

Life Cycle Assessment of Anaerobic Digestion Plant for Treating Municipal Solid Wastes in Dhaka City, Bangladesh

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ABSTRACT

Dhaka, the capital of Bangladesh, is grappling with a growing problem: how to manage its ever-increasing municipal solid waste (MSW). Anaerobic digestion (AD) has emerged as a potential solution, but concerns linger about its environmental impact. To address this, this study conducts a life cycle assessment (LCA) of AD technology based on the waste composition in Dhaka city, Bangladesh. The aim of this study is to estimate the plant's global warming potential (GWP) through emissions of greenhouse gases (GHG) like CO₂, CH₄, and N₂O. Additionally, the assessment looks at the plant's contribution to acidification through hydrogen chloride gas (HCl) and sulfur dioxide (SO₂) emissions, as well as the potential release of harmful dioxins. The total power generated by this method is also calculated. The results show that 3856.08 GWh/yr electricity can be generated from the generated MSW in Dhaka city. In terms of environmental impacts, AD significantly reduces GWP by 92% and acidification potential (AP) by 99.5% compared to traditional landfilling (LF). Additionally, dioxin emission (1.97×10^{-5} kg) of the AD plant is very low. By comparing the findings of the LCA of AD with Dhaka's current MSW management practices, such as LF, the research aims to provide a clear picture of the environmental trade-offs associated with AD. This is achieved by identifying the areas (GWP, AP, and Dioxin Emissions) where AD has most significant environmental impact. Ultimately, the study aspires to equip policymakers and waste management professionals with the data they need to make informed decisions that will steer Dhaka towards a sustainable waste management future.

Keywords: Life Cycle Assessment, Municipal Solid Waste, Waste-to-Energy, Anaerobic Digestion, Global Warming Potential.



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1. Introduction

In the context of global energy consumption, high-income countries typically utilize a balanced mix of renewable and non-renewable energy sources. However, in developing countries like Bangladesh, the dependency on non-renewable energy sources remains predominant due to limited infrastructure and investment in renewable energy technologies [1]. As the population of Bangladesh continues to grow, particularly in urban centers like Dhaka, the demand for energy is increasing rapidly [2]. This surge in energy consumption exacerbates the country's dependency on non-renewable sources, which poses significant environmental and economic challenges [3]. Bangladesh's energy consumption profile reveals a stark contrast between renewable and non-renewable energy usage. According to recent data, non-renewable energy sources account for a substantial portion of the country's total energy supply [1]. For instance, the energy profile report for Bangladesh in 2021 by International Renewable Energy Agency (IRENA) in Fig. 1 reveals that, non-renewable energy constituted approximately 77% of the total energy consumption, while renewable sources contributed only 23% [2]. This heavy reliance on fossil fuels not only depletes natural resources but also contributes to environmental pollution and GHG emissions [3]. To mitigate these issues and reduce dependency on non-renewable energy, effective waste management strategies are crucial. Among the various waste management techniques, anaerobic digestion (AD), incineration (Inc), and landfill gas recovery (LGR) are

prominent [4]. AD, in particular, is highly suitable for Bangladesh due to the high organic content in the country's waste stream [5].

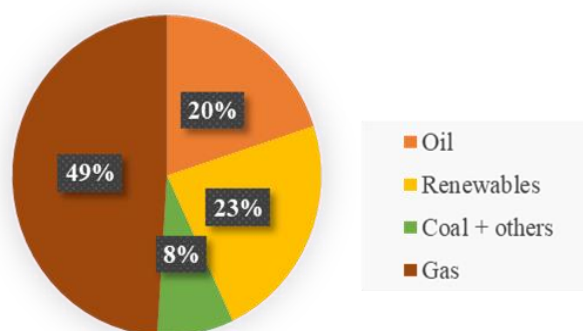


Fig. 1: Total energy supply in the world in 2021.

