogen deficiency.

Rice husk has a high lignin content, which can be difficult for microbes to break down. Some forms of pretreatment and considerations may be beneficial to improve digestibility, such as:

- Enzymatic pretreatment using lignose enzymes.
- Physical or chemical pretreatment to break down the lignocellulosic structure.
- Biogas yields can increase by 30-55% with proper rice husk addition and C/N ratio optimisation.
- Co-digestion of food waste and rice husk yields maximum biogas at a C/N ratio of 20
- The C/N ratio of rice husk is likely between 100 and 110. However, the exact ratio can vary depending on the rice variety, growing conditions, and processing methods. When using rice husk to adjust the C/N ratio in biogas digesters, it's recommended to start with minor additions and gradually increase to find the ideal ratio, as the optimal C/N ratio for anaerobic digestion is typically between 20 and 30.

4.6 Proposed Waste Handling and Energy Use Strategies with Pathways to Integrate Biogas Technology

Depending on the waste stream, a different treatment technology will be preferred. Key treatment technologies for the waste streams arising in the textile sector are as follows:

Table 9: Proposed Treatment Technologies for Different Waste Types

Treatment Technology	Description	Waste Types
Anaerobic Digestion (AD)	The AD process breaks down organic matter in the absence of oxygen producing biogas and digestate. It is an excellent choice for treating organic waste.	- Food leftovers from factory cafeterias - Food processing remains - Toilet waste - Biodegradable packaging materials - Organic cleaning agents - Well-segregated biodegradable textile production waste
Combustion (Boiler)	Combustion in boilers can generate heat or steam for various textile production processes. Certain types of boilers are suitable for burning fibrous waste from textile production. It is crucial to note that boilers should be equipped with exhaust gas filter units to mitigate flue gas issues and reduce air pollution.	- Lint and dust - Yarn waste - Fabric scraps - Natural fibres
Recycling	Recycling is a sustainable option for certain clean textile wastes, depending on market conditions. It can reduce the demand for virgin resources and minimize waste sent to landfills.	- Yarn - Fabric scraps - Fibrous and natural fibres
Pyrolysis	Pyrolysis is a thermal decomposition process that can be used to treat combustible waste streams in the absence of oxygen. Also, the digestate from anaerobic digestion can be further processed through pyrolysis, creating a synergy between these two technologies.	- Fibrous waste - Yarn waste - Fabric scraps - Natural fibres - Biodegradable packaging materials
Hazardous Disposal	Dyeing and finishing waste requires special handling due to its chemical content. It needs to dispose of according to local regulations. This may involve specialized treatment facilities or secure landfills.	- Dyes - Pigments - Finishing chemicals - Heavy metals

Based on collected data, stakeholder exchanges and expert panel input, three key variations for managing waste streams in textile factories were identified. These variations represent different combinations of the above technologies, tailored to specific factory conditions and waste stream compositions. By implementing these variations, textile factories can maximize resource recovery, minimize environmental impact, and potentially reduce operational costs through energy recovery and waste valorisation.

4.6.1 Variation 1 – Segregation of Waste Streams for Anaerobic Digestion (Segregation for AD)

This variation effectively treats biodegradable waste, producing biogas that can be used to generate electricity and heat. The resulting digestate can serve as a valuable soil amendment. Variation 1 offers a more straightforward and cost-effective approach when high-quality organic waste can be segregated.

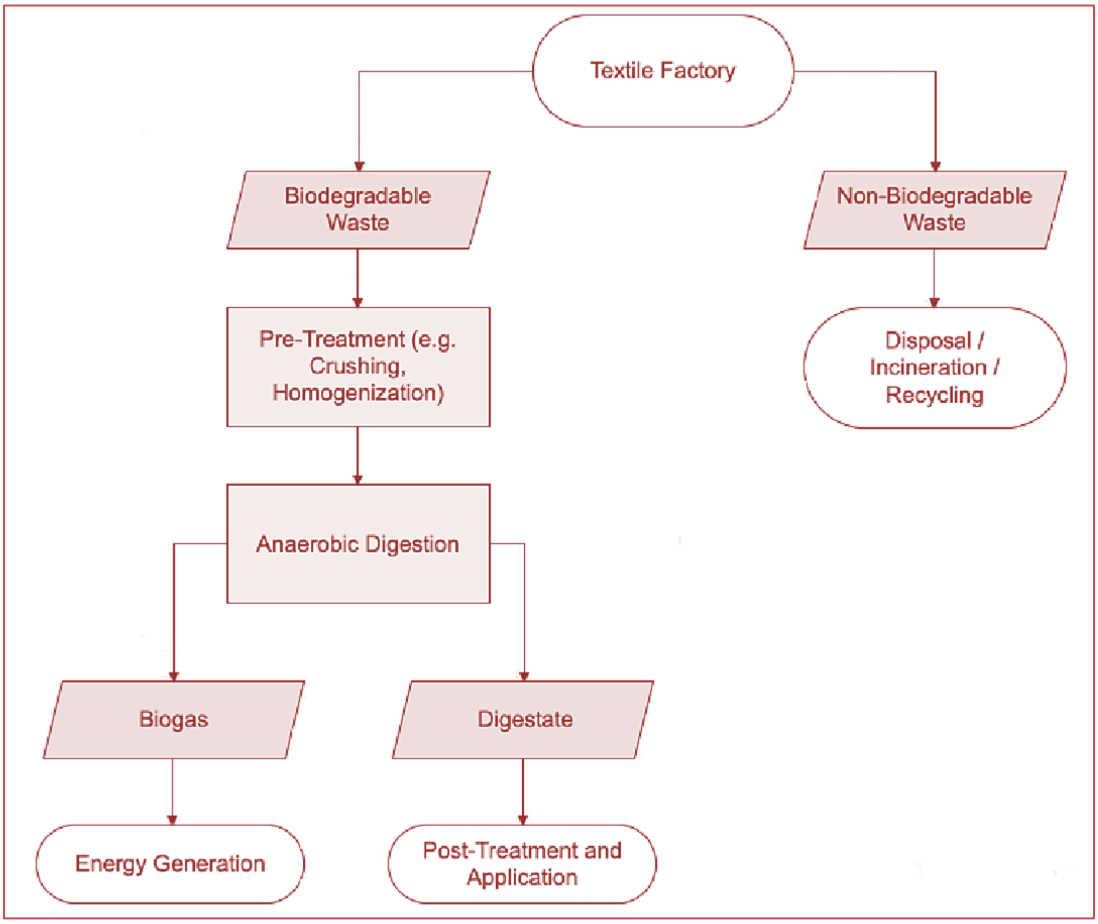


Figure 15: Simplified Process Flow for Variation 1

This method relies on careful waste stream management. The process assumes strict waste segregation at source to isolate pure organic feedstocks, including:

- Food and kitchen waste,
- Wet packing waste (paper-based),

- Organic textile scraps, and
- Septic sludge.

Only these carefully segregated organic materials enter the AD process. This selective input ensures that only biodegradable matter undergoes the digestion process, minimizing contamination and improving the quality of the end products, particularly the digestate.

For the anaerobic digestion process, a semi-continuous dry fermentation option, the plug-flow digester, can be chosen. This type of digester can handle dry matter contents up to 39%, requires less water and process energy. More suitability aspects are explained in chapter 4.7.2.

The primary output of the AD process is biogas, which can be used on-site to generate electricity and heat, potentially offsetting a significant portion of the factory’s energy needs.

Furthermore, the process yields digestate, that – assuming a meticulous waste segregation – is a nutrient-rich product. It is required that after the AD process, the resulting digestate undergoes sanitization to ensure safety and compliance with regulatory standards. Once sanitized, the digestate can be utilized. Using a plug-flow digester and assuming higher a dry matter content of the input mixture, the process produces a more solid digestate that is easier to handle, and transport compared to liquid slurry. To further ensure that the digestate is stackable and easy to manage, post treatment such as dewatering and composting can be integrated. This approach can produce a soil conditioner that may be more acceptable for use in Bangladesh.

Implementing this variation offers several benefits to textile factories. Primarily, it produces biogas that supplements energy needs. Further, it produces high-quality digestate suitable for agricultural or commercial use, potentially creating a new revenue stream or reducing costs associated with waste disposal. This integration of this process may reduce the amount of waste sent to landfills, aligning with environmental regulations and sustainability goals. It also minimizes the need of additional waste treatment steps.

However, the success of this AD variation hinges on efficient waste segregation at source. This requirement presents both a challenge and an opportunity. While it necessitates careful planning and execution of waste management protocols, it also promotes a culture of environmental responsibility within the factory. Encouragingly, in factories visited during the field survey, segregation systems were already in place. This existing infrastructure provides a solid foundation for implementing Variation 1.

4.6.2 Variation 2 – Mixed Waste Stream with Materials Recovery Facility and Anaerobic Digestion Unit and Pyrolysis (MRF + AD + Pyrolysis)

This variation combines materials recovery, biogas technology and pyrolysis to handle mixed waste streams. The process produces biogas and biochar. Variation 2 is suited for handling mixed waste streams and maximizing energy recovery and environmental benefits through biochar production, but it involves more complex processing steps.

This variation assumes that the waste streams are not segregated at source. All non-recycled waste streams together, including organic and non-organic materials go to a Materials Recovery Facility

(MRF). Sludge from Effluent Treatment Plants, found in four surveyed factories, is also considered co-feedstock. The MRF handles the waste separation to filter the organic fraction goes into an Anaerobic Digestion (AD) unit. After anaerobic digestion, the digestate undergoes drying before it is processed in a pyrolysis unit to produce biochar.

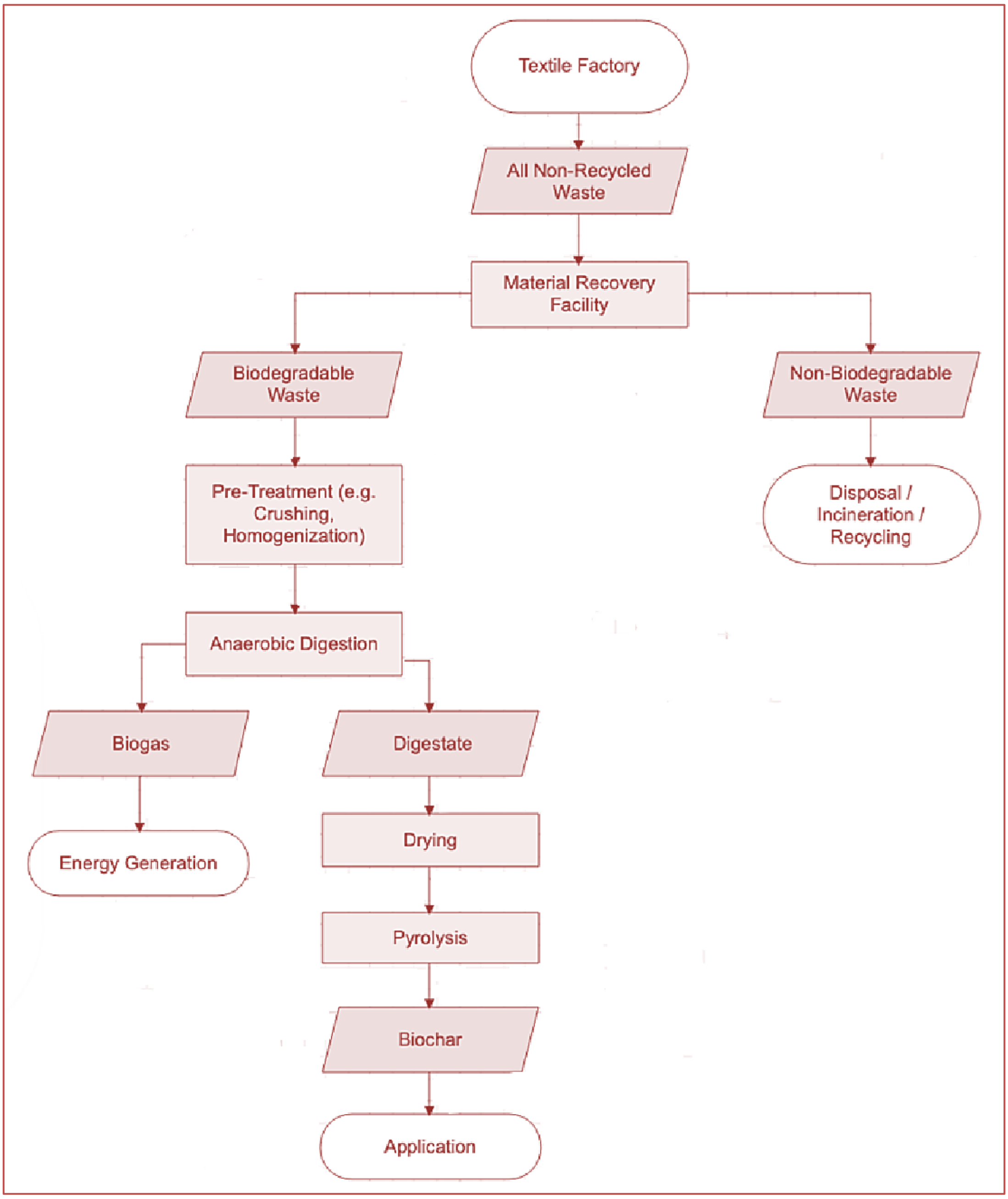


Figure 16: Simplified Process Flow of Variation 2

Like variation 1, the primary output of the AD process is biogas, which can be used on-site to generate electricity and heat, potentially offsetting a portion of the factory's energy needs. Further, the pyrolysis process produces biochar, a valuable carbon-rich material used for soil amendment or sold commercially. Biochar has gained attention for its potential in carbon sequestration offering an option to lock carbon into the soil for extended periods. Thereby, it contributes to climate change mitigation efforts and applies for carbon finance.

