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Life cycle assessment of waste incineration technology: A case study on Dhaka city, Bangladesh

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Abstract

Bangladesh, a developing country with a rapidly expanding urban economy, faces significant challenges related to increased waste generation and a prolonged power crisis. Waste-to-energy (WTE) technology offers a potential solution by addressing both issues simultaneously. The most widely adopted WTE technologies are incineration, landfill gas recovery, and anaerobic digestion. This study focuses on the life cycle assessment of incineration technology, a popular method in South Asian countries, based on the waste generation characteristics of Dhaka City, Bangladesh. The assessment evaluates the electricity generation potential, global warming potential (GWP), acidification potential (AP), and organic pollutant (OP) emissions throughout the incineration plant's life cycle. The results reveal that the incineration process exhibits 1.2944×10^{9} kg CO_2eq/year of GWP, 1.307×10^{5} kg SO_2eq/year of AP, and 0.0116843 kg/year of OP, while producing 5.541×10^{7} kWh/year electricity. In contrast, landfilling has a lower GWP (1.0252×10^{9} kg CO_2eq/year) but a significantly higher AP (2.999×10^{7} kg SO_2eq/year) than incineration, with no measurable OP emissions. Additionally, the damage to human health (DHH) and the damaging effects on the ecosystem (DEE) were calculated for incineration as 104.843 DALY and 0.713 species.year, respectively, compared to 83.039 DALY and 6.842 species.year for landfilling. These findings suggest that although incineration contributes more to global warming and human health risks, it is a more environmentally sustainable alternative to landfilling when considering its energy generation potential and lower ecosystem damage.

Keywords: Waste to energy, incineration, GWP, life cycle assessment.

1. Introduction

Bangladesh has struggled with overpopulation, energy shortages, and global warming in recent decades. Rapid population growth and limited economic progress have intensified the challenge of meeting rising energy needs [1]. Bangladesh's energy supply is limited, primarily relying on natural gas and coal. Indigenous natural gas is the main fuel, but its reserves are expected to run out in 10–15 years unless new sources are discovered [2]. To address the energy crisis, Bangladesh should consider alternative solutions. Embracing renewable energy could significantly help mitigate the energy shortage. Figures 1(a) and 1(b) represent the primary energy sources for consumption and the renewable energy-based energy consumption scenario, respectively, in Bangladesh. Global municipal solid waste (MSW) production reached 2 billion tonnes in 2011 and is projected to reach 9.5 billion tonnes annually by 2050 [3]. Waste-to-energy (WTE) technologies are comparatively friendly methods that convert MSW into electricity. WTE technology includes incineration, pyrolysis, gasification, anaerobic digestion, and landfilling with gas recovery. In developing countries, incineration is frequently seen as the most dependable and economical approach for burning large quantities of municipal solid waste to generate electricity, all without requiring pre-treatment [4].

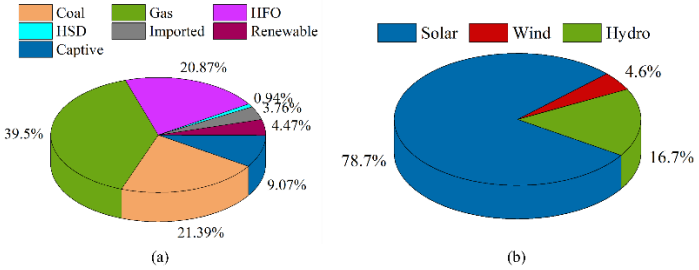


Fig 1. (a) Primary energy sources for consumption (a)[5] and (b)Renewable energy-based energy consumption[6]