Through the breakdown of organic waste in the absence of oxygen, biogas is produced, which can be used as a sustainable energy source [6]. Several studies have highlighted the potential of AD. For example, Rahman et al. (2014) assessed the AD capacity in Bangladesh and found that the country has significant potential for biogas production from organic waste [5]. Another study by Hossain et al. (2022) compared the environmental implications of mono-digestion and co-digestion of livestock manure and food waste, demonstrating the benefit of co-digestion in reducing environmental impact [6]. Additionally,

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research by Habib et al. (2021) emphasized the feasibility of AD for waste-to-energy conversion in urban areas like Dhaka [7]. In contrast, Inc and LGR also play roles in waste management but come with their own challenges. Inc, while effective in reducing waste volume, can lead to air pollution and requires significant investment in pollution control technologies [4]. LGR, on the other hand, captures methane emissions from decomposing waste in landfills, converting it into energy [8]. However, this method is less efficient compared to AD due to the lower energy yield and higher operational costs [7]. The summary is shown in **Table 1**.

Table 1: Comparison between various techniques.

Technique	Environmental Impact	Economic Viability	Resource Recovery
AD	Low (reduces greenhouse gas emissions, produces renewable energy)	Moderate (can generate revenue from biogas and digestate)	High (biogas, biofertilizer)
Incineration	High (air pollution, potential for toxic emissions)	High (requires significant investment and operational costs)	Low (limited energy recovery, ash disposal)
Landfill Gas Recovery	Moderate (reduces methane emissions, but still produces landfill leachate)	Moderate (requires investment in gas collection and processing infrastructure)	Moderate (biogas)

Given the high organic waste content in Bangladesh and the need for sustainable waste management solutions, AD emerges as the most viable option for a life cycle assessment (LCA) study. Dhaka, being the capital of Bangladesh and generates a substantial amount of organic waste shown in **Fig. 2**, making it an ideal location for implementing anaerobic digestion plants [5]. The LCA for AD plant in Dhaka city has not done yet. By focusing on Dhaka, this study aims to estimate the environmental benefits of AD, contributing to the broader goal of sustainable energy management in Bangladesh.

2. Methodology

2.1 Data collection

The physical properties of the MSW stream shown in **Table 2** and the chemical properties shown in **Table 3**.

MSW Characteristics

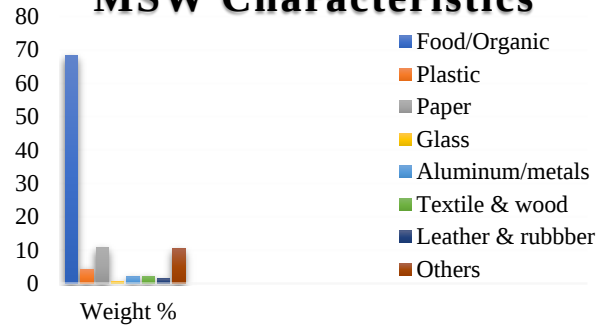


Fig. 2: MSW characteristics of Dhaka by % of weight.

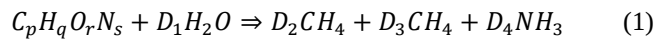
It is clear that the MSW contains mostly food waste which is organic in nature. Other types of wastes are papers, plastics and others and those data were utilized from a research by Islam [9].

Table 2: Physical properties of the MSW in Dhaka city.

Physical properties	Wet weight fraction (%)	Moisture content (%)	Dry weight fraction (%)
Plastic	2	0.53	1.99
Food wastes	80	72.34	22.13
Grass & straw	2	38.21	1.24
Metals	1	0	1
Glass & ceramic	1	0	1
Paper	8	3.2	7.74
Others	6	8.67	5.48

2.2 Electricity generation potential by AD

One of the most popular techniques for producing biogas in absence of oxygen is AD. The following equations were used to estimate total theoretical methane production by AD of compound $C_pH_qO_rN_s$ [10], [11].



