Comparative Life Cycle Assessment of Gasification and Landfