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From Waste to Energy: Evaluating the Potential of Incineration and Anaerobic Digestion for Energy Generation in Underdeveloped Countries

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Abstract

Waste management has become a big concern globally, affecting countries from lower-income to lower-middle-income and even mostly developed ones. Urban areas are the hub of solid waste generation and house a significant portion of the world's population, with a much higher population density than rural areas. Municipal solid waste (MSW) generation is expected to increase substantially in the coming years with the increasing population growth rate. Developed countries, while advancing in waste management and trying to make use of this waste by recycling or harnessing energy in various established and emerging technologies, developing and underdeveloped countries are still struggling to manage waste and largely rely on landfills. Managing these wastes in alternative ways is an environmental demand, as landfills can never be a long-term waste management solution, and harvesting energy from these wastes can add to the economies of these countries. This paper reviews the different available and emerging technologies to generate energy from waste and aims to find out the prospects of these technologies, particularly for underdeveloped nations. Our results show that potential power outputs from incineration are 415 MW in Bangladesh, 2 MW in Ethiopia, 110 MW in Sudan, 48 MW in Senegal, 92 MW in Nepal, and 389 MW in Cambodia, while for anaerobic digestion, energy can be generated at 681 MW, 3 MW, 93 MW, 35 MW, 41 MW, and 255 MW, respectively. Additionally, the study has compared the carbon emissions of these waste-to-energy (WTE) technologies with those of traditional power plants on a per-unit-of-power-produced basis. This work has proposed a viable model for implementing these technologies, addressing the barriers that currently hinder their adoption. The goal of this work is to explore how these technologies can reduce environmental impacts, promote economic development through sustainable practices, and create job potential for the respective countries.

Keywords: Waste management, Municipal Solid Waste (MSW), Incineration, Anaerobic Digestion (AD), Underdeveloped countries.

1. Introduction

The concept of energy recovery from waste is becoming a popular and feasible solution for waste management in many countries nowadays as it has the potential to harness useful energy from waste reducing the need for landfilling simultaneously. Due to this, despite the recent economic crisis, the global market for WTE technologies has seen significant development, and there are already more than 1,200 active plants in 40 different countries [1]. Material wasted by single and multi-family homes, hotels, motels, and other similar permanent or transient living places or facilities is included in household garbage [2].

MSW is a mixture of different types of waste materials, including food waste, paper, plastic, yard waste, textile wood-based and other products. Almost 85 percent of MSW may be burned as fuel to produce electricity in the US. Moreover, trash-to-energy facilities reduce trash volume by roughly 87% and turn 2,000 pounds of garbage into ash that weighs between 300 and 600 pounds [3].

The rate of worldwide waste generation is accelerating with the rising population. In 2020, 2.24 billion tons of solid garbage were produced globally, and that number is expected to rise to 3.88 billion tons by 2050 [4]. An estimation of the MSW generation growth rate from 2016 to 2050 suggests that MSW generation in underdeveloped, developing, and developed countries will increase by 204%, 110%, and 29% respectively [5], as a result of Urbanization, industrialization, and rapid economic growth [6]. Due to inefficient waste management systems, waste has become a global issue [7]. According to the World Health Organization (WHO), over 2 billion tons of MSW are produced annually, which leads to air, water, and soil contamination and causes negative health

effects. Moreover, waste contributes to climate change because decomposing organic waste releases methane gas, a greenhouse gas that causes global warming [8].

Several studies have delved into waste management systems [9]. Hossan et al. in his recent work, conducted a comprehensive global study to assess the potential for waste-to-energy (WTE) conversion from municipal solid waste (MSW), focusing on domestic solid waste by calculating both the lower calorific value (LCV) and higher calorific value (HCV) of the total household waste using the Dulong and Vandralek formulas. Their findings recommended anaerobic digestion (AD) as the most suitable waste-to-energy process, especially in the case of developing and underdeveloped countries, which can produce 0.325 MWh of electrical energy per ton of waste [4]. Mostakim et al. in a separate study [10], analyzed MSW data in Bangladesh. Mostakim et al. compared various waste-to-energy (WTE) methods including pyrolysis, incineration, anaerobic digestion (AD), gasification, and hydrothermal carbonization (HTC) and suggested HTC to be ideal considering energy efficiency and environmental impact. By calculating the LCV of the total MSW, Mostakim et al. uncovered a significant potential of 6-7 MJ/kg in low to medium-income economies which may rise to an impressive 13 MJ/kg in higher-income economies. In another highly insightful study, Hoque et al. aimed to illustrate MSW generation and management within the precincts of Rajshahi City Corporation (RCC) emphasizing Waste-to-Energy (WTE) approaches [11], Employing ultimate analysis techniques, Hoque et al. calculated the HCV of the MSW, arriving at an impressive 14.9 MJ/kg. Furthermore, the study projected a potential power generation of 159.4 MWh/day for an average waste generation of 0.4214 kg/person/day. The research culminated in a compelling recommendation for the implementation of anaerobic digestion (AD) which showcased the potential to retrieve a substantial 3.58 MW of power, promising a notable payback period of 4.9 years [11].

This research endeavor aims to provide a comprehensive overview of global municipal solid waste (MSW) generation, and prevailing trends in MSW management to discern the most feasible and viable WTE conversion technologies for particularly underdeveloped nations.

2. Current Waste Generation Scenario

MSW generation scenario for the selected six underdeveloped countries representing Bangladesh, Nepal, Cambodia, Senegal, Sudan, and Ethiopia is plotted in Fig-1 and Fig-2. Although survey time is a very important factor in comparing MSW generation rates among different countries; however, due to the lack of available reported information, the data presented in Figures does not share similar survey times.

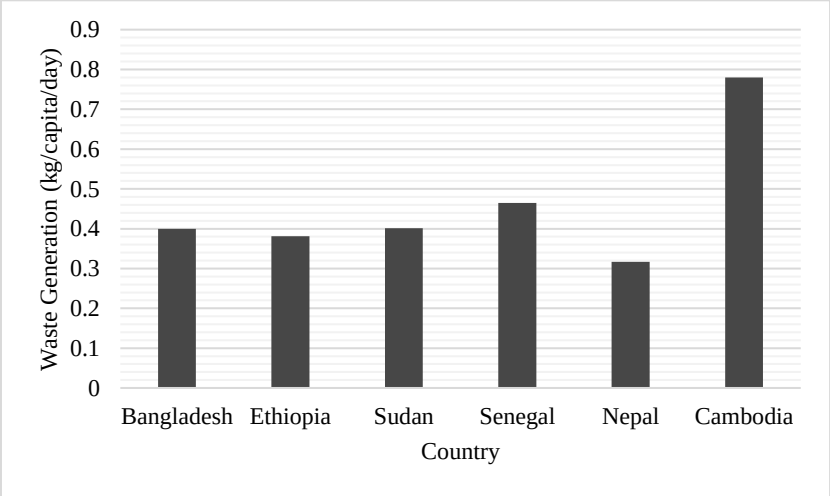


Fig. 1. Waste generation rate (kg/capita/day) [12],[13], [14], [15],[16],[17]

Table 1. (a) Waste composition [13], [17], [18], [19], [20], [21] **(b)** Ultimate Analysis [17], [28]

(a)

Country	MSW Composition			
	Food (%)	Paper (%)	Plastic (%)	Textile (%)
Bangladesh	74.5	9.1	3.5	1.9
Ethiopia	67	6	8	0
Sudan	49	11.8	12.7	4.6
Senegal	44	13	18	0
Nepal	40	21	22	2
Cambodia	46.2	7.1	21	8.1

(b)

Waste Type		C(%)	H(%)	O(%)	N(%)	S(%)	Ash(%)
Bangladesh	Food	48	6.6	37.6	0.1	5	4.51
	Paper	43	6	44	0.2	0.3	6
	Plastic	60	22.8	7.2	0.1	0	10
	Textile	55	6.6	31.2	0.1	4.6	2.5
Cambodia	Food	47	7	42	3.8	0.1	4
	Paper	44	6	49	0.2	0.02	10
	Plastic	74	11	11	0	0	9
	Textile	58	5	36	1	0	5

As MSW is a type of waste mostly produced by households, every country considered in this study has an extensively high portion of organic waste compared to the other types. It is mostly due to the agriculture-based economy in these less developed countries.

In the advancing world, efficient waste management has become imperative for sustainable development and environmental stability. Waste-to-Energy (WTE) conversion offers a promising solution by not only managing waste but also converting it into valuable energy resources, as energy demand is also increasing day by day. Currently available WTE technologies include incineration, anaerobic digestion (AD), gasification, and pyrolysis. Incineration is a well-established Waste-to-Energy technology that involves the combustion of waste materials at high temperatures in a controlled environment. The main advantage of incineration is bolstered by its capability to utilize both organic and inorganic waste to generate heat, which is then used to produce steam and subsequently drive turbines to generate electricity. The combustion process also reduces the volume of waste significantly [22]. Pyrolysis is a thermal decomposition process that involves heating waste in the absence of oxygen to produce a mixture of gases, liquids known as pyrolysis oil, and solid char. The pyrolysis oil can be used as a fuel, and the gases can be combusted for energy generation [23]. Gasification is a highly efficient thermochemical WTE process that converts carbon-rich waste materials into a gaseous fuel called syngas (synthetic gas) in the presence of controlled amounts of oxygen and/or steam. The syngas can be used to produce energy of different forms, including electricity, heat, or biofuels [24]. The biodegradable MSW fraction has a high potential for energy production. Biological treatment technology (BTT) is another method for utilizing organic waste which is designed and engineered for natural biological processes working with the organic-rich fraction of MSW. According to the operating condition, these treatments are divided into two different types: the aerobic process or composting (in the presence of oxygen) and the anaerobic process (in the absence of oxygen). Anaerobic Digestion (AD) is one of the prominent waste-to-energy conversion methods that involves biological processes and utilizes microorganisms to break down organic waste in the absence of oxygen and produces biogas, primarily composed of methane and carbon dioxide. This biogas can further be used to generate electricity or simply for heating by burning them and fuel vehicles [25].

3. Methodology

Data Collection

The countries covered in this study are chosen as underdeveloped according to the most recent UN data as of December 2023 [26]. The research was conducted using secondary data available on various literatures for the selected nations. This prevented the study from selecting data from a single period of time for all countries. However, efforts were made to keep the time as close as possible. First, each country's solid waste production per capita per day, as well as the percentage composition of the waste, was collected and the per capita waste generation was calculated. The percentage composition data provided information about the type of waste produced. Fig-1 and Table 1 show the per capita waste generation in a day and the percentage composition of the type of waste, in each country respectively.

Incineration

For incineration, food, paper, plastic, and textile waste were selected to undergo the process. At first, the Higher Heating Value (HHV) for each type of waste was measured by following the suggested formula by [27],

$$HHV=0.3491C+1.1783H+0.1005S-0.1034O-0.015N-0.0211A \quad (1)$$

Where C, H, S, O, N, and A refer to Carbon, Hydrogen, Sulfur, Oxygen, Nitrogen, and Ash-content, respectively. The sources of these values were from the ultimate analysis result data for each type of waste, mainly available for Bangladesh [28] and Cambodia [17]. As there was a scarcity of data related to the ultimate analysis for the selected countries, the values for Bangladesh were used for other countries too except Cambodia. The moisture content by percent for these wastes was found for Cambodia to be food 78, plastic 17, paper 20, and textile 3 [17]. For Bangladesh, the data was found for Dhaka and Chittagong city [28], and by means of the weighted average, it was calculated as, for food 73.72%, for plastic 0.574%, for paper 3.42%, and for textile 4.01%, which were used for other countries too except Cambodia. After subtracting the moisture content, the dry portion of the waste was calculated. Previously calculated HHV by equation (1) for each type of waste was used to calculate the overall HHV for each country. Then the heat generated during the incineration process was computed from the following relation [29],