Equation (2) was utilized to calculate the mole ratio of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). This information can then be utilized to compute the variables p, q, r, and s, suggested by Salami et al. (2011). [11]:

$$Mole\ Ratio = \frac{K[C,H,O,N]}{M[C,H,O,N]} \quad (2)$$

Where, K is the composition of the elements found based on the final investigation, and M is the molar mass of the corresponding chemical components. The values of D_1 , D_2 and D_3 were determined as follows:

$$D_1 = \frac{(4p - q - 2r + 3s)}{4} \quad (3)$$

$$D_2 = \frac{(4p - q + 2r + 3s)}{8} \quad (4)$$

$$D_3 = \frac{(4p+q-2r-3s)}{8} \quad (5)$$

Table 3: Chemical properties of the MSW in Dhaka city.

Chemical properties	(C _{or} g, %)	(C _{ior} g, %)	A (%)	S (%)	N (%)	O (%)	H (%)
Plastic	0	60	10	0	0.1	7.2	22.8
Food wastes	48	0	5	2.6	0.4	37.6	6.4
Grass & straw	47.8	0	4.5	3.4	0.3	38	6
Metals	0	4.5	0.4	0	0	4.3	0.6
Glass & ceramic	0	0.5	98.9	0.1	0	0.4	0.1
Paper	45.3	0	6	0.3	0.2	44	6
Others	24.3	0	68	0.2	0.5	4	3

The following equation was used to determine total methane (CH₄) production in kg (M_{CH_4}) from AD:

$$M_{CH_4} = \frac{16 \times D_3}{(M_C \times p) + (M_H \times q) + (M_O \times r) + M_N} \times 1000 \quad (6)$$

Here, M_C , M_H , M_O and M_N (gm) are the molar masses of C, H, O, and N respectively. The entire volume of methane, V_{CH_4} (m³/yr) was determined as follows:

$$V_{CH_4} = \frac{M_{CH_4}}{\rho_{CH_4}} \times OFW_{AD} \quad (7)$$

Here, ρ_{CH_4} is the methane density (0.717 kg/m³) [12] and OFW_{AD} represents the organic fraction of the waste (tonne/yr). Since only the organic wastes will be supplied to the digestion chamber, equation (7) only takes into account the organic fraction of wastes for determining the V_{CH_4} from AD.

Based on the production of biogas from AD, the quantity of electrical power that may be produced was determined by the equation (8) [12]:

$$E_{p,AD} = \frac{LHV \times V_{CH_4} \times 0.85 \times \eta_{generator}}{C} \quad (8)$$

Here, LHV is the lower heating value of methane (37.2 MJ/m³), the gas-fired generator's efficiency is represented by $\eta_{generator}$, whose value of 0.26 was assumed [13], and C is the MJ to kWh conversion factor and was taken 3.6 [13].

2.3 Global warming potential (GWP)

Air pollutants can be classified into five categories: heavy metals, organic pollutants, greenhouse gases (GHG), acidic gases, and criterion air pollutants [11]. The main components of GHG include CH₄, CO₂, hydro fluorocarbons (HFCs) and nitrous oxides (NO_x).

The bio-gas generated during AD can be used to produce electricity. Biogas combustion emits minimum GHGs, which can be avoided with proper cleaning methods [12]. The following is the formula for the determination of the GWP of AD technology [12].

$$GWP_{AD}(kgCO_2eq) = V_{CH_4} \times 0.05 \times GWP_{CH_4} \times 0.717 \quad (9)$$

When there is no WTE process followed and all waste (apart from recyclables) is landfilled, GHG are immediately released into the atmosphere, which causes significant air contamination. The GWP of the waste disposal process has been calculated with the use of the subsequent equation:

$$GWP_{LF}(kgCO_2eq) = V_{CH_4} \times 0.75 \times GWP_{CH_4} \times 0.90 \times 6.67 \times 10^{-4} \times 1000 \quad (10)$$

Here, since that 90% of the CH₄ was emitted into the environment, the factor 0.90 was employed [14] and 6.67×10^{-4} is the factor used to convert m³ to tonne [14], [15].