While the focus of this variation is on biodegradable waste, the residual inorganic waste that is separated by the MRF can still be diverted for incineration or recycling, ensuring a comprehensive waste management solution.

This variation offers several benefits. Through the MRF, it allows for waste segregation and can handle mixed waste streams, making suitable for factories where strict waste separation at source might be challenging. The production of biochar offers additional environmental benefits, such as carbon sequestration. Biochar is versatile and can be used for a variety of applications, ranging from agricultural use to incorporation in various industrial processes.

However, the variation has also some challenges. The implementation requires a higher capital expenditure (CAPEX) and operational expenditure (OPEX) due to the need for MRF, AD, and pyrolysis units. The complexity of the waste management process and the advanced technology requirements necessitate specialized knowledge and skilled personnel for operation and maintenance.

A potential concern arises regarding the presence of heavy metals in the initial waste streams. If present, the concentration of these metals could become concentrated in the biochar, which could lead to environmental concerns if the biochar is applied to soil. However, alternative uses for biochar such as incorporation into building materials like concrete or bricks, providing insulation and improving material properties is possible and can mitigate this risk.

Careful monitoring and quality control measures are essential. Regular testing of both input waste streams and output products is necessary to ensure that potential contaminants do not impact the safety or quality of the final biochar products. These monitoring requirements add another level of complexity to the operation, but it is crucial for maintaining environmental standards and product integrity.

4.6.3 Variation 3 – Anaerobic Digestion for Pure Organic Waste and Boiler for Combustible Waste Streams (AD + Boiler)

This third variation uses anaerobic digestion for biodegradable waste and a boiler for non-recyclable waste to recover energy as heat or steam, providing a balanced approach. It leverages AD for organic waste and combustion for non-recyclable combustible waste, allowing energy recovery from both types of waste. This option is particularly efficient when organic waste is available in substantial quantities for AD, and steam or heat is needed in factory operations.

In this process, it is assumed that waste segregation at source takes place. The organic waste streams, including food and kitchen waste, septic sludge, and biodegradable textile waste, are directed into an Anaerobic Digestion (AD) unit. Simultaneously, combustible waste streams such as non-recyclable textile scraps, packaging materials, and other combustible waste that cannot be sold to recycling markets, are diverted to a boiler for combustion to generate heat and/or steam. This dual-stream process allows for efficient energy recovery from both types of waste.

The AD process yields biogas for energy generation (electricity or heat) and digestate that can be sanitised and used as a soil improver. The boiler process, on the other hand, burns non-recyclable combustible waste to produce heat or steam, which can be used for factory operations, such as textile processing, or for electricity generation.

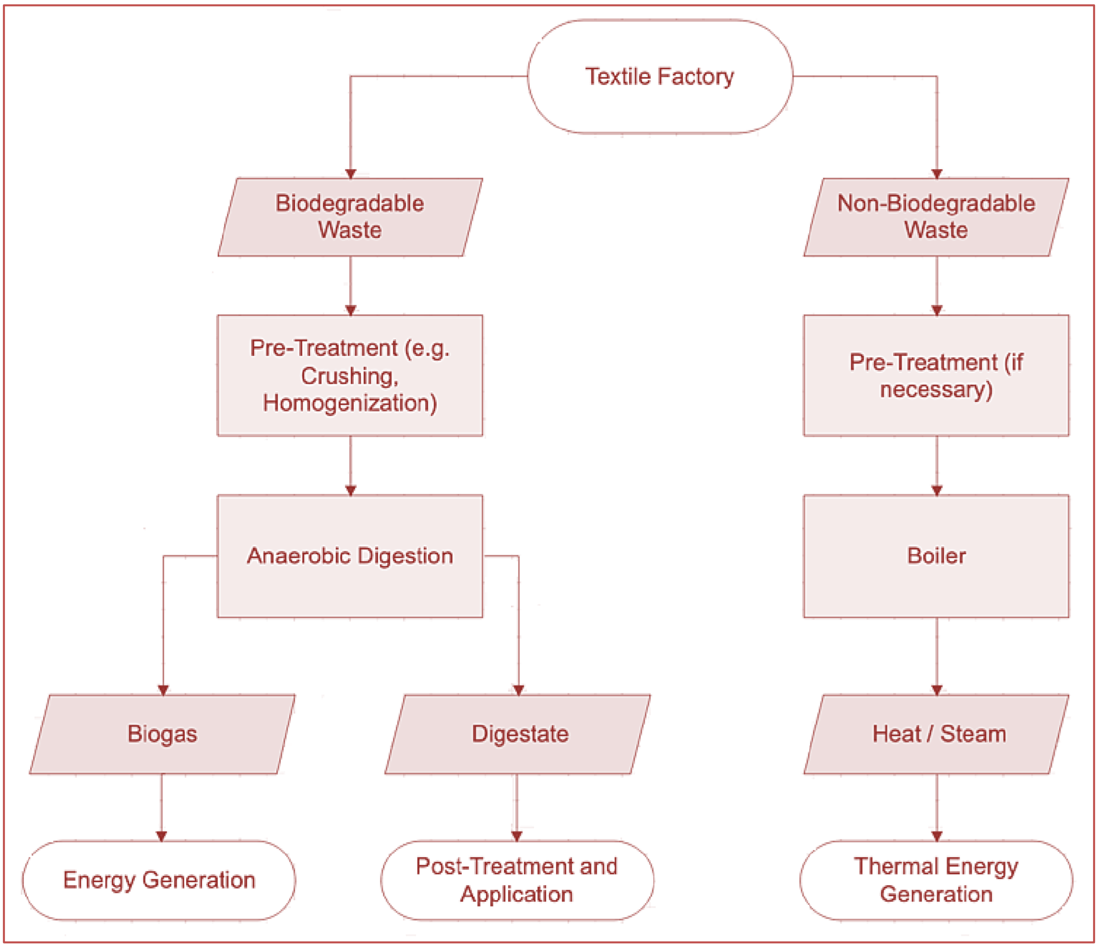


Figure 17: Simplified Process Flow of Variation 3

This variation also offers several benefits. It maximises the use of different waste streams for energy recovery, utilizing both biogas from AD and heat/steam from the boiler. Further, it reduces the dependency on landfills by utilising non-recyclable combustible waste. Moreover, it can lead to lower energy costs for textile factories by integrating the boiler's heat or steam into production processes. The process also simplifies waste management, as it reduces the need for complex separation for recycling of the combustible waste.

However, the boiler requires proper emission control to minimise environmental impacts like air pollution. This necessity may increase the complexity and costs of the installation. Additionally, the operation of both and AD unit and a boiler may lead to higher operational costs compared to simpler waste management systems. Another consideration is the management of ash resulting from the combustion process, which requires proper disposal or potential reuse strategies.

4.7 Suitable Biogas Production Technologies

Several biogas production technologies could be suitable for Bangladesh's textile sector. However, the choice of digester type should be based on specific site conditions, waste characteristics, scale of operation, and available resources. Each design has advantages and limitations, and the optimal choice may involve a combination of technologies, or a hybrid design tailored to the facility's specific needs. Here are the pros and cons of each digester type.

4.7.1 Continuously Stirred-Tank Reactors (CSTR)

Suitable for large-scale operations with consistent waste input, CSTRs offer high efficiency in biogas production by continuously mixing the input material to maintain uniform conditions throughout the reactor. This technology is particularly effective for facilities which generate substantial and consistent amounts of cotton dust and fabric scraps, which can be mixed with the other available wet waste streams.

Table 10: Characteristics of Continuously Stirred Tank Reactors

Continuously Stirred-Tank Reactor	
Suitability	• For all types of pumpable substrates with low and midrange of dry matter concentrations • Suitable of continuous, intermittent and quasi-continuous feeding
Advantages	+ Design is cost-effective for large volumes + CSTRs are versatile and can handle varying flow rates, a variety of substrate types and concentrations more easily than other designs
Challenges	- Pre-treatment may be required, especially in case textile waste contains cellulose - Different textile wastes have varying levels of biodegradability and different lag phases before biogas production begins - Segregation of non-biodegradable wastes prior introduction into the tank is essential as it may otherwise accumulate inside the tank

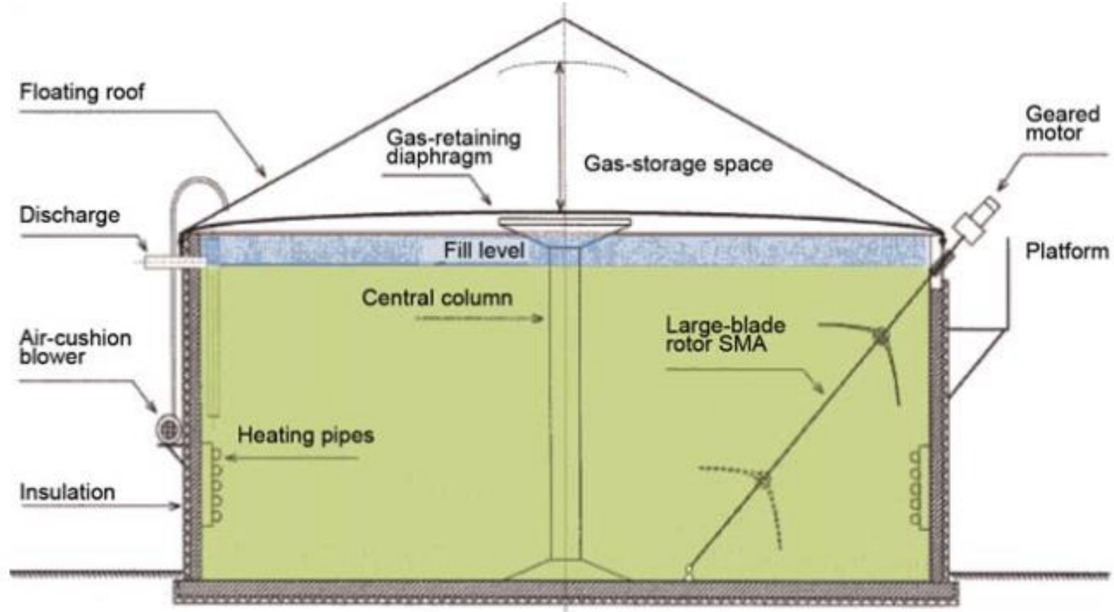


Figure 18: Schema of a Continuously Stirred-Tank Reactor[24]

4.7.2 Plug-Flow Digesters

Ideal for facilities with variable waste output and space constraints, plug-flow digesters allow the different kinds of waste mixes to move through the reactor in a plug-flow manner, providing a steady biogas production process. This type suits factories, which produce consistent but variable amounts of fabric and food waste.