$$Q_{inc}=\frac{b\times HHV(100-e)}{100} \quad (2)$$

Here, b is the dry mass of the waste in kg, which was obtained by multiplying the total dry waste production per capita with the population of the respective regions of each country from where the data was collected, HHV is

the previously calculated higher heating value in MJ/kg, and e is the sum of all efficiency losses. However, as the estimation was done for different countries, for convenience, e was assumed to be 0 here. The generated heat can be used to run steam turbines to produce mechanical power, which may further be used to produce electricity. The output mechanical power was calculated as,

$$E_{p_inc}\frac{Q_{inc}\times\eta\times 365}{3412.14} \quad (3)$$

Where, E_{p_inc} is in MWh/year and η is the efficiency of the steam turbine, which was taken as 0.29 [30].

Anaerobic Digestion

As it is already known that this WTE technology requires organic materials for WTE conversion, only the food waste available in the countries was taken into consideration for this process. For being underdeveloped nations, these countries produce a large portion of food or organic waste compared to other types of waste. First, the Buswell equation [31] was used as follows to calculate the mole ratio of Carbon, Hydrogen, Oxygen and Nitrogen available in the organic component,

$$C_aH_bO_cN_d+(a-4b-2c+43d)\ H_2O\rightarrow(a-8b+4c-83d)\ CH_4+(a+8b-4c+83d)\ CO_2+dNH_3 \quad (4)$$

Which can be simplified as [27],

$$C_aH_bO_cN_d+D_1H_2O\rightarrow D_2CH_4+D_3CO_2+D_4NH_3 \quad (5)$$

Where, $D_1=\frac{4a-b-2c+3d}{4}$

$D_2=\frac{4a-b+2c+3d}{8}$

$D_3=\frac{4a+b-2c-3d}{8}$

The total methane generation was calculated by the formula [27],

$$M_{CH4}=\frac{16\times D_3}{(M_C\times a)+(M_H\times b)+(M_O\times c)+Mn}\times 1000 \quad (6)$$

Where, M_{CH4} is in kg/ton of food waste and M_C, M_H, M_O, M_N are the gram molar masses of Carbon, Hydrogen, Oxygen, and Nitrogen respectively. The volume in m^3/ton/day was calculated by following the equation [27],

$$V_{CH4}=\frac{M_{ch4}}{\rho_{ch4}} \quad (7)$$

Where ρ_{CH4} is the density of Methane taken as 0.717 kg/m^3 [32]. Then, the amount of electricity that can be produced with this methane was calculated by,

$$E_{AD}=\frac{LHV\times V_{CH4}\times 0.85\times\eta_{generator}}{C_f} \quad (8)$$

Here, the LHV value is put as 37.2 MJ/m^3, $\eta_{generator}$ is the efficiency of the methane gas-fired generator assumed as 0.26, and C_f is the MJ to kWh conversion factor [30]. The emission from each of the energy conversion techniques was calculated to evaluate the sustainability of the processes. In this study, only CO_2 emission was considered as it is primarily responsible for greenhouse effect and consequent global warming. The amount of CO_2 emitted from incineration was calculated in kg/kWh using the following formula[33],

$$CO_{2\ (emitted,\ inc)}=C\times b\times\alpha\times M_{CO2} \quad (9)$$

Where $CO_{2\ (emitted)}$ is the amount of CO_2 generated through incineration in kg, C is the fossil carbon component, b is the total dry waste supplied to the incineration plant, α is the oxidation factor which was taken as 1, and M_{CO2} is the molecular mass of CO_2 which is 44 kg/mol. The value of the fossil carbon component, C, was calculated for each country using the weighted average of the carbon percentage from the ultimate analysis data used earlier [28] [17]. For Anaerobic Digestion (AD), the emission of CO_2 was calculated by the following formula [27] in terms of kg/ton of total organic waste,

$$CO_{2\ (emitted,\ AD)}=\frac{44\times D_2}{(M_C\times a)+(M_H\times b)+(M_O\times c)+M_n}\times 1000 \quad (10)$$