Recently, there has been increasing interest in the study of WTE. In 2006, China produced 46.2 million kWh of electricity from 137,325 tonnes of MSW, powering over 30,000 households [7]. A Waste-to-Energy (WTE) incineration plant in Rajshahi City Corporation, with an initial cost of 1.84 billion BDT and a payback period of 9 years, is financially viable and expected to generate a lifetime profit of 6.74 billion BDT. Moreover, the plant generates 35 MW/day of electricity [8]. Another study in Taiwan shows that by the end of 2008, Taiwan's MSW incineration facilities, equipped with cogeneration systems, were processing over 24,000 tonnes of waste daily and generating about 622.5 MW of electricity for Taipower [9]. The study evaluated the environmental effects of a municipal solid waste incineration plant in Yongcheng City, China, and compared these effects with those of landfills and coal-fired power plants. The research concluded that incineration power generation has a lower environmental impact than landfills and coal-fired power plants and can also generate 8.23×10^7 kWh of power [10]. A study shows that the implementation of Waste-to-Energy (WTE) projects to generate energy and consumables will contribute to ensuring a sustainable energy supply in Bangladesh. By 2050, Bangladesh could generate an annual total revenue of USD 791 million, including carbon credits from cities such as Dhaka and Chittagong[11]. The recent research on WTE initiatives in Dhaka and Chittagong suggests promising opportunities, with power plant sizes of 169 MW and 83 MW, respectively. These facilities demonstrate exergoeconomic indicators of 61%, as well as energy and exergy efficiencies of 32% and 27%, respectively. Additionally, the estimated production costs range from 53.9 to 56.7 USD/MWh. Moreover, they are anticipated to lower greenhouse gas emissions and achieve ecological efficiencies exceeding 87% [12]. Another study in Chittagong City emphasizes that incineration technology can generate up to 560.43 MWh of electricity and 1668.84 GJ of heat per day, and is the best solution for managing municipal solid waste in Chittagong City. [13]. Although there has been research on power generation from municipal solid waste (MSW) using Waste-to-Energy (WTE) technology in Bangladesh, a life cycle assessment of WTE technology, especially incineration, based on the waste generation characteristics in Bangladesh is yet to be explored [14].

This paper aims to assess the amount of organic pollutants (OP), acidification potential (AP), and global warming potential (GWP) of waste incineration technology, as well as its effects on human health and the ecosystem. Lastly, it provides a thorough life cycle assessment of waste incineration technology in Dhaka, Bangladesh.

2. Methodology

The study is based on Dhaka city observing several local areas depending on their data availability. Dhaka, with an approximate area of 1463.60 sq. km. and a population of about 12,043,977 produces a significant amount of domestic as well as commercial waste every day [15]. According to Dhaka South City Corporation (DSCC), in 2019-2020, total waste generated per capita per day was found to be 0.72 kg in their region [16]. The major fraction (75%) of MSW in Bangladesh is food waste [11]. In 2020-2021, a total of 5873001 metric tonnes of food waste were collected from 12 City Corporations and 328 Paurashavas in Bangladesh[17]. Table 1 provides both the physical and chemical compositions of generated MSW in Dhaka city.

Table 1. Physical and Chemical compositions of food wastes in Dhaka [11].

Physical Compositions			Chemical Compositions						
Wet weight fraction (%)	Moisture content (%)	Dry weight fraction (%)	Organic carbon (C_{org}, %)	Inorganic carbon (C_{iorg}, %)	Ash(%)	Sulphur (S, %),	Nitrogen (N, %),	Oxygen (O, %),	Hydrogen (H, %)
80	72.34	22.13	48.00	0	5.00	2.60	0.40	37.60	6.40

Analysis of electricity generation potential

Electricity is a prominent source of energy, and MSW contains a significant amount of energy potential that can be converted into heat and electricity. The process of waste-to-energy conversion can be both thermochemical and biochemical. For the selected region, incineration can be a useful and reliable thermochemical method.

Incineration

Incineration of MSW is a thermochemical process in which the combustion of solid waste generates heat, which further can be applied to a steam turbine to generate electricity. The following equation estimates the amount of generated heat from the incineration process [18].

$$Q_{INC} = \frac{b \times HHV(100 - e)}{100} \quad (1)$$

The heat generated from the incineration process is represented by Q_{INC} in terms of MJ. HHV (MJ/kg) refers to the higher heating value of the dry waste, which was derived using equations proposed by [18], b (kg) refers to the amount of dry waste fed into the plant. Lastly, e denotes the total sum of efficiency losses. The output power of the steam turbine is calculated as follows.

$$E_{P_{INC}} = \frac{Q_{INC} \times \eta \times 8760}{3412.14} \quad (2)$$

Here, $E_{P_{INC}}$ is the output power of the steam turbine in kWh/yr and η is its efficiency which was taken at 0.29[18].

Global warming potential (GWP)

Global Warming Potential (GWP) measures and compares the relative climate impact of different greenhouse gases based on their emissions [19]. The following equation has been used to calculate the (GWP) of the waste disposal process or landfilling.

$$GWP_{Landfill}(kgCO_2eq) = V_{CH_4} \times 0.75 \times GWP_{CH_4} \times 0.90 \times 6.67 \times 10^{-4} \times 1000 \quad (3)$$

V_{CH4} represents the total volume of methane generation per year. Landfills generate 11% of global methane emissions [20]. Also, methane has 21 times the potential to contribute to global warming compared to carbon dioxide (CO_2) [20]. Along with methane, carbon dioxide is also produced by landfill gas. However, only methane has been included in the global warming potential calculation since the landfilling process only emits biogenic CO_2 which does not have any impact on the global warming issue. Therefore, the GHG emissions from incineration termed GWP in kg CO_2.eq. can be estimated using the equations below.