Table 11: Characteristics of Plug-Flow Digesters

Plug-Flow Digester	
Suitability	• Suitable for substrates with high dry matter content • Designed for quasi-continuous or continuous feeding
Advantages	+ Compact, cost-effective design for small-scale plants + Separation of digestion stages (dwell times are as predicted without flow short-circuits) + Plug-flow digesters are good at handling “slug loads”
Challenges	- Pre-treatment may be required - Segregation of non-biodegradable waste prior digester is required - Lack of mixing in this type of digester might make it challenging to maintain stable conditions throughout the reactor

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[24] FNR: https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf, 29.01.2025

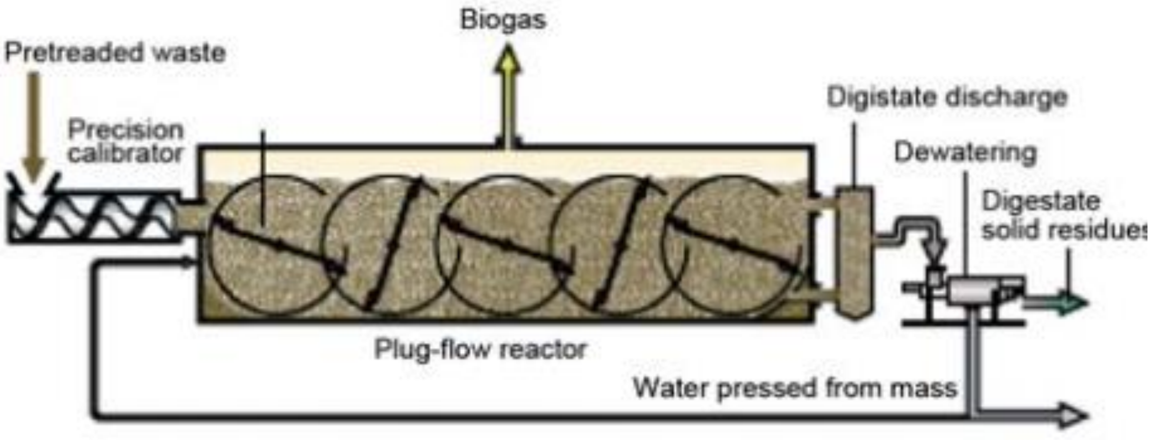

Figure 19: Schema of a Plug-Flow Biogas Digester[25]

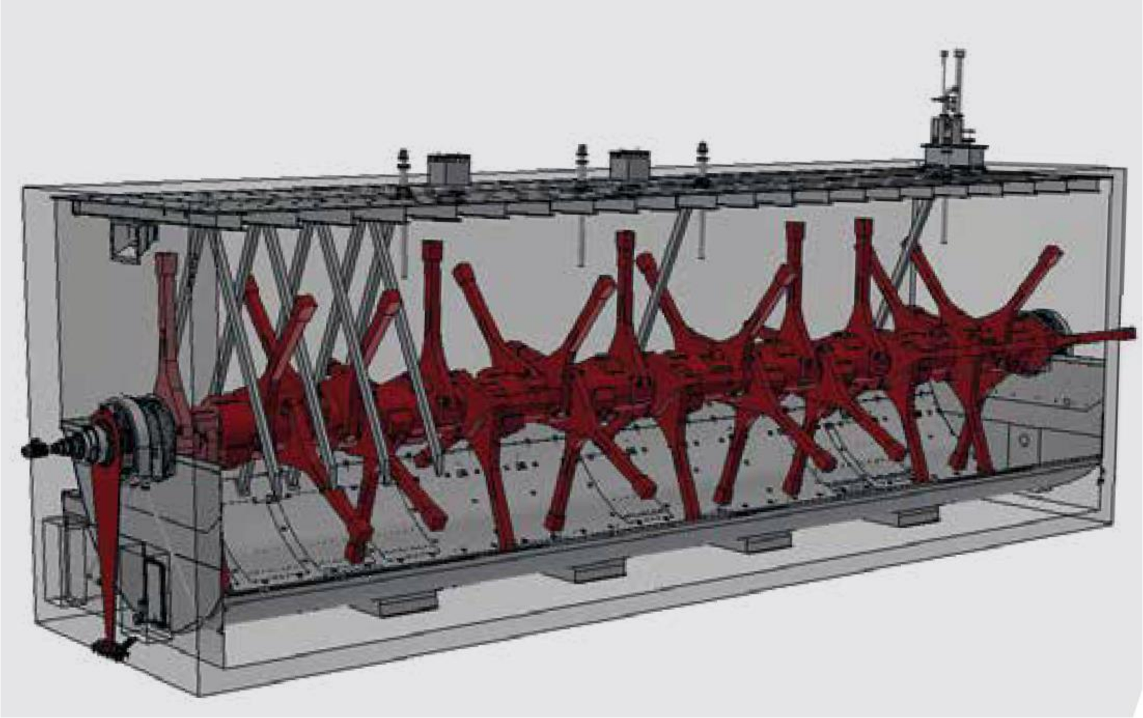

Figure 20: Plug-Flow Biogas Digester[26]

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[25] FNR: https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf, 29.01.2025
[26] Thöni

4.7.3 Fixed-Dome Digesters

Cost-effective for smaller operations with limited space, fixed dome digesters are simple, durable, and well-suited for facilities which produce moderate waste and have additional access to manure from nearby farms.

Table 12: Characteristics of Fixed-Dome Digesters

Fixed-Dome Digester	
Suitability	• Can handle a variety of organic substrates with higher solids content • Can be operated as mono-feedstock system as well as co-digestion system • Suitable for small to medium-scale applications
Advantages	+ Low construction costs using locally available materials such as bricks and mortar or cement + Durability due to their simple design and lack of moving parts + Space efficient since usually installed underground
Disadvantages	- Limited accessibility since these types of digesters are usually installed underground - Skilled bricklayers are required to ensure the structure is gas-tight and durable - These types of digesters are usually prone to fluctuating gas pressure and require additional regulating devices to ensure a steady gas flow

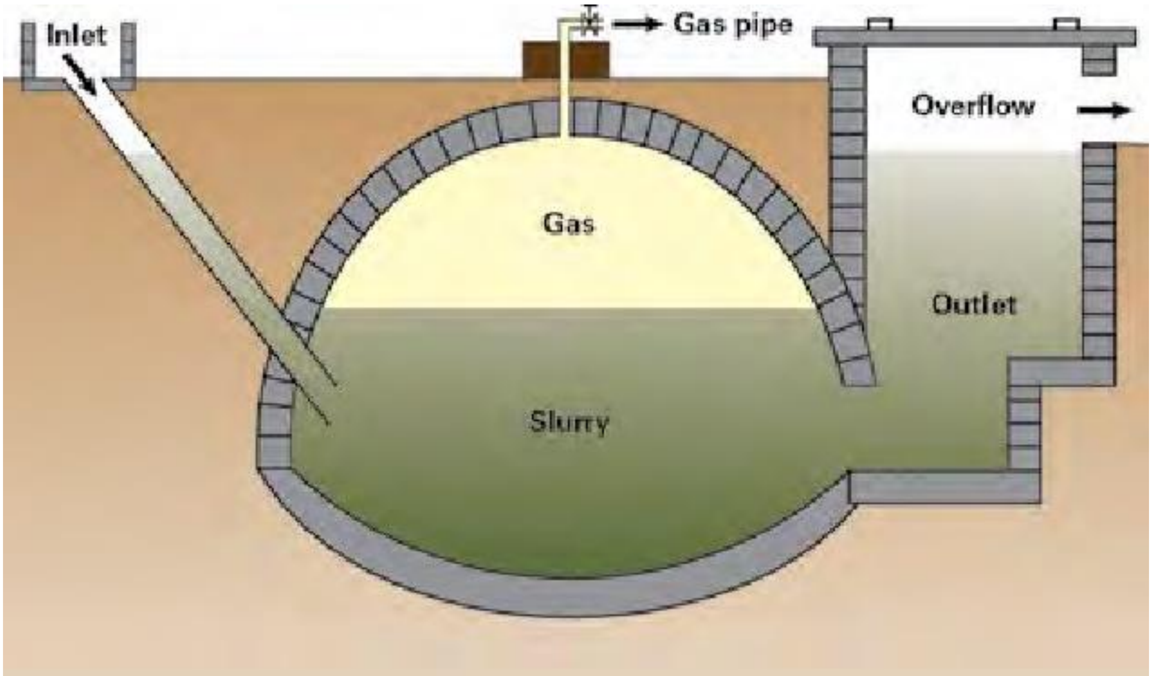

Figure 21: Schema of a Fixed-Dome Digester[27]

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[27] EAWAG: file:///Users/st/Downloads/AnaerobicdigestionofBiowasteinDevelopingCountries.pdf, 29.01.2025

4.7.4 Other Digester Designs

a) Lagoon Digesters

A simple, low-cost system for treating large volumes of diluted waste requires a lot of land.

Table 13: Advantages and Disadvantages of Lagoon Digesters

PROS	CONS
- Low construction and operational costs - Suitable for large volumes of diluted waste - Simple operation and maintenance	- Requires large land area - Potential for odour issues and methane emissions

b) Up-flow Anaerobic Sludge Blanket (UASB) Reactor

A compact, highly efficient system for treating high-strength wastewater, requiring skilled operation and sensitivity to temperature fluctuations.

Table 14: Advantages and Disadvantages of UASB Reactors

PROS	CONS
- High treatment efficiency for high-strength wastewaters - Compact design with a small footprint - Low energy consumption - Produces less excess sludge	- Requires skilled operation and monitoring - Sensitive to temperature fluctuations - It may require long start-up periods

c) Anaerobic Filters

A compact design efficient for high-strength wastewaters with good biomass retention but prone to clogging and requiring higher initial investment.

Table 15: Advantages and Disadvantages of Anaerobic Filters

PROS	CONS
- Efficient for treating high-strength wastewaters - Good biomass retention - Resistant to shock loads - Compact design	- Potential for clogging of filter media - Higher initial investment costs - It may require recirculation for optimal performance

4.8 Integration with Existing Factory Infrastructure

Integrating biogas production systems with existing textile factory infrastructure requires an approach that addresses the opportunities and challenges of transitioning from current waste management practices to a more sustainable, biogas-oriented system. This strategy would incorporate the following elements:

The transition from informal to structured waste management

Based on the assessment of current waste handling practices, factories rely heavily on informal waste handling systems or landfilling. A phased transition plan must be developed to shift from these practices to a structured waste collection system, which is required for integrating biogas technology. Staff training programs are also needed to adapt to new waste management protocols.

Waste collection and transportation

Establishing an efficient system for collecting and transporting waste from various points within the factory to the biogas plant.

Storage and pre-treatment

Should be implemented to ensure a steady and suitable feedstock supply and storage facilities and pre-treatment processes.

Biogas production and utilization

Anaerobic digestion systems shall be tailored to the factory’s waste profile. The produced biogas requires capture and purification systems. Biogas can be used directly, upgraded, or transformed into electricity and heat. Generating electricity through the existing power grid or directly to nearby factories and establishing a district heating network to distribute heat to nearby industrial facilities.

Digestate management

Developing systems for treating and utilising the digestate, potentially as a soil improver for agricultural use. Further digestate treatment can include liquid-solid separation, drying, co-composting with lignin-rich material, charring (pyrolysis), and controlled combustion (“omni-processor” or as co-fuel for the cement industry), depending on the final destiny of the digestate, construction material market value, and agricultural value.

Wastewater management

A crucial consideration for textile factories is treating wastewater and waste, mainly removing heavy metals. This is an essential step before the digestate can be safely discharged. Textile wastewater often contains heavy metals such as chromium, lead, copper, and zinc, harming the environment and inhibiting biogas production. To address this issue, the following treatment methods can be integrated into the existing wastewater treatment infrastructure:

- Chemical Precipitation involves adding chemicals to the wastewater to convert dissolved heavy metals into insoluble compounds that can be easily removed through sedimentation or filtration.
- Ion Exchange: This process uses specialised resins to effectively remove heavy metals by exchanging them with less harmful ions.

- Adsorption: Activated carbon or other adsorbents can remove heavy metals from the wastewater.
- Membrane Filtration: Technologies such as reverse osmosis or nanofiltration can separate heavy metals from the wastewater.
- Electrocoagulation: This process uses electrical current to remove heavy metals and contaminants from wastewater.

5 Economic Feasibility

5.1 Capital Investment Requirements

The capital investment for setting up a biogas plant in a textile industrial zone includes costs for the digester, auxiliary equipment, installation, and infrastructure modifications. Based on similar projects and the scale of the proposed plant, the initial investment positions are as follows:

- Anaerobic Digester and Equipment: Includes the digester, gas collection system, and monitoring equipment
- Installation and Infrastructure: Covers site preparation, piping, electrical work, and integration with existing factory systems
- Other Costs (Permits, Planning, etc.): Includes regulatory compliance, engineering design, and project management

5.2 Operational Costs

The estimated monthly operational and maintenance cost positions for the biogas plant are:

- Labour and Supervision: Includes salaries for operators, technicians, and supervisory staff
- Maintenance and Repairs: Covers routine maintenance, replacement parts, and periodic servicing.
- Feedstock Handling and Miscellaneous: Includes costs for waste collection, pre-treatment, and other miscellaneous expenses.
- Digestate/slurry Handling: Post-processing and disposal.

5.3 Potential Cost Savings and Revenues

The primary revenue streams and cost savings from the biogas plant include:

- Energy Savings: Biogas can be used for on-site heating and electricity, reducing energy costs.
- Electricity Sales: Assuming surplus electricity can be sold to the grid.
- Heat Distribution: Revenue from selling surplus heat generated from biogas for heating buildings, greenhouses, or other applications.
- Digestate Sales: Digestate can be sold as fertilizer to nearby farms.
- Climate Emission Reduction Credits: If the project is eligible and succeeds in the certification, an additional revenue stream can be created from carbon credit sales.

5.4 GHG Emission Reductions Benefits

The financial and economic figures will improve if we consider the GHG emission reduction and the potential revenue from selling CO_2 reduction credits, known as carbon credits. For a first preliminary assessment of these changes, we will incorporate the following key aspects:

GHG Emission Reductions

The biogas produced from waste significantly reduces methane (CH_4) emissions, a potent greenhouse gas. By capturing and utilising this methane, the biogas plant helps reduce emissions compared to landfilling or uncontrolled waste decomposition.