The resulting values were then divided by the respective energy produced by each technology in order to make a relevant comparison between the two, which is shown in Fig. 4. After analyzing the energy generation and the environmental impact, the study aims to obtain a brief overview of the socioeconomic effects by analyzing the

job opportunity that may be created with the establishment of the incineration and AD plants in the respective region of each country. This has been evaluated by following the relations [27],

Manufacturing (Local Uses) = MW installed/year in region × Manufacturing Employment Factor × Regional Job Multiplier for Year × (% Local Manufacturing)

Construction = MW installed/year in region × Construction Employment Factor × Regional Job Multiplier for Year

Operation and Maintenance (O&M) = Cumulative Capacity (MW) × O&M Employment Factor × Regional Job Multiplier for Year

Jobs in Region = Manufacturing (Local Uses) + Construction + Operation and Maintenance (O&M)

These factors of SAARC region are taken for the job estimation of Bangladesh and Nepal, MENA region for Ethiopia and Sudan, and Sub-Sahara Africa and Southeast Asia for Senegal and Cambodia respectively [34].

4. Results and Discussion

The study reveals significant differences in energy generation and environmental impact between incineration and anaerobic digestion (AD) in several underdeveloped countries. From Fig. 3 and Fig. 4, incineration is seen to be a highly effective option for power generation in countries like Cambodia (389 MW), Sudan (110 MW), and Senegal (48 MW), where it can harness the higher calorific value of non-organic waste. However, it emits more CO_2, raising environmental concern. AD, on the other hand, is more suitable for Bangladesh (681 MW) and Ethiopia (3 MW) due to the domination of organic waste over other types of waste, and has the potential to create more job opportunities too.