$$GWP_{INC}(kgCO_2eq) = CO_{2(emitted)} + CH_{4(emitted)} + N_2O_{(emitted)} \quad (4)$$

$$CO_{2(emitted)} = C \times b \times \alpha \times \frac{M_{CO_2}}{M_C} \quad (5)$$

$$CH_{4(emitted)} = b \times GWP_{CH_4} \times LHV \times E_{CH_4} \times \%NB \quad (6)$$

$$N_2O_{(emitted)} = b \times GWP_{N_2O} \times LHV \times E_{N_2O} \times \%NB \quad (7)$$

Here, $CO_{2(emitted)}$, $CH_{4(emitted)}$, and $N_2O_{(emitted)}$ represent the emissions of CO_2, CH_4, and N_2O gases respectively and all of them are brought to the equivalent amount of CO_2. α is the oxidation factor (α=1), M_{CO_2} and M_C are the molecular masses of CO_2(44 kg/mol) and carbon(12 kg/mol) [21]and C denotes the fossil carbon component. For CH_4 and N_2O, the emission factors are assumed to be 30 kg/TJ and 4 kg/TJ correspondingly. The GWP of N_2O about CO_2 is represented by GWP_{N_2O}, which is equivalent to 298 kg CO_2. Finally, 20% is the fraction of non-biogenic carbon (%NB) assumed in this study[21].

Acidification potential (AP)

Most of the WTE technologies emit acidic pollutants during the process, such as SO_2, NO_x, HCl, H_2S, HF, and ammonia gases which lead to acid rain and forest degradation [21]. By the following equation, the mass emission (MEp) of SO_2 and HCl, in kg/yr, is calculated [18].

$$ME_P = \frac{Q_p \times MW_p}{8.205 \times 10^{-5} \times (273 + T)} \quad (8)$$

In this equation, MW_P is the molecular weight (g/mol) of the pollutants. The landfill temperature T was taken to be at 28 ◦C [21]. Furthermore, Q_P denotes the rate of emission of 'p' in m^3/yr which can be calculated from the equation[18].

$$Q_P = \frac{V_{CH4} \times C_p}{0.50 \times 10^6} \quad (9)$$

Here, the methane concentration is used as 0.50 [18]. Cp represents the concentration of the pollutant, which is 33 ppmv for SO_2 and 72 for HCl. Since there is little concentration of N_2O, this study mainly focuses on the emission of HCl and SO_2. The acidification potential was calculated in terms of SO_2 equivalent to the other acid gas. The calculation was accomplished by taking the equivalent factor of each gas and multiplying it by its emission

potential. The following equations were used to determine the acidification potential for landfilling and incineration [18].

$$AP_{Landfill} = \sum_{p=1}^{2} ME_p \times EQ_P \tag{10}$$

$$AP_{INC} = \sum_{p=1}^{2} SEF_{p,INC} \times b \times EQ_P \tag{11}$$

In both equations, EQ_p represents the equivalence factor for the pollutants, which is taken at 0.88 for HCl and 1 for SO_2. In the case of incineration, the specific emission factor was assumed to be 0.277 kg/tonne for SO_2, as well as 0.106 kg/tonne for HCl. For SO_2 the value of 'p' is considered 1 and 2 for HCl [18].

Estimation of the organic pollutants (OP)

Dioxins and furans can be produced due to insufficient combustion and heterogeneous catalytic reactions on the surface of fly ash, which are quite harmful to health [21]. To estimate the amount of organic pollution that can be generated from incineration, the following equations can be used [21].

$$OP_{INC} = SE_{INC} \times b \tag{12}$$

SE_{INC}(3.31×10^8 kg/tonne) is the specific emission factor for dioxin materials and b denotes the dry waste amount that is supplied into the incineration plant in tonnes [21].

Damage to human health and ecosystem

Emissions like GHG, organic pollutants, and acidic gases that impact the ecosystem as well as human health can be represented with terms such as Damaging Effect on the Ecosystem (DEE) and Damage to Human Health (DHH) [16]. These DHH and DEE values depending on GHG emissions were calculated from the subsequent equation [18].

$$Damage = \sum_{p} \sum_{t}^{8760} C_{d,p} \times E_{p,t}, d \in DHH, DEE \text{ and } p \in CO_2, NO_X, SO_X \tag{13}$$

Here in the equation, C is termed the characterization factor, which can be estimated from the ReCiPe2016 method using the SimaPro software [22], and lastly, E is the type of GHG emissions per year.