Carbon Credits

Each carbon credit unit represents a GHG emissions reduction of 1 ton of CO_2 equivalent (tCO_2e). Many biogas projects which have been certified under specific carbon crediting mechanisms or carbon market standards, such as the CDM (Clean Development Mechanism), the Gold Standard (GS) and the Verified Carbon Standard (VCS), generate carbon credits like CDM Certified Emission Reductions (CERs), GS Verified Emissions Reductions (VERs) or VCS Verified Carbon Units (VCUs). These carbon credits can be sold in mandatory and voluntary carbon markets and can be an essential additional source of revenue for biogas projects.

Pricing

The market price for a carbon credit unit generated by a biogas project depends on many factors (supply, demand, project quality, market eligibility, etc.) and can vary considerably. It ranges from 5 to 15 Euro per unit on average, but prices might increase to 30 Euro and higher until 2030. Generally, it can be said that the better a biogas project's impact on climate change mitigation and sustainable development and the lower the potential project risks, the higher the achievable carbon credit sales price.

Considering the reduction in GHG emissions and the potential carbon finance revenue from selling carbon credits (i.e., reducing the amount of CO_2 equivalent), each variation's financial and economic figures can improve significantly.

The GHG emission reduction is calculated based on the amount of CO_2 equivalent avoided by capturing and utilising methane (CH_4) from waste. Methane has a Global Warming Potential (GWP) of 25, meaning that 1 ton of methane emissions avoided is equivalent to 25 tons of CO_2. In the anaerobic digestion (AD) context, the methane captured and used for biogas generation contributes to significant CO_2 emission reductions.

5.5 Financial and Economic Analyses

Several analyses may be required for a feasibility study to select the best biogas systems as a waste-to-energy plant for the textile industry. These analyses should be combined with technical assessments of different biogas systems (e.g., CSTR, PFR, Fixed-Dome, Covered Lagoon, Dry Fermentation) for a comprehensive feasibility study to determine the most suitable and economically viable option for the textile industry. The choice will depend on available feedstock, energy demand, space constraints, and local economic conditions. Such analyses typically include:

Net Present Value (NPV)

NPV is a crucial metric for evaluating the economic viability of a waste-to-energy project. It calculates the present value of all future cash flows, both positive and negative, over the project's lifetime[28]. A positive NPV indicates that the project is expected to be profitable. For waste-to-energy biogas projects, NPV calculations typically include Initial investment costs (construction, equipment), Ongoing operational costs, Revenue from energy and subproduct sales (heat, digestate), and Potential government incentives or subsidies.

Benefit-Cost Ratio (BCR)

The BCR is particularly relevant for waste-to-energy projects as it compares the present value of benefits to the present value of costs[29]. A BCR greater than 1.0 suggests the project is economically viable. For waste-to-energy biogas plants, benefits may include revenue from energy sales, savings from reduced landfill costs, and environmental benefits (e.g., reduced greenhouse gas emissions). Costs typically include initial capital investment and ongoing operational and maintenance costs.

Internal Rate of Return (IRR)

IRR is the discount rate that makes the NPV of all cash flows equal to zero[30]. It represents the project's expected rate of return. For a waste-to-energy biogas project to be considered financially attractive, its IRR should exceed the company's cost of capital or required rate of return, which should be higher than the average Bangladesh bank interest rate.

Return on Investment (ROI)

ROI measures the efficiency of the investment by comparing the net profit to the initial cost[31]. While not mentioned in the search results, it's a metric that businesspeople often use to gauge a project's profitability.

Payback Period

This calculates the time required to recover the initial investment. There are two types: (a) Simple Payback Period: Payback Period = Initial Investment / Annual Cash Inflow, (b) Discounted Payback Period: This considers the time value of money and is calculated by finding the time when cumulative discounted cash flows equal the initial investment.[32]

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[28] Investopedia: https://www.investopedia.com/terms/n/npv.asp, 29.01.2025
[29] Investopedia: https://www.investopedia.com/terms/b/bcr.asp, 29.01.2025
[30] Investopedia : https://www.investopedia.com/articles/investing/111715/return-investment-roi-vs-internal-rate-return-irr.asp, 29.01.2025
[31] Investopedia: https://www.investopedia.com/articles/investing/111715/return-investment-roi-vs-internal-rate-return-irr.asp, 29.01.2025
[32] Investopedia: https://www.investopedia.com/terms/p/paybackperiod.asp, 29.01.2025

Cost of Energy (CoE)

CoE = Total Annualized Cost / Annual Energy Production. This metric is crucial for comparing different energy production systems.[33]

Considerations for Waste-to-Energy Biogas Projects

1) Variability in outcomes: Cost-benefit analyses for projects like waste-to-energy biogas plants can be challenging due to numerous assumptions and uncertainties. Therefore, it's essential to consider a range of potential outcomes.
2) Environmental factors: While only sometimes easily quantifiable, environmental and ecological benefits should be considered in an overall assessment.
3) Scale and efficiency: The financial viability of waste-to-energy systems can depend on their scale. Sometimes, these systems may only fulfil a small percentage of electricity demand.
4) Government policies: Tariffs, subsidies, and environmental regulations can significantly impact the financial feasibility of waste-to-energy projects.

5.6 Current Energy Prices for the Textile Industry in Bangladesh

Natural Gas

- For large industries (including textile): Tk 30 (0.24 Euro) per m3, up from Tk 11.98 (0.095 Euro) previously (a 150% increase)
- For power production: Tk 14 (0.11 Euro) per m3
- For captive power plants: Tk 30 (0.24 Euro) per m^3

Grid Electricity

- The business price of electricity per kWh unit is Tk 10.39 (0.083 Euro), and since March 2024, the bulk tariff has been Tk 7.04 (0.056 Euro). Without the existing electricity subsidy, this rate would be at most Tk 12 (0.096 Euro).
- The Bangladesh Power Development Board purchases electricity generated from the WTE Power Plant North Dhaka - owned by the China Machinery Engineering Corporation (CMEC) - for Tk 18.29 (0.15 Euro) per unit for 25 years.

Captive Power Plants

- Many textile mills have their own gas-based captive power plants
- Gas price for captive plants increased to Tk 2,750 (21.91 Euro) per million British thermal units (MMBtu), a 223% increase since January 2023

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[33] Greenmatch: https://www.greenmatch.ch/en/knowledge-center/how-to-calculate-the-levelized-cost-of-energy-lcoe/#:~:text=The%20levelized%20cost%20of%20energy%20(LCOE)%20is%20a%20central%20key,coal%20power., 29.01.2025

- The conversion result shows that Tk 2,750 per MMBtu equals approximately Tk 9.38 (0.075 Euro) per kWh.

This conversion helps to put the gas price in perspective, especially when comparing it to other energy sources like grid electricity. It's worth noting that this significant price increase (223% since January 2023) for gas used in captive power plants has substantially impacted the operating costs of textile mills in Bangladesh. To provide some context:

1. This current price is lower than the projected grid electricity prices for industrial consumers.
2. However, the gas price increase still represents a significant cost hike for textile mills operating captive power plants.
3. The price increase likely contributes to the reported reduced capacity (30-40%) at which many mills operate due to energy cost and supply issues.

Diesel:

- Diesel price increased to Tk 107.75 (0.86 Euro) per litre in June 2024.

LPG:

- Tk 121.32 (0.97 Euro) per kg for October 2024
- A 12 kg LPG cylinder costs Tk 1,517 (12.08 Euro) for retail consumers

Natural gas for cooking in residential buildings in Bangladesh:

- As of 2022, the price of residential natural gas was Tk 18 (0.14 Euro) per cubic meter. The monthly gas bill for double burners was fixed at Tk 1,080 (8.60 Euro) and Tk 990 (7.89 Euro) for single burners. However, a proposal has been made to raise prices further, potentially increasing bills to Tk 1,592 (12.68 Euro) for double burners and Tk 1,380 (10.99 Euro) for single burners.

- Due to natural gas shortages and price increases, many urban households are switching to LPG for cooking. The government encourages using cleaner energy sources like LPG as an alternative to natural gas. LPG is becoming more widely available, with distribution networks expanding to rural and remote areas.

- The government aims to reduce its reliance on natural gas for residential use and prioritise its supply for industrial purposes. It is also pushing to redirect natural gas supply from households (which consume about 13% of the total supply) to industries to generate more foreign currency.

Key points:

Energy prices, especially gas and electricity, have increased significantly over the past year. The textile industry needs help with these high costs and unreliable supplies. Due to gas shortages, many mills operate at reduced capacity (30 – 40%). High energy costs are impacting the competitiveness of Bangladesh's textile exports.

5.7 Financing Options

Several financing options are available for implementing a biogas project:

- **Government Grants:** The Bangladesh government offers incentives for renewable energy projects. Potential grants could cover up to 30% of the initial investment.
- **Development Bank Loans:** Organizations like the Asian Development Bank provide low-interest loans for sustainable energy projects in developing countries.
- **Private Equity:** Local and international investors interested in renewable energy projects in Bangladesh could provide equity financing.
- **Green Bonds:** Issuing green bonds could attract investors interested in supporting environmentally friendly projects.
- **Public-Private Partnerships:** Collaborating with government agencies could provide access to additional funding and support.
- **Carbon Finance:** Registering the project under carbon credit schemes could provide additional revenue streams.

By leveraging a combination of these financing options, the initial capital investment can be secured, reducing the financial burden on the participating textile factories and improving the overall economic feasibility of the project.

5.8 Potential Incentives and Support Mechanisms

Several incentives and support mechanisms are in place or proposed to promote sustainable practices and green investments in the textile sector:

1. Financial Incentives:

- Bangladesh Bank has four direct refinancing schemes and additional foreign currency funds, a total of over Tk 15.5 billion, to promote investments in green projects.
- Corporate income tax waiver for 15 years for private power generation projects.
- Relaxed customs duties on imports for 12 years for power generation projects.
- Tax exemptions on royalties, technical know-how fees, and capital gains for foreign investors in the power sector.

2. Renewable Energy Incentives:

- 15% VAT exemption on all renewable energy equipment and related raw materials.
- Corporate tax waiver for the first five years for renewable energy project investors.
- Incentive tariff of 10% higher than the highest purchase price of electricity from private generators.

3. Energy Efficiency Incentives:

- Subsidies for installing energy-efficient facilities and equipment.
- Preferential taxation (tax reduction or exemption) for energy efficiency investments.

4. Extended Producer Responsibility (EPR):

- The government is exploring the application of an EPR system for textile waste, like the one being developed for plastic waste.

5. Green Financing:

- Bangladesh Bank has set targets for banks and financial institutions to accelerate financing for green investments.
- Introduction of green bonds and green credit to encourage private investment in green projects.
- Leveraging green bonds and sustainable finance mechanisms to secure low-cost funding from institutions like IDCOL.

6. Public-Private-Partnerships (PPP):

- Engaging in PPPs to share risks and benefits with private investors, ensuring robust financial backing and operational expertise.

7. Fiscal Incentives for “Green” RMG Factories:

- RMG factories with green building certification pay income tax at a special rate of 10%, while without this certification, the rate is 12%. While this tax benefit may not appear attractive due to the high overall investment costs for green initiatives, in the long run, the operational costs are lower. Factories may experience buyer preference and long-term economic resilience.
- While more than biogas technology is required to receive the Leadership in Energy and Environmental (LEED) certification, incorporating biogas for waste handling would be favourable. It aligns with the certification’s goals for waste reduction and diversion from landfills. Further, it contributes to on-site renewable energy generation, a crucial aspect of LEED’s “Energy and Atmosphere” category.
- Further, the payback period for investments certified by the LEED & Green Building Certification is as low as 3 to 5 years, after which the factories can benefit from ongoing cost savings.

To support the adoption of biogas technology, the following policy adjustments are recommended:

1. **Economic Incentives:** Provide financial incentives such as subsidies or tax breaks for companies investing in biogas technology.

2. **Technical Innovation:** Encourage research and development to improve the efficiency and reduce the costs of biogas technology.

3. **Regulatory Measures:** Implement regulations requiring large waste producers to adopt sustainable waste management practices, including biogas production.

4. **Collaboration**: The textile industry and research/academic organisations could have a close link to accelerate biogas technology.
5. **Public Awareness:** Increase public awareness about the benefits of biogas technology to garner broader support for such projects.

These policies and incentives create a supportive environment for implementing biogas projects in the textile sector. However, challenges regarding enforcement, awareness, and more specific regulations tailored to the textile industry's waste management needs still need to be addressed. The government should consider developing a comprehensive national strategy for circular textiles to guide the sector's transformation over the next 5-10 years. This strategy should encompass the entire lifecycle of textile products, from production to disposal.

6 Case Studies

Some variations were elaborated in the industrial workshops in early October 2024:

- A centralised model suitable for large industrial zones
- The individual plant model is ideal for large, progressive factories

Only the readily biodegradable waste stream was considered. The above-described pyrolysis is the best solution if non-organic textile waste streams are included. It can also be used as pyrolysis feedstock mixed with dewatered digestate, which is not part of this study.

Some specific aspects must be considered when integrating a biogas plant into a textile industry:

Substrates

The studies are designed to analyse the specific substrate mix from the textile company's different biodegradable waste streams. The composition and quantities of these substrates have been recorded.