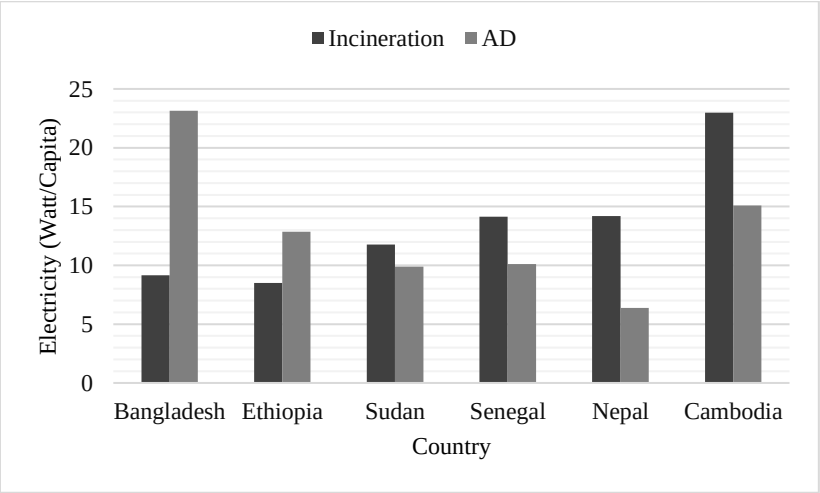


Fig. 2. Comparison of energy generated from incineration and AD

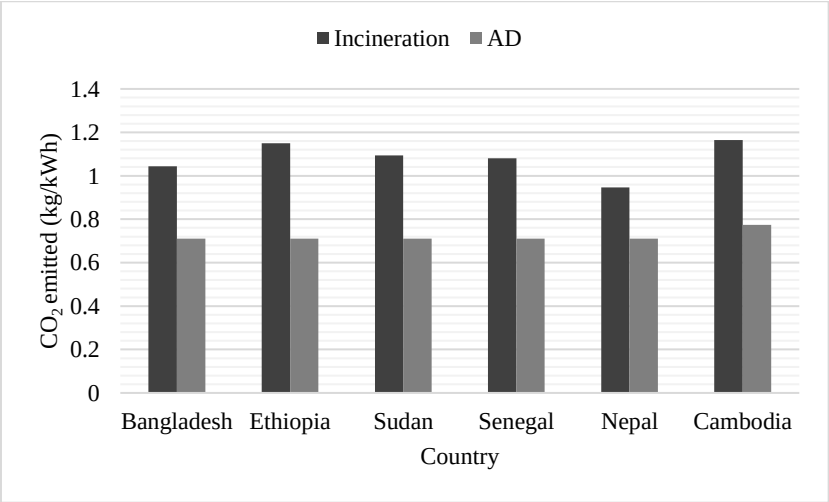


Fig. 3. Comparison of emissions (CO_2) from incineration and AD

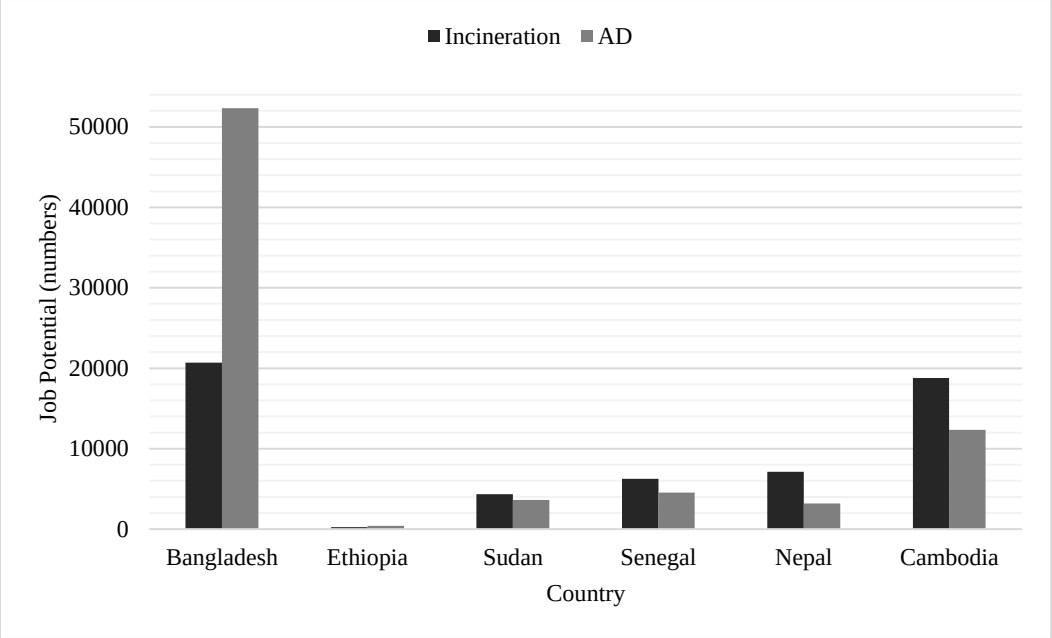


Fig. 4. Job potential for incineration and AD

The results also indicate that, although AD is environmentally friendlier, incineration offers higher electricity generation, making it more practical in regions like Sudan, Senegal, Nepal, and Cambodia creating more job opportunities in those countries. These findings underscore the need for a customized WTE strategy, where both power generation capacity and environmental impact are considered. While incineration might be a necessary compromise in some nations, future research should focus on mitigating its environmental downsides.

6. Conclusions

The study evaluates waste-to-energy (WTE) technologies, focusing on incineration and anaerobic digestion (AD) in underdeveloped countries. It highlights the potential for energy recovery and environmental benefits. The results show that AD is a sustainable waste management option for Bangladesh and Ethiopia due to its higher energy generation along with lower CO_2 emissions. However, in Sudan, Senegal, Nepal, and Cambodia, incineration, despite being a little harmful for the environment, can be a practical waste management solution as it has the potential to generate substantially higher rates of electricity in those countries. A proposed WTE model addressing barriers could be further refined to assess economic and policy impacts for practical implementation which has the potential to create a significant amount of jobs in the selected regions.

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