3. Results and Discussion

The findings of this study are summarized clearly and concisely, highlighting key insights and implications

Table 2. In this table, the values are the calculated values of GWP, AP, OP, Electricity generation, DHH, and DEE for the incineration and landfill

Processes	GWP ($kgCO_2eq$/year)	AP ($kgSO_2eq$/year)	OP (kg/year)	Electricity Generation (kWh/year tonne)	DHH (DALY) (Disability Adjusted Life years)	DEE (species. yr)
Incineration	1.2944×10^9	1.307×10^5	0.0116843	43.374	104.843	0.713
Landfill	1.0252×10^9	2.999×10^7	-	-	83.039	6.842

The incineration process produces a large amount of greenhouse gas (GHG). These include methane, carbon dioxide, hydrofluoric carbons, and nitrous oxides. Landfilling also produces GHG, CO_2, and SO_2. For these two processes, the value of GWP was very close, in the case of incineration it was 1.2944×10^9 $kgCO_2eq$/year and for landfilling it was 1.0252×10^9 kgCO2eq/year. On the other hand, the values of AP varied between those two processes (more than 200 times). It was noticeable that there was no value of OP for landfill. It was evident that the lack of OP value for the landfill was due to the absence of solid waste burning. Above all, the outcome results of DHH and DEE were particularly concerning. The value of DHH for both processes was 104.843 DALY and 83.039 DALY respectively. The value was a little bit higher for incineration compared to landfilling process. However the value of DEE was much higher for landfilling compared to incineration, the values were respectively

6.842 and 0.713 species. yr. Thus, incineration will be beneficial for the environment. Here the incineration produced 43.374 kWh/year tonne of electricity. Moreover, an incineration power plant in Yongcheng City China produced 187.90 kWh/year tonne of electricity from 438,000 tonnes [10]. According to recent research findings, it has been determined that approximately 65.48 kWh/year tonne of electricity can be produced in Rajshahi [8]. The fluctuation in electricity generation is due to variations in moisture content and the low calorific value. Higher moisture content leads to lower electricity generation. While waste-to-energy plants can provide valuable electricity, the emissions of greenhouse gases (GHG), SO_2, and NOx are concerning. By implementing a multi-level incineration process and utilizing percolate treatment, it is possible to reduce the emission of GHGs. In China, it has been proposed to use the UOD framework to reduce moisture content and increase the calorific value of waste to lower GHG emissions. [23]. By adding calcium-based additives, CaO can reduce the emission of SO_2. There are two ways to reduce the emission of NO_x gas. The first one is using flue gas treatment technology, and another one is reducing the formation of NO_x gas in the combustion chamber so that NO_x emission can be prevented before the flue gas leaves the combustor [24]. Higher authorities, industrialists, and environmentalists can help create a positive public perception about it. Lastly, after examining all the information it will be feasible to establish an incineration power plant rather than landfilling.

4. Conclusion

In this study, different parameters (GWP, AP, OP, DHH, DEE) were considered to assess the aftereffects of incineration and landfill processes on the ecosystem and human health in Dhaka city. The Global Warming Potential (GWP) of 1.2944×10^9 $kgCO_2eq$/year has been calculated for incineration and 1.0252×10^9 $kgCO_2$ eq/year for landfills, where these values are relatively close to each other. Acidification Potential (AP) has shown a significant disparity, with values of 1.307×10^5 $kgSO_2eq$/year for incineration, compared to 2.999×10^7 $kgSO_2eq$/year for landfill, demonstrating that AP is notably higher for landfill operations. The calculated value of Organic Pollutant (OP) is 0.0116843 kg/year for incineration. The final two important factors DHH and DEE have been calculated based on these three factors (GWP, AP, and OP). The value of DHH for incineration and landfill is 104.83 DALY and 83.039 DALY respectively. This shows that incineration is more harmful to human health than landfills. Conversely, the DEE for landfills was significantly higher at 6.842 species. yr, compared to 0.713 species.yr for incineration, suggesting that landfill operations have a more detrimental effect on the ecosystem. Additionally, incineration has the advantage of generating a substantial amount of electricity, estimated at 43.374 kWh/year per tonne, while landfill operations yield no energy output. To address and minimize the harmful effects of incineration some advanced combustion technologies such as Fluidized Bed Incinerators and Gasification along with emission control systems like Scrubbers, Electrostatic Precipitators, and Selective Catalytic Reduction can be employed. Therefore, the analysis suggests that incineration is a good option for Dhaka city for the generation of power to reduce the amount of waste that is deposited and to alleviate the huge demand for electricity for a sustainable environment.

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