Biogas potential

Literature research determined the biogas potential of the various substrates. The potential from a substrate mix (co-digestion) could deviate from standard values, especially for textile waste such as cotton dust.

Pre-and post-treatment

Any necessary pre-treatment steps for the textile-specific waste and the digestate were considered. This could mean additional costs and energy expenditure. At least a liquid/solid separation after digestion is required.

Continuous substrate availability

The study investigated whether there is sufficient substrate all year round or whether seasonal fluctuations are to be expected.

Energy Requirements of the Textile Company

The company’s heat and electricity requirements were analysed to determine the optimal use of the biogas.

Integration into production processes

The possibility of using biogas (for cooking or in boilers) or waste heat (from Combined Heat and Power engines) in textile production processes was investigated.

Cost-effectiveness

The profitability calculation includes savings from avoided waste disposal costs. Potential cost savings through energy self-generation were also considered.

Environmental aspects

Reducing greenhouse gas emissions through waste recycling and energy production was quantified.

6.1 Case Study 1 - Background and Context

The factory is a significant employer and a large-scale producer within the national textile industry, with a strong focus on sustainability and innovation in waste management. Three factories are located on the same ground, which covers 22 ha of land. About 22,500 employees work in three factories. The company offers free meals for each employee. The employees are taking one meal at a canteen. 30% of the total employees live inside the factory residential buildings. The following key types of biodegradable production waste were identified: Cotton Dust and Fabric Scraps.

Figure 21: Typical set-up of several factories in one compound (integrated production)

The following table summarizes the waste types and quantities that are generated together by the facilities in the compound.

Table 16: Waste Types and Approximate Waste Quantities Generated by the Representative Compound - Case Study 1

Waste Type	Quantity (kg/day)
Cotton Dust	3,650
Cotton Yarn Waste	250
Cotton Fabric Scraps Waste	250
Cow Dung	450
Food Waste	4,400
Leaves and Grass Clippings	150

An effluent treatment plant (ETP) treats industrial wastewater. About one-third of treated wastewater is reused inside the factory, and two-thirds is discharged into the local canal. The factory area has a compost plant capacity of 5 tons/month. Surrounding Waste Sources Exploration of additional biodegradable waste sources in nearby areas indicated that adjacent garment factories and local markets could provide supplementary organic waste, enhancing the potential feedstock for biogas production. A good number of other garment factories and markets are located nearby. The factory also has a nearby dairy farm.

Integrating biogas production into the factory's existing waste management practices is intended. The company wants to replace residential natural gas, bought for Tk 500,000 monthly, with a price of Tk 18 per m^3 (27,778 m^3/month or 926 m^3/day). The potential for improving energy self-sufficiency and reducing environmental impact aligns with their broader corporate sustainability goals. The company buys 1,404,814 kWh of grid electricity annually.

6.1.1 Proposed Set-up and Process Description

The delivery takes place in a flat bunker. There, the waste is fed using a conveyor belt to the rough processing, which consists of a shredding unit, a metal separator and a screen. The screen overflow is transported to an intermediate storage facility by conveyor belt, where the waste is homogenised accordingly.

The digesters are charged by blenders (dosing devices), and piston pumps pump the substrate into the digesters. The digester is designed as a plug-flow digester and equipped with a standard gas holder (gas bag). The digestate remains in the heated digester for at least 50 days. There, under anaerobic process conditions (= in the absence of oxygen), biogas is obtained from the digestate. After the digestion process, the digestate is pumped to the screw presses using a piston pump and then separated into press cake and press water. Some press water is used directly to moisten and dilute the input material for the digesters. The rest is stored in storage tanks and used in agriculture.

The solid digestate is processed into valuable compost in the existing composting halls. The methane produced in the fermenters is refined into biomethane in a biogas treatment plant and fed into the company's gas grid. Alternatively, electricity is made with a GENSET or CHP, and electricity (and heat) is provided in the company grid.

Core Process

- Flat bunker delivery system
- Conveyor belt feeding system
- Rough processing unit (shredding, metal separation, screening)
- Plug-flow digester with gas holder
- 50-day digestion period
- Screw press digestate separation system

6.1.2 Potentiality Assessment

Table 17: Waste Characteristics and Potential Biogas and Thermal Energy Output - Case Study 1

Waste Type	INPUT (kg/day)	Volume to handle (l/day)	Biogas (m^3/day)	Thermal energy potential (kWh/day)	Dry matter (DM) in mixed substrate (kg)	Organic dry matter (VS) in the mix (kg)
Cotton Dust	**3,650**	7.30	583.79	4,086.51	3,321.50	1,727.18
Cotton Yarn waste	**250**	1.67	184.00	1,104.00	230.00	184.00
Cotton fabric scraps waste	**250**	1.11	133.89	803.31	175.00	143.50
Cow Dung	**450**	0.45	18.05	108.32	76.50	61.20
Food Waste	**4,500**	8.18	658.13	3,948.75	1,125.00	1,012.50
Leaves and Grass Clippings	**150**	0.43	17.21	89.51	45.00	38.25
Total	**9,250**	**18.50**	**1,595.06**	**10,140.40**	**4,973.00**	**3,166.63**
Average dry matter content in the mix					27%	
Average methane content			64%			

Key aspects

- Focus on readily biodegradable waste
- Including cotton dust and fabric scraps
- Potential additional sources: adjacent garment factories, local markets, nearby dairy farms
- Integration with existing ETP
- Connection to current compost plant

Table 18: Process and Design Parameters for the Biogas System – Case Study 1

Process and Design Parameters	Value
Target DM in feedstock mix in % (Plug-Flow Digester)	25%
Dilution factor to add (treated wastewater, returned digestate water, or sucked faecal sludge)	1.08
Amount of liquid to add (m^3) daily, the biogas potential of this liquid is not considered in the calculation, this dilution liquid will be provided from the septic tank desludging or from recycled digestate water, or from the effluent of the ETP	1.39
Daily feedstock volume to handle (m^3)	19.89
Hydraulic retention time (days)	50
Volume of digester (m^3)	995
If biogas is used for cooking it replaces residential NG (m^3/day)	1,070
% of replacement	116%
Construction cost (CAPEX) in Euro (without GENSET)	440,887
Construction cost / m^3 digester volume (Euro)	443.28
C/N ration in the feedstock mix w/o dilution liquid	29.43
Digestate amount (m^3/day)	18.02
Specific weight for 1 m^3 biogas produced (kg/m^3)	1.18
Losses in organic DM converted to biogas (kg)	1,875.75
Dry matter content in the remaining digestate (%)	17.2%
Dry matter content in the remaining digestate (kg)	3,097.25
Organic loading rate in the digester (OLR) (kg/m^3)	3.18

6.1.3 Economic Assessment for Residential Gas Replacement

Table 19: Project Parameters for Economic Assessment of Residential Gas Replacement – Case Study 1

Project Parameters	
Exchange rate Tk 1 in Euro	0.007728
Project Lifetime (years)	20
Investment Costs (Euro)	440,887
Annual Operating Costs (Euro)	13,227
Annual OPEX in % from CAPEX	3%
Discount Rate (%)	10%
Daily residential natural gas (NG) consumption (m^3)	926
Annual Biogas Production (m^3)	582,198
Biogas Value based on residential NG replacement (Euro)	54,323
Replacement potential residential NG by biogas (%)	116%

Table 20: Results of Financial Analysis for Residential Gas Replacement - Case Study 1

For residential NG replacement	
Net Present Value (NPV) (Euro)	-523,627
Internal Rate of Return (IRR) (%)	7%
Return on Investment (ROI)	-0.1
Simple Payback Period (Years)	10.7
Cost of Energy (CoE) for NG (Euro)	0.06
Benefit-Cost-Ratio	1.54

Interpretation of the values for Residential Natural Gas Replacement Scenario

1. Net Present Value (NPV) = -523,627 Euro

A negative NPV means that the project’s expected discounted cash inflows do not cover the initial investment and subsequent costs when accounting for the time value of money. In other words, under the assumed discount rate and projected financials, the project would destroy value rather than create it. This suggests that the project is not attractive from a strictly financial perspective.

2. Internal Rate of Return (IRR) = 7%

An IRR of 7% is relatively modest. While not an outright loss in a simple sense, it does not provide compelling profitability compared to typical expected returns on similar investments.

3. Return on Investment (ROI) = -0.1

A negative ROI indicates that the total returns over the project's life are less than the initial investment. This project never recovers costs in a straightforward, undiscounted profit-and-loss sense.

4. Simple Payback Period = 10.7 years

A payback period of nearly 11 years is quite long, especially for waste-to-energy projects that often target shorter horizons due to uncertainties in policy, market prices, and technological changes. Investors in Bangladesh prefer payback periods under 7 years. A long payback period increases the project's risk and lowers its attractiveness.

5. Cost of Energy (CoE) = 0.06 Euro

A CoE of 0.06 Euro per unit of thermal energy generated is lower than the current natural gas, which is 0.24 Euro per m^3. Therefore, it is cost competitive as the current price of natural gas is higher and provides a substantial environmental premium that can be monetised. It appears to offer an economic advantage over traditional options.

6. Benefit-Cost Ratio (BCR) = 1.54

At first glance, a BCR above 1 suggests that total undiscounted benefits exceed total costs. However, the discrepancy between a positive BCR and a negative NPV indicates that while the sum of benefits over the entire project life outweighs costs in nominal terms, the timing and the discounting of those benefits (when brought back to present value terms) are unfavourable. In other words, the benefits may occur too far, or the discount rate used makes these future benefits much less valuable today.

6.1.4 Economic Assessment for Captive Power and Heat Production

Table 21: Project Parameters for Economic Assessment of Power and Heat Production – Case Study 1

Project Parameters			
Exchange rate Tk 1 in Euro	**0.007728**		
Project Lifetime (Years)	**20**		
Plant Capacity (kW)	176		
Investment Costs (Euro)	617,242		
Annual Operating Costs (Euro)	30,862		
Electricity Price (Euro/kWh)	0.09	Tk 12 is the in 2026 expected industry price w/o subsidy,	
Annual Electricity Generation (kWh)	1,480,498		
Heat value (Euro/kWh)	0.075		
Annual Heat Generation (kWh)	1,850,623		
Discount Rate (%)	10%		
Operational hours/day (Hours)	23		
CAPEX per kW$_{installed}$ capacity (Euro)	3,500	Figure from IDCOL, including GENSET	
Annual OPEX in % from CAPEX (including generator engine maintenance)	5%		
CHP electrical efficiency (%)	40%	CLARKE ENERGY	
CHP thermal efficiency (%)	50%	CLARKE ENERGY	
Replacement potential Grid-Electricity by biogas (%)	**105%**		

Table 22: Results of Financial Analysis for Power and Heat Production - Case Study 1

For electricity and heat generation	
Net Present Value (NPV) (Euro)	688,263
Internal Rate of Return (IRR) (%)	39%
Return on Investment (ROI)	5.8
Simple Payback Period (Years)	2.6
Cost of Energy (CoE) for the electricity part (Euro)	0.04
Benefit-Cost Ration (BCR)	4.41

Interpretation of the revised values for the same plug-flow biogas plant investment but aimed at producing electricity and heat

1. Net Present Value (NPV) = 688,263 Euro

A positive NPV, notably a large one, suggests that the projected discounted revenues significantly exceed the project's upfront and ongoing costs. This strongly indicates that the investment is financially sound under the assumptions used.

2. Internal Rate of Return (IRR) = 39%

An IRR of 39% is exceptionally high for a waste-to-energy project. This means the project is expected to generate returns well above typical industry discount rates or the cost of capital, making it highly attractive to investors.

3. Return on Investment (ROI) = 5.8

An ROI of 5.8 implies that for every Euro invested, the project is projected to return 5.80 Euro in profit over its lifetime. This shows a substantial payoff compared to the initial investment, suggesting strong profitability.

4. Simple Payback Period = 2.6 years

For a capital-intensive renewable energy project, recovering the initial outlay in around two and a half years is relatively quick. A short payback period reduces financial risk and increases the project's appeal to investors and lenders.

5. Cost of Energy (CoE) = 0.04 Euro

At 0.04 Euro per kWh of electricity generated, the project's energy is very cost-competitive, potentially even cheaper than grid sources. Given rising energy costs and volatility, producing electricity at such a low CoE provides a distinct competitive advantage.

6. Benefit-Cost Ratio (BCR) = 4.41

A BCR of 4.41 means that the project's benefits are over four times its costs. This high ratio underscores the economic efficiency and robustness of the project.

6.1.5 Expected Results and Impact

Biogas could replace residential gas **or** grid electricity entirely. In this factory compound, upgraded biogas could replace the residential gas. In summary, about 59% more biogas volume (with 60% methane content) is needed to replace natural gas, although additional factors such as cleaning must be considered.