2.4 Acidification potential (AP)

Landfilling (LF) produces pollutants such as volatile organic carbon (VOC), SO₂ and HCl, in addition to methane and CO₂. Similarly, an AD plant produces pollutants that contribute to AP, including SO₂ and HCl. However, VOC concentration is low and can be neglected and thus, emission of mass (ME_p) of SO₂ and HCl, in kg/yr, were evaluated in this study using the following equation [16]:

$$ME_p = \frac{Q_p \times MW_p}{8.205 \times 10^{-5} \times (273+T)} \quad (11)$$

Here, MW_p is the molecular weight (g/gmol) of the pollutant 'p' (SO₂ and HCl), and T indicates the temperature of the landfill region was used as 28° C [16]. Also Q_p , the rate of emission of the pollutant 'p' in m³/yr and can be evaluated from equation (12):

$$Q_p = \frac{V_{CH_4} \times C_p}{0.50 \times 10^6} \quad (12)$$

Where, C_p is the concentration of the pollutant (33 ppmv for SO₂ and 72 for HCl), and 0.50 is the CH₄ concentration [16]. AP is the SO₂ equivalent of the released gases (HCl and SO₂) and is expressed in kg-SO₂.eq/year. The AP of the LF and AD technology were calculated as follows [16]:

$$AP_{LF} = \sum_{p=1}^2 ME_p \times EQ_p \quad (13)$$

$$AP_{AD} = \sum_{p=1}^2 SEF_{p,AD} \times E_{AD} \times EQ_p \quad (14)$$

Where, $p = 1$ implies SO₂ and 2 implies HCl. $SEF_{p,AD}$ is the specific emission factor for AD of the pollutant p (1.00524 $\times 10^{-5}$ kg/kWh for SO₂ and 0 for HCl). Moreover E_{AD} is the electricity generation potential from AD in kWh/yr and EQ_p is the equivalency factor of pollutant p (0.88 for HCl and 1 for SO₂) [17].

2.5 Organic pollutants (OP)

One of the primary concerns with current WTE technologies is the formation of organic pollutants like dioxins, which are regarded as a severe hazard to human well-being because of their poisonous and harmful nature. The emissions of dioxin from AD were evaluated using the formulae below [16]:

$$OP_{AD} = SE_{AD} \times E_{AD} \quad (15)$$

Here, SE_{AD} (5.10354×10^{-12} kg/MWh) is the specific emission factor for dioxins of AD [16]. Also E_{AD} in MWh is the electricity generation potentials of AD. For LF, dioxin has a specific emission factor of zero and so the organic pollutant is not considered here [18].

2.6 Damage to human health and ecosystem

Damage to human health (DHH) is measured as disability-adjusted life years (DALY), indicating the amount of years lost as a result of healthcare issues [19]. GHG emissions have a major impact on the ecosystem, as reflected by the detrimental effect (DEE). DEE is indicated as a species.yr unit measures the decline of local species over a year [20]. The following equation was used to evaluate the DHH and DEE [20]:

$$Damage = \sum_p \sum_t^{8760} C_{d,p} \times E_{p,t}$$

$d \in DHH, DEE$ and $p \in CO_2, NO_x, SO_x$ (16)

Where, Here, C is the characterization factor [20], to evaluate DHH and DEE. E indicates the type of GHG emission over year.