Using biogas instead of natural gas without converting the gas-using end devices presents some technical challenges:

- Processing to biomethane: Biogas must be processed to biomethane to achieve the same quality as natural gas. In particular, the CO_2 content must be reduced, and the methane content must be increased to over 95%. This processing is technically complex and costly.
- Fluctuating gas quality: The composition of biogas can vary depending on the source materials and season. This requires continuous monitoring and adjustment of the treatment processes.
- Storage and transportation: The decentralised biogas production requires storage if the existing natural gas network can be used.
- Seasonal fluctuations: Biogas production is subject to seasonal fluctuations, making it difficult to ensure a continuous supply.
- Economic efficiency: Producing biogas is often more expensive than extracting natural gas, which makes it difficult to compete economically.

These technical challenges clarify that partially replacing natural gas with biogas is possible, although biogas is considered a supplementary component in a diversified energy mix.

Replacing NG with upgraded biogas might become attractive under more favourable financing conditions (lower required returns or interest rates). Policy incentives, grants, or subsidies could tip the scales positively by improving the NPV. Environmental and strategic benefits—although not fully captured in these financial metrics—could justify the project for stakeholders focused on sustainability or energy security. Ultimately, this scenario is a borderline financial proposition. It is not a clear-cut “no,” but it would likely require improved terms (cheaper financing, subsidies, better feed-in tariffs), reduced investment costs, or policy support to become unambiguously appealing.

The figures for replacing grid or captive electricity and providing additional heat present a highly positive and financially attractive proposition. With a strong NPV, very high IRR, excellent ROI, short payback period, low CoE, and high BCR, the project appears viable and very lucrative. Moreover, producing clean energy from waste provides potential environmental and strategic benefits, such as reduced dependency on traditional fuels and improved waste management. While real-world conditions and policy frameworks may still affect outcomes, the revised financial metrics indicate that investing in a biogas plant for electricity and heat generation could be a smart strategic move under the given assumptions.

When biogas displaces natural gas in Bangladesh, the following carbon credits can be issued:

- Voluntary emission reductions (VERs): These credits can be traded in the voluntary carbon market independently of regulated systems.
- Specific biogas-related credits: Methane avoidance credits, as biogas reduces methane emissions from organic waste. Renewable energy credits for the generation of clean energy from biogas.
- Improved cook stove credits: Additional credits can be generated if biogas is used in improved cook stoves.
- Waste management credits: For processing organic waste for biogas production.
- Agricultural emission reduction credits: If biogas is also produced from agricultural waste.

The exact number of carbon credits awarded depends on various factors, such as:

- The amount of natural gas replaced
- The efficiency of biogas production and use
- The specific project details and the methodology for calculating emissions

It is important to note that Bangladesh already has experience selling carbon credits. Since 2006, the country has sold 2.53 million carbon credits worth 16.25 million USD (15.50 million Euro), mainly through projects such as improved cooking stoves and solar home systems.

Recommendations for implementations

- Conduct detailed substrate analysis before implementation
- Assess seasonal waste availability
- Evaluate integration costs within existing infrastructure
- Consider a hybrid energy approach rather than a complete replacement
- Calculate potential carbon credits based on specific, accurate project parameters

6.2 Case Study 2 - Background and Context

A unique industrial park has emerged, showcasing a collaborative approach to waste management and energy utilisation. This park is characterised by its high density of small and medium-sized, mainly textile industries situated near one another. The industrial park consists primarily of small and medium-sized enterprises (SMEs) specialising in various aspects of textile production. These industries are tightly packed, with neighbouring facilities often sharing walls or separated by narrow alleys. This close-knit arrangement creates both challenges and opportunities for resource management.

Recognising the potential for improved efficiency and sustainability, the industries within the park have expressed interest in forming an association to manage their waste and collectively use biogas energy. This initiative stems from the realisation that their waste, particularly cotton waste from spinning, knitting, and cutting processes, can be a valuable resource rather than a burden.

The proposed cooperative biogas plant system offers significant potential for the industrial park:

- Waste Collection: A centralised system would collect various types of biodegradable textile waste, including cotton micro-dust, cutting, and knitting waste, from participating industries.
- Anaerobic Digestion: The collected waste would undergo anaerobic digestion after specific pre-treatment in large-scale biogas plants. This process is sustainable, cost-effective, and eco-friendly, particularly suitable for Bangladesh's context.
- Energy Production: The biogas generated could be used for multiple purposes within the industrial park:

    - Powering industrial machinery, such as yarn singeing machines
    - Generating electricity for the facilities
    - Providing fuel for cooking or heating purposes

- Slurry Utilization: The separated solid digestate produced after biogas generation can be used as a bio-compost, potentially benefiting local agriculture or landscaping within the industrial park.

This cooperative approach to waste management and energy production offers several advantages:

- Reduction of CO_2 emissions by avoiding the burning of cotton waste
- Creation of a circular economy within the textile industry
- Cost savings on energy and waste disposal for participating industries
- Potential for additional revenue streams from biogas and compost sales

While the concept shows promise, implementing such a system would require careful planning and coordination:

- Establishing a fair and efficient waste collection system
- Designing the biogas plant to handle the diverse types of textile waste
- Ensuring equitable distribution of the produced energy and benefits
- Complying with local environmental regulations and safety standards

The following table shows the waste types and approximate waste quantities that are collectively generated by the facilities in the industrial park.

Table 23: Waste Types and Approximate Waste Quantities Generated by the Representative Compound - Case Study 2

Waste Type	Quantity (kg/day)
Cotton Dust	25
Cotton Yarn waste	30
Cotton fabric scraps waste	3,100
Food Waste	40
Faecal sludge	1,005

A central effluent treatment plant (ETP) treats industrial wastewater.

The intention is to integrate biogas production into the factory’s waste management practices. Each company wants to replace some heat and part of its grid electricity with biogas; the average monthly electricity consumption is 3,229,899 kWh/company.

6.2.1 Proposed Set-up and Process Description

Various waste streams are delivered to a mixing bunker. From there, the waste is fed using a conveyor belt to the rough processing unit, which consists of a shredding unit, a metal separator, and a screen. The screen overflow is transported by conveyor belt to an intermediate storage facility, where the waste is homogenised accordingly.

Blenders (dosing devices) charge the Continuously Stirred Tank Reactor (CSTR) digesters, and piston pumps transfer the substrate. The CSTR digester is designed for efficient mixing. The plant maintains a consistent 10% dry matter content by co-digesting various waste streams. This setup allows for better process control and optimised biogas production.

The digester has a standard gas holder (membrane gas cover) to collect the produced biogas. The digestate remains in the digester for an average of 40-50 days. Under anaerobic process conditions (without oxygen), biogas is obtained from the organic matter in the waste streams.

After the digestion process, the digestate is pumped to screw presses using a piston pump and then separated into press cake and press water. Some press water is used directly to moisten and dilute the input material for the digesters, maintaining the optimal 10% dry matter content. The rest is delivered to the ETP.

The solid digestate is processed into valuable compost in the existing composting halls, providing an additional value stream from the waste treatment process.

The methane produced in the fermenters is desulphurised and dried. It is then used to generate electricity using a GENSET or Combined Heat and Power (CHP) unit. This unit provides electricity (and heat) to the company grid.

The CSTR digester system with co-digestion of various waste streams at 10% dry matter content offers several advantages:

- Improved process stability: The continuous mixing in the CSTR helps maintain uniform conditions throughout the digester.
- Enhanced biogas yield: Co-digestion of various waste streams can improve nutrient balance and increase biogas production.
- Feedstock flexibility: The system can handle a wide range of organic waste streams, making it adaptable to changes in waste availability.
- Efficient resource recovery: The process produces biogas for energy generation, liquid fertiliser, and compost, maximising the value extracted from the waste streams.

6.2.2 Potentiality Assessment

Table 24: Waste Characteristics and Potential Biogas and Thermal Energy Output - Case Study 2

Waste Type	INPUT (kg/day)	Daily volume to handle (m^3)	Biogas Production (m^3/day)	Thermal energy potential (kWh/day)	Dry matter in substrate (kg)	Organic dry matter in the mix (kg)
Cotton Dust	**25**	0.05	4.00	27.99	22.75	11.83
Cotton Yarn waste	**30**	0.20	22.08	132.48	27.60	22.08
Cotton fabric scraps waste (*Jhut, Jhoot*)	**3,100**	13.78	1,660.18	9,961.08	2,170.00	1,779.40
Faecal Sludge sucked	**1,005**	1.01	3.52	22.86	20.10	14.07
Food Waste	**40**	0.07	5.85	35.10	10.00	9.00
Total	**4,200**	**15.11**	**1,695.63**	**10,179.51**	**2,250.45**	**1,836.38**
Average dry matter in the co-digestion feedstock mix					15%	

Methane content in the biogas from co-digestion	60%

Key aspects

- Focus on readily biodegradable waste
- Including cotton dust and fabric scraps
- Potential additional sources: adjacent garment factories
- Integration with existing ETP
- Connection to current compost plant

Table 25: Process and Design Parameters for the Biogas System – Case Study 2

Process and Design Parameter	Value
Target DM in feedstock mix in % (CSTR Digester)	10%
Dilution factor to add (treated wastewater, returned digestate water, or sucked faecal sludge)	1.49
Amount of liquid to add (m^3) daily, the biogas potential of this liquid is not considered in the calculation, this dilution liquid will be provided from the septic tank desludging or from recycled digestate water, or from the effluent of the ETP	7.40
Daily feedstock volume to handle (m^3)	22.50
Hydraulic retention time (days)	40
Volume of digester (m^3)	900
Installed GENSET/CHP capacity (kWh)	177
Construction cost (CAPEX) in Euro (with GENSET)	619,623
Construction cost / m^3 volume digester (Euro)	688.33
C/N ration in the feedstock mix w/o dilution liquid	34.37
Digestate amount (m^3/day)	20.43
Specific weight for 1 m^3 biogas produced in kg/m^3	1.22
Losses in organic DM converted to biogas (kg)	2,069.63
Dry matter content in the remaining digestate (%)	0.9
Dry matter content in the remaining digestate (kg)	189.82
Organic loading rate in the digester (OLR) (kg/m^3)	2.04

6.2.3 Economic Assessment for Captive Power and Heat Production

Table 26: Project Parameters for Economic Assessment of Power and Heat Production – Case Study 2

Project Parameters			
Exchange rate Tk 1 in Euro	**0.007728**		
Project Lifetime (years)	**20**		
Plant Capacity (kW)	177		
Investment Costs (Euro)	619,623		
Annual Operating Costs (Euro)	30,981		
Electricity value (Euro/kWh)	0.09	Tk 12 is the in 2026 expected industry price w/o subsidy,	
Annual Electricity Generation (kWh)	1,486,209		
Heat value (Euro/kWh)	0.075		
Annual Heat Generation (kWh)	1,857,761		
Discount Rate (%)	10%		
Operational hours/day (hours)	23		
CAPEX per $kW_{installed}$ capacity (Euro)	3,500	Figure from IDCOL, including GENSET	
Annual OPEX in % from CAPEX (including generator engine maintenance)	5%		
CHP electrical efficiency (%)	40%	CLARKE ENERGY	
CHP thermal efficiency (%)	50%	CLARKE ENERGY	
Replacement potential annual Grid-Electricity by biogas (%)	**4%**		

Table 27: Results of Financial Analysis for Power and Heat Production - Case Study 2

For electricity and heat generation	
Net Present Value (NPV) in Euro	690,918
Internal Rate of Return (IRR)	39%
Return on Investment (ROI)	5.8
Simple Payback Period (Years)	2.6
Cost of Energy (CoE) (only Electricity) in Euro	0.04
Benefit-Cost Ration (BCR)	4.41

Interpretation of the values

1. Net Present Value (NPV) = 690,918 Euro

A positive and substantial NPV indicates that the project's expected discounted cash flows exceed the initial investment. After accounting for all costs and revenues over the project's lifetime and discounting future values back to the present, the project would create approximately 690,918 Euros of net value, which strongly suggests it is financially viable.

2. Internal Rate of Return (IRR) = 39%

The IRR is the discount rate at which the project's NPV equals zero. An IRR of 39% is considered very high for most infrastructure or waste-to-energy projects. It indicates that the project's returns greatly surpass typical hurdle rates (often 8–15% for many energy projects, depending on the country and capital markets). A 39% IRR suggests a desirable investment, as it provides a significant margin above typical financing costs or alternative investment benchmarks.

3. Return on Investment (ROI) = 5.8

An ROI of 5.8 means that for every Euro invested, the project returns 5.80 Euro in profit. This is an influential figure, reflecting a project that recovers costs and generates substantial surplus returns over its lifetime.

4. Simple Payback Period = 2.6 years

The simple payback period is the time it takes for the cumulative cash flows to cover the initial investment. At 2.6 years, this is considered relatively short, especially for a capital-intensive renewable energy project. A short payback period enhances the project's attractiveness by reducing risk exposure, as capital is quickly recovered.

5. Cost of Energy (CoE) (only Electricity) = 0.04 Euro

This metric indicates the levelized cost of producing one unit of electricity (often expressed in Euro/kWh). At 0.04 Euro, this is notably low and competitive. It suggests the plant can generate electricity at a cost well below typical market electricity prices. However, grid electricity could only be partly replaced by biogas, which is estimated at 4%.

6. Benefit-Cost Ratio (BCR) = 4.41

A BCR of 4.41 means that for every 1 Euro of cost, the project yields 4.41 Euros of benefits over its lifetime. This is a strong indicator of economic efficiency, showing that the financial returns are more than four times the invested capital.

6.2.4 Expected Results and Impact

All the indicators—high IRR, positive and significant NPV, short payback period, low CoE, high ROI, and robust BCR—point to the project being a desirable investment. The figures suggest that converting easy biodegradable textile waste components into biogas for electricity and heat in Bangladesh is environmentally beneficial and profitable under the given assumptions.

Recommendations for implementations

- Conduct detailed substrate analysis before implementation
- Assess seasonal waste availability
- Evaluate integration costs within existing infrastructure
- Consider a hybrid energy approach rather than a complete replacement
- Calculate potential carbon credits based on specific, accurate project parameters

7 Conclusions and Recommendations

Based on the feasibility study and case study analysis, we can conclude that biogas production from textile industry waste in Bangladesh is technically feasible and economically viable. Implementing biogas technology offers significant benefits in terms of waste management, energy production, and environmental sustainability.

7.1 Key Conclusions

- Biogas production can significantly reduce the environmental impact of textile factory waste.
- The technology is adaptable to various scales, from individual factories to industrial zones.
- Economic benefits include energy cost savings and potential revenue from by-products.
- Biogas projects align with national and global sustainability goals.

7.2 Recommendations

- Policy Support: The government should develop a comprehensive national strategy for circular textiles, including specific incentives for biogas projects.
- Financial Mechanisms: Establish green financing options and public-private partnerships to overcome initial investment barriers.
- Technical Capacity Building: Invest in training programs for biogas plant operation and maintenance.
- Pilot Projects: Implement pilot projects in crucial textile clusters to demonstrate feasibility and benefits.
- Waste Segregation: Improve waste segregation practices in factories to enhance feedstock quality.
- Market Development: Create markets for biogas and digestate products, potentially through government procurement policies.
- Research and Development: Support ongoing R&D to improve biogas technology efficiency and reduce costs.
- Awareness Campaigns: Conduct awareness programs for factory owners and workers on the benefits of biogas technology.
- Regulatory Framework: Strengthen and enforce regulations on waste management and renewable energy in the textile sector.
- International Collaboration: Engage with international organisations and countries with successful biogas implementations to leverage best practices.
- By implementing these recommendations, Bangladesh's textile industry can lead the way in sustainable waste management and renewable energy production, setting a model for other developing countries with significant textile sectors.

8 Additional sources

8.1 Literature Review on Biogas Potentials

This table provides a general overview and comparison of the different feedstocks. Experimental tests on the actual substrates are recommended for specific applications, as local variations and specific characteristics can significantly impact the anaerobic digestion process and biogas yields. Please note that not all information is available for every feedstock, and some values are approximated or range based on typical values, as reported in the literature.

a) Food and kitchen waste

Food and kitchen waste have significant potential for biogas production through anaerobic digestion.

- Food waste's biochemical methane potential (BMP) has been reported to be 0.56 m^3 CH_4/kg volatile solids (VS).
- A study on market waste found that fruit and vegetable waste had a BMP of 0.3 m^3 CH_4/kg VS.
- The biodegradability of food waste was calculated to be 83.6%, indicating a high potential for methane production.

Food waste typically has a high moisture content, with one study reporting an average of 92% water content and 8.08% solids. This high moisture content can be beneficial for the anaerobic digestion process. Food waste has shown significant potential for biogas production through anaerobic digestion, with various studies exploring its characteristics and performance under different conditions:

- Food waste has demonstrated high biogas yields in anaerobic digestion processes.
- In a study comparing different substrates, food waste produced 558 N dm^3 kg^{-1} VS^{-1} of biogas when co-digested with carrot pomace and kale by-products.

Biochemical Methane Potential (BMP)

- The biochemical methane potential of food waste can vary depending on its composition and treatment methods.
- A study on thermally pretreated food waste reported the highest cumulative methane yield of 442 (± 8.6) mL/gVS added, which represented a 28.1% enhancement compared to untreated food waste.

Co-digestion Performance

1. Food waste and sewage sludge:

- The highest biogas production, at 255.14 mL/g VS, was achieved by co-digestion of food waste and sewage sludge in a 1:1 ratio.
- This was 1.53 times higher than the mono-digestion of food waste and 14.5 times higher than the thermal hydrolysis pretreatment of sewage sludge (THSS).

2. Food waste and animal waste:

- Co-digestion of food waste with various animal wastes has shown promising results for biogas production.
- Different combinations were studied, including poultry and food waste, cattle and food waste, and swine manure with corn straw.

Factors Affecting Biogas Production

1. C/N Ratio:

- The C/N ratio of food waste can significantly impact biogas production.
- Optimal C/N ratios for anaerobic digestion typically range from 20:1 to 30:1.

2. Organic Loading Rate:

- The organic loading rate of food waste affects biogas production and digester stability.
- Studies have investigated the impact of different organic loading rates on anaerobic digestion performance.

3. Pretreatment:

- Thermal pretreatment of food waste can enhance biogas production.
- A study examining thermal pretreatment at 80°C, 100°C, 120°C for 2 hours, and 140°C for 1 hour found that pretreatment at 80°C resulted in the highest methane yield.

4. Solubilization:

- Thermal pretreatment increased the solubilisation of organic matter in food waste.
- Soluble COD and soluble protein increased linearly with pretreatment temperature.
- Carbohydrate solubilisation was enhanced (30% higher) at lower temperatures (80°C).

Volatile Fatty Acids (VFAs) Production

- The distribution of VFAs during anaerobic digestion of food waste has been studied.
- No significant variation in VFA trends was observed during biochemical methane potential (BMP) tests under various pretreatment conditions.

Digestate Characteristics

Co-digestion of food waste with septic sludge can affect the digestate's properties:

- The dewaterability of the digestate deteriorated sharply after co-digestion, with a decrease of 54.92% for a 1:1 ratio of food waste to sludge.
- Co-digestion reduced the apparent viscosity and shear stress compared to mono-digestion, indicating higher flow properties of the co-digestion matrix.

In conclusion, food waste demonstrates excellent potential for biogas production through anaerobic digestion. Its high organic content and biodegradability make it an attractive substrate for biogas plants. Co-digestion with other organic wastes, such as faecal sludge or animal manure, can further enhance biogas yields. Pretreatment methods, particularly thermal pretreatment, can significantly improve the methane yield from food waste. However, carefully considering factors such as C/N ratio, organic loading rate, and co-digestion strategies is crucial for optimising biogas production and maintaining digester stability when using food waste as a substrate.

b) Sludge from septic tanks

Faecal sludge has shown significant potential for biogas production through anaerobic digestion, with various studies exploring its characteristics and performance under different conditions:

- Fresh faecal sludge has demonstrated comparable cumulative biogas (CBG) production to fresh food waste, ranging from 615 to 627 mL/gVS.
- Stored faecal sludge shows a wide range of gas production, from 13 to 449 mL/gVS, indicating that storage conditions significantly affect biogas potential.

Factors Affecting Biogas Production

1. Total Solids (TS) Content:

A study examining fresh faeces with 8% and 12% TS content found that higher TS content generally led to slightly higher organic removal rates and gas production per gram of volatile solids (VS) removed.

2. Temperature:

Mesophilic (37°C) and thermophilic (55°C) conditions were compared:

- At 37°C, Gas production per gram of VS removed was 224-233 mL
- At 55°C, Gas production per gram of VS removed was 366-448 mL

3. Storage and Freshness:

Fresh faecal sludge produces significantly more biogas than stored faecal sludge.

4. Co-digestion:

Co-digestion with food waste significantly enhanced biogas production:

- Fresh faecal sludge: 1.2 times increase
- Dewatered faecal sludge: 1.5 times increase
- Stored faecal sludge: 29-36 times increase.

Organic Matter Degradation

Organic removal rates in different experimental groups ranged from 45.4% to 48.5%. In some cases, biphasic biogas production was observed, readily biodegradable organics degrading during the first week. The C/N ratio of sludge is typically low, which can be improved by co-digestion with other substrates.

Co-digestion of faecal sludge with other substrates has shown promising results:

1. Faecal sludge and food waste:

- Co-digestion significantly enhanced biogas production, especially for stored faecal sludge.
- Under mesophilic conditions (37°C), co-digestion of faecal sludge and food waste yielded 287.5 mL CH_4/g VS.

2. Faecal sludge, food waste, and biochar:

Adding rice straw-derived biochar to the co-digestion of faecal sludge and food waste further improved methane yield:

- At 37°C: 396 mL CH_4/g VS
- At ambient temperature (20-26°C): 275 mL CH_4/g VS

Considerations for Anaerobic Digestion of Faecal Sludge

When using faecal sludge for biogas production, several factors should be considered:

- Freshness: Fresh faecal sludge has significantly higher biogas potential than stored sludge.
- Temperature: Thermophilic conditions (55°C) generally produce more gas than mesophilic conditions (37°C).
- Co-digestion: Mixing faecal sludge with other substrates, particularly food waste, can significantly enhance biogas production.
- Additives: Using powdered biochar as an additive can improve methane yield in co-digestion setups.
- Pretreatment: Pretreatment or co-treatment may be necessary to produce viable biogas from stored faecal sludge.
- Microbial community: Slow-growing methanogens (Heliobacteria) indicate potential hydrolysis limitations in anaerobic digestion.

In conclusion, faecal sludge shows considerable potential for biogas production, especially when fresh and co-digested with other organic wastes. The anaerobic digestion of faecal sludge provides a renewable energy source and a solution for sustainable waste management. However, carefully considering freshness, temperature, and co-digestion strategies is crucial for optimising biogas production from this substrate.

c) Cotton dust and cotton waste

Cotton dust and various forms of cotton waste have shown potential for biogas production through anaerobic digestion.

- Cotton waste has significant potential for biogas generation.
- A study comparing agricultural substrates showed that cotton waste produced the highest methane yield of 317.6 ml/g of volatile solids.

Types of Cotton Waste Studied

Several forms of cotton waste have been investigated for biogas production:

- Cotton stalks
- Cotton seed hull
- Cotton oil cake
- Cotton yarn waste (CYW)
- Cotton stem

Cotton yarn dust and other textile wastes have shown potential for anaerobic digestion, although they may present some challenges:

- Textile waste, including cotton, is becoming one of the most polluting wastes in the world. It is often discarded in landfills.
- Cotton yarn production generates approximately 3% of waste as micro dust, typically not further processed for textile applications.
- Valorising textile waste through anaerobic digestion can help conserve resources, reduce environmental impact, and foster a circular economy.

Factors Affecting Biogas Production

1. Composition:

The cotton stem is a suitable bioethanol and biogas production feedstock due to its composition.

2. Co-digestion:

Anaerobic digestion of cotton stem alone achieved 40.35% total biogas with a 12.76% increase in net CH_4 volume compared to co-digestion with buffalo dung.

3. Substrate preparation:

- Chopped cotton waste could be a biogas production substrate.
- In one study, the cotton stalk was gradually used to replace gobar (cow dung) content as a substrate, with the digester performing well up to 90% feeding of the cotton waste substrate.

4. Temperature control:

- Maintaining optimal temperature is crucial for biogas production from cotton waste.
- A study investigated using sawdust as a low-cost material for temperature control in the anaerobic digestion of cotton yarn wastes (CYW).

Experimental Results

1. Maximum biogas generation:

In one study, the maximum biogas generation detected was 1.3 m^3 using chopped cotton waste.

2. Temperature control comparison:

Digesters controlled by temperature using a water bath showed the highest biogas yield (2481.23 ± 5.50 mL per g-VS), followed by sawdust-controlled (1856.51 ± 6.98 mL per g-VS) and room-temperature (1084.29 ± 5.71 mL per g-VS).

3. Methane content:

The methane content of biogas from agricultural wastes, including cotton waste, ranged from 57% to 64%.

The highest methane content was obtained from digestion controlled by a water bath (62.35%), followed by sawdust-controlled digestion (52.45%) and uncontrolled digestion (45.28%).

Challenges and Considerations

1. Digester clogging:

The study using chopped cotton waste reported repeated choking of the digester, indicating a need to address this issue for practical applications.

2. Pretreatment:

Chemical, biological, and thermal pretreatments can significantly increase the digestion process efficiency for textile wastes, including cotton.

3. Co-digestion:

Co-digestion of natural textile waste (including cotton) with carbon—and nitrogen-rich substrates can improve anaerobic digestion efficiency up to twofold.

4. Lignin content:

The lignin and hemicellulose content in agricultural substrates, including cotton waste, can limit biodegradability and methane production.

In conclusion, cotton dust and various forms of cotton waste show promising potential for biogas production through anaerobic digestion. The high methane yield from cotton waste, particularly compared to other agricultural substrates, makes it an attractive option for renewable energy production. However, challenges such as digester clogging and the need for effective temperature control must be addressed for practical applications. Future research could focus on optimising pretreatment methods, exploring co-digestion strategies, and developing solutions to overcome the challenges of using cotton waste as a substrate for biogas production.

d) Other organic waste from textile production

Textile industry wastes have been studied for their biogas production potential:

Natural textile wastes such as cotton and wool can be co-digested with carbon—and nitrogen-rich substrates to improve anaerobic digestion efficiency up to twofold.