3. Results and Discussions

The LCA of the proposed AD system in Dhaka, Bangladesh, revealed significant environmental benefits compared to traditional landfilling (LF) practices. The energy generation potential is very significant in this system. The system was estimated to generate 3856.08 GWh/yr (1544 kWh/tons) of electricity shown in **Table 4**, reducing the city's reliance on fossil fuels. This electricity generation capacity compares favorably to that of India (2.34 kWh/tons) [21], and Pakistan (666.4 kWh/tons) [21]. It is evident that Dhaka's AD system can generate more electricity per ton than India and Pakistan, demonstrating the potential of AD to contribute to Dhaka's energy needs. Moreover, it was found from **Table 4** that the AD process in the MSW plant significantly reduced GHG emissions from 2.07×10^{10} (kg.CO₂.eq) in LF to 1.65×10^9 (kg.CO₂.eq). Specifically, it was achieved a 92% reduction in GWP by capturing and utilizing methane for energy generation. This substantial reduction indicates that AD is a highly effective strategy for mitigating climate change. Methane, a potent greenhouse gas, is captured and utilized for energy generation, thereby preventing its release into the atmosphere. In terms of AP, the difference was even more striking. AD reduces emissions from 6.05×10^8 (kg.SO₂.eq) with LF to just 3.88×10^4 (kg.SO₂.eq), achieving a 99.5% reduction. This near-complete elimination of AP is crucial for reducing the production of acidic compounds that can contribute to acid rain and ocean acidification. Additionally, the study found that dioxin emissions from the AD plant was very low, at 1.97×10^{-5} kg. This process also substantially decreased DHH by 92% and DEE by 99.4%. The **Fig. 3** shows variation of human damage effect when AD is used and when not used. The AD process decomposes harmful substances that can pose risks to human health, such as heavy metals and organic pollutants. Also it is highly effective in reducing the depletion of the ozone layer.

The research findings deliver strong evidence for the environmental viability of anaerobic digestion as a sustainable MSW management solution for Dhaka. The significant reduction in GWP, AP, DHH, and DEE highlights

the potential of AD to mitigate climate change, air pollution, and adverse health impacts. Furthermore, the low dioxin emissions demonstrate that the AD process can be implemented without presenting serious threats to the environment and public health.

Table 4: Various results found in this study.

Particulars	Values
$E_{p,AD}$ (GWh/yr)	3856.08
GWP_{AD} (kg.CO ₂ .eq)	1.65×10^9
GWP_{LF} (kg.CO ₂ .eq)	2.07×10^{10}
AP_{AD} (kg.SO ₂ .eq/yr)	3.88×10^4
AP_{LF} (kg.SO ₂ .eq/yr)	6.05×10^8
OP_{AD} (kg-dioxins)	1.97×10^{-5}
OP_{LF} (kg-dioxins)	0
DEE (AD)	133.65
DEE (LF)	1676.70
DHH (AD)	0.88
DHH(LF)	138.02

DEE & DHH comparison between Anaerobic Digestion and Land fill

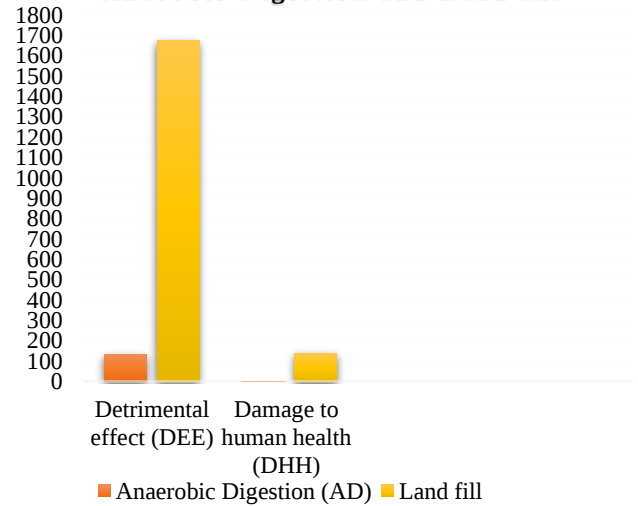


Fig. 3: Comparison between AD and LF in case of human damage.

4. Conclusions

The life cycle assessment (LCA) of the proposed anaerobic digestion (AD) plant in Dhaka, Bangladesh, highlights significant environmental advantages over traditional landfilling (LF) methods. With the AD plant in operation, Dhaka can expect to generate an impressive 3856.08 GWh/yr of electricity. This generation is not just a numerical value; it represents a substantial step towards sustainable energy solutions for the city. Environmental benefits of the AD process are particularly noteworthy. When considering GWP, AD decreases 92% compared to LF, reduced by 99.5%, this drastic cut in acidifying pollutants points to significant improvements in air quality and reduced environmental damage. Furthermore, the emission of harmful dioxins is almost negligible with AD compared to no emissions recorded for LF. This minimal dioxin emission indicates that the AD process can be implemented with minimal hazards to both the environment and public health. The results also highlight the AD plant's performance in other crucial environmental indicators. The Damaging Effect on Ecosystem (DEE) for AD was significantly lower than for

LF, demonstrating AD's overall reduced environmental impact. Additionally, the Damage to Human Health (DHH) impact of AD was substantially lower. This highlights the AD process's ability to mitigate adverse health impacts associated with waste management. Overall, the LCA study demonstrates AD's environmental viability for Dhaka's MSW management. AD significantly reduces GHG emissions, generates renewable energy, and minimizes air pollutants. Integrating AD with waste reduction, recycling, and composting can help Dhaka achieve a more sustainable and efficient system, promoting a greener, resilient future.

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NOMENCLATURE

AD	: Anaerobic Digestion
AP	: Acidification Potential
C	: Carbon
CH ₄	: Methane
C _{iorg}	: Inorganic Carbon
C _{org}	: Organic Carbon
CO ₂	: Carbon Dioxide
C _p	: Concentration of the Pollutant
DALY	: Disability-Adjusted Life Years
DEE	: Detrimental Effect on the Ecosystem
E _{AD}	: Electricity Generation Potential from AD, GWh/yr
E _{p,AD}	: Electrical Power produced from AD, GWh/yr
EQp	: Equivalency Factor of Pollutant p
GHG	: Greenhouse Gases

GWP : Global Warming Potential	MW_p : Nitrogen
GWP_{AD} : GWP of AD Technology, kg.CO ₂ .eq	N : Ammonia
$GWP_{(CH_4)}$: GWP of CH ₄ relative to CO ₂	NH_3 : Nitrous Oxides
GWP_{LF} : GWP of the Waste Disposal Process, kg.CO ₂ .eq	NO_x : Nitrous Oxide
H : Hydrogen	N_2O : Number of Nitrogen atoms in the compound
H_2O : Water	N_s : Oxygen
HCl : Hydrogen Chloride Gas	O : Organic Fraction of the Waste for AD (tonne/yr)
$HFCs$: Hydro fluorocarbons	OFW_{AD} : Organic Pollutants
$IRENA$: International Renewable Energy Agency	OP : Organic Pollutants from AD, kg-dioxins
K : Composition of elements found based on the final analysis	OP_{AD} : Number of Oxygen atoms in the compound
LCA : Life Cycle Assessment	O_r : Rate of Emission of the Pollutant p
LF : Landfilling	Q_p : Sulphur
LHV : Lower Heating Value	S : Specific Emission Factor for Dioxins of
M : Molar Mass	SE_{AD} AD,kg/MWh
M_C : Molar Mass of Carbon, gm	: Specific Emission Factor for AD of the Pollutant
M_H : Molar Mass of Hydrogen, gm	$SEF_{(p,AD)}p$
M_N : Molar Mass of Nitrogen, gm	: Sulphur Dioxide
M_O : Molar Mass of Oxygen, gm	SO_2 : Volume of Methane, m ³ /yr
$M_{(CH_4)}$: Total Methane production, kg	$V_{(CH_4)}$: Volatile Organic Carbon
ME_p : Emission of Mass of SO ₂ and HCl	VOC : Waste-to-Energy
MSW : Municipal Solid Waste	WTE : Efficiency of the generator
: Molecular Weight of the Pollutant p	$\eta_{generator}$: Density of Methane,kg/m ³
	$\rho_{(CH_4)}$