Pretreatment methods, including chemical, biological, and thermal processes, can significantly improve textile waste's digestion and methane yield.

Co-digestion and Substrate Mixing

Co-digestion of different substrates has shown promising results in improving biogas production:

- A study on charcoal and kitchen waste co-digestion found that a ratio of 1:4 (charcoal: kitchen waste) produced the highest cumulative CH_4 production.
- Co-digestion can help balance C/N ratios and improve process efficiency.

Considerations for Substrate Selection

When selecting substrates for anaerobic digestion, several factors should be considered:

- C/N ratio: An optimal C/N ratio is crucial for efficient anaerobic digestion. Co-digestion can help balance this ratio.
- Organic dry matter and volatile solids content: Higher VS content correlates with higher biogas potential
- Biodegradability: Substrates with higher biodegradability, such as food waste, tend to produce more biogas.
- Pretreatment requirements: Some substrates, particularly textile wastes, may require pretreatment to enhance their biogas potential.
- Synergistic effects: Combining multiple substrates can lead to synergistic effects, improving overall biogas production.

Textile industry waste encompasses a variety of materials, including natural and synthetic fibres and processing residues. Various studies have explored the potential of these wastes for biogas production through anaerobic digestion (AD), exploring their characteristics and performance.

e) Types of Textile Waste

1. Natural fibre waste:

- Cotton waste (including cotton dust, yarn waste, and cotton stalks)
- Wool waste
- Silk waste
- Jute and flax waste

2. Synthetic fibre waste:

- Polyester waste

3. Processing residues:

- Dye effluents
- Sizing agents
- Other chemical residues

Biogas Production Potential

- Textile wastes have demonstrated significant potential for biogas generation through anaerobic digestion.
- The efficiency of AD processes for textile wastes can be improved through various pretreatment methods and co-digestion strategies.

Factors Affecting Biogas Production

1. Recalcitrant Materials:

- Recalcitrant materials in textile waste can reduce the efficiency of the AD process.

2. Chemical Residues:

- Chemicals used in textile processing can be toxic to anaerobic microorganisms, affecting biogas production.

3. Pretreatment Methods:

- Chemical, physical, and biological pretreatments can significantly increase the digestion process efficiency for textile wastes.
- Biological pretreatments are more efficient and eco-friendlier, increasing CH_4 yield by up to 360%.

4. Co-digestion:

- Co-digestion of natural textile waste with carbon—and nitrogen-rich substrates can improve anaerobic digestion efficiency up to twofold.

Environmental Impact and Sustainability

1. Life Cycle Assessment (LCA):

- LCA studies have been conducted to evaluate the environmental impact of various textile fibres, including natural and synthetic options.
- Factors such as fossil resource scarcity, global warming potential, land use, terrestrial ecotoxicity, and water consumption are significant in assessing the environmental impact of textile production.

2. Waste Management Strategies:

- Recycling, upcycling, and composting are key strategies for managing textile waste.
- Effective waste management can create new industries and job opportunities in recycling facilities, resale markets, and sustainable fashion companies.

3. Circular Economy:

- Anaerobic digestion of textile waste contributes to a circular economy approach by transforming waste into clean energy and enabling water recovery.

Challenges and Considerations

1. Fibre Composition:

   - Different types of textile waste may require specific pretreatment or co-digestion strategies to optimise biogas production.

2. Chemical Contaminants:

   - Dyes, sizing agents, and other chemical residues can inhibit anaerobic digestion.

3. Variability in Waste Composition:

   - The heterogeneous nature of textile waste streams may require careful characterisation and sorting to ensure consistent biogas production.

4. Scale-up and Implementation:

   - Transitioning from laboratory-scale studies to industrial-scale applications may present challenges in maintaining process efficiency and stability.

In conclusion, organic waste from textile production shows promising potential for biogas production through anaerobic digestion. Applying appropriate pretreatment methods, particularly biological pretreatments and co-digestion strategies, can significantly enhance biogas yields. However, the complex and varied nature of textile wastes necessitates careful consideration of waste composition, potential inhibitors, and process optimisation to maximise biogas production and contribute to sustainable waste management in the textile industry.

d) Packing materials in textile industries

Textile industries use various packing materials for storage, transportation, and product protection.

1. Cardboard and paper:

   - Boxes, cartons, and wrapping paper

2. Plastic:

   - Polythene bags, plastic wraps, and containers

3. Natural fibres:

   - Jute bags and cotton bags

4. Synthetic fibres:

   - Polyester and nylon packaging materials

5. Wood:

   - Pallets and crates

Biogas Production Potential

The potential for biogas production from packing materials varies depending on their composition:

1. Cellulose-based materials (cardboard, paper, natural fibres):

- These materials have good potential for anaerobic digestion due to their organic nature.
- Cardboard, when shredded, can be an effective co-substrate in anaerobic digestion processes.

2. Plastic and synthetic materials:

- They are generally not suitable for anaerobic digestion due to their non-biodegradable nature.
- However, some biodegradable plastics have the potential for biogas production.

3. Wood:

- While wood can be digested anaerobically, it typically requires extensive pretreatment due to its high lignin content.

Factors Affecting Biogas Production

1. Material composition:

The cellulose, hemicellulose, and lignin content of packing materials significantly affect their digestibility.

2. Pretreatment:

Many packing materials, especially those with high lignin content, may require pretreatment to enhance their biodegradability.

3. Co-digestion:

Mixing packing materials with other organic wastes can improve biogas yield and process stability.

4. Particle size:

Shredding or grinding packing materials can increase their surface area, potentially improving digestion efficiency.

Environmental Considerations

1. Waste reduction:

Using packing materials for biogas production can help reduce waste sent to landfills.

2. Circular economy:

Incorporating packing waste into biogas production aligns with circular economy principles.

3. Energy recovery:

Biogas production from packing materials represents a form of energy recovery from waste.

Challenges and Considerations

1. Contamination:

Packing materials may contain inks, adhesives, or other contaminants that could affect anaerobic digestion.

2. Sorting and preparation:

Effective sorting of different packing materials is crucial to ensure optimal digestion.

3. Recalcitrant materials:

Some packing materials, particularly those with high lignin content or synthetic materials, may resist anaerobic digestion.

4. Variability in composition:

The diverse packing materials used in textile industries may lead to inconsistent biogas yields.

Potential Research Areas

1. Pretreatment optimisation:

Investigating effective pretreatment methods for different packing materials to enhance their biodegradability.

2. Co-digestion strategies:

Exploring optimal mixtures of packing materials with other textile industry wastes for improved biogas production.

3. Life cycle assessment:

Comprehensive LCA studies must be conducted to evaluate the environmental impact of using packing materials for biogas production compared to other disposal methods.

4. Biodegradable packaging alternatives:

Researching and developing new biodegradable packaging materials that are functional for textile industry needs and suitable for anaerobic digestion.

There is potential for incorporating these materials into anaerobic digestion processes, particularly for cellulose-based packaging. However, careful consideration must be given to material composition, pretreatment requirements, and potential contaminants. Further research is needed to optimise the use of these materials in biogas production and to develop more sustainable packaging solutions for the textile industry.

e) Leaves and grass cuttings from textile industry compounds

Landscaping waste from textile industry compounds, including leaves and grass cuttings, can be valuable for biogas production through anaerobic digestion. Grass clippings and leaves are rich in organic matter and can be effectively used for biogas production.

- The biogas potential of grass clippings can range from 300 to 500 litres of biogas per kg of volatile solids (VS).
- Leaves typically have a lower biogas yield than grass clippings due to their higher lignin content.

Characteristics Affecting Biogas Production

1. C/N Ratio:

- Grass clippings generally have a C/N ratio of 10-25:1, which is relatively low for optimal anaerobic digestion.
- Leaves typically have a higher C/N ratio, often above 30:1.
- Mixing leaves and grass can help balance the C/N ratio for improved digestion.

2. Moisture Content:

- Fresh grass clippings have a high moisture content (around 80%), favouring anaerobic digestion.
- Leaves may have variable moisture content depending on their freshness.

3. Lignin Content:

- Leaves generally have higher lignin content compared to grass, which can reduce their biodegradability.

Factors Affecting Biogas Production

1. Seasonality:

- The availability and composition of landscaping waste can vary seasonally, affecting consistent biogas production.

2. Pretreatment:

- Mechanical pretreatment (e.g., shredding or chopping) can improve the digestibility of leaves and grass cuttings.
- Ensiling grass clippings can help preserve them for year-round use and enhance biogas production.

3. Co-digestion:

- Mixing landscaping waste with other organic wastes from textile production can improve overall biogas yield and process stability.

4. Particle Size:

- Reducing particle size through shredding or mowing can increase the surface area available for microbial action, potentially improving digestion efficiency.

Environmental Benefits

1. Waste Reduction:

- Using landscaping waste for biogas production reduces the amount of organic waste sent to landfills.

2. Nutrient Recycling:

- The digestate produced from anaerobic digestion can be used as a soil improver, returning nutrients to the soil.

3. Reduced Transportation:

- On-site use of landscaping waste eliminates the need for transportation to off-site disposal facilities.

Challenges and Considerations

1. Seasonal Variability:

- The quantity and quality of landscaping waste can vary throughout the year, requiring careful feedstock management.

2. Contamination:

- Landscaping waste may contain inorganic materials (e.g., stones, plastic) that must be removed before digestion.

3. Lignin Content:

- The higher lignin content in leaves may require longer retention times or specific pretreatment methods.

4. Collection and Storage:

- Efficient collection and storage systems must be implemented to ensure a steady feedstock supply.

Leaves and grass cuttings from textile industry compounds represent a potentially valuable resource for biogas production. Their use can contribute to sustainable waste management practices and renewable energy generation within the textile industry. However, to optimise biogas production from these materials, careful consideration must be given to seasonal variability, pretreatment requirements, and co-digestion strategies. Incorporating landscaping waste into the anaerobic digestion process can further enhance the overall sustainability of textile industry operations.

f) Cow Dung

Cow dung is a widely available substrate for biogas production and has been extensively studied for its methane potential. The physicochemical characteristics of cow dung typically include:

- Humidity: 79.17%
- Dry Matter: 20.83%
- Organic Matter: 57%
- Density: 208.33 kg/m³
- Carbon content: 32.53%
- Nitrogen content: 1.82%
- C/N ratio: 21.30

In a 27-day anaerobic digestion experiment under mesophilic conditions (27°C to 31°C), cow dung produced 22.6 litres of biogas.

The biogas potential of cow dung can vary depending on the cow's diet. A study comparing different types of cow dung based on nutritional processes found:

- Cows fed 100% grass produced the highest biogas yield (1250 ml)
- Cows fed 80% grass, and 20% bran produced 1080 ml of biogas
- Cows fed 95% grass, and 5% bran produced 780 ml of biogas

Co-digestion with Cow Dung

Co-digestion of cow dung with other substrates has shown promising results for enhancing biogas production:

1. Cow dung and food waste:

- A study examining different mixing ratios of food waste (FW), and cow dung (CD) found that the optimal mixture was 75% FW and 25% CD, producing the highest biogas yield of 7151.67 ± 11.55 mL and a bio-methane potential (BMP) of 401.88 ± 1.98 $mLCH_4/g$ VS at 55°C.
- Another study reported that co-digestion of food waste with cow dung (100% grass-fed) produced 67.2% biogas, compared to 53.9% when using cow dung from cows fed 95% grass and 5% bran.

2. Cow dung and corn cob:

In a co-digestion experiment, the cow dung and corn cob mixture produced 38.7 litres of biogas, higher than the individual substrates (cow dung: 22.6 litres, corn cob: 28.4 litres).

These results demonstrate that co-digestion of cow dung with other substrates can significantly improve biogas production compared to mono-digestion.

Considerations for Anaerobic Digestion

When using cow dung for biogas production, several factors should be considered:

1. C/N ratio: The C/N ratio of cow dung (21.30) is within the optimal range for anaerobic digestion. However, co-digestion with other substrates can help optimise this ratio further.
2. Organic matter content: Cow dung has a relatively high organic matter content (57%), which is favourable for biogas production.
3. Moisture content: Cow dung's high moisture content (79.17%) can benefit anaerobic digestion.
4. Feeding regime: The cows' diet significantly affects the biogas potential of their dung. Grass-fed cows seem to produce dung with a higher biogas potential.
5. Temperature: Mesophilic conditions (35°C to 37°C) are typically used for the anaerobic digestion of cow dung, but thermophilic conditions (55°C) can lead to higher biogas yields in co-digestion setup.

In conclusion, cow dung is a valuable substrate for biogas production, with its potential further enhanced through co-digestion with other organic wastes. The characteristics of cow dung make it a suitable base substrate for anaerobic digestion, and its wide availability makes it an attractive option for biogas production in many regions.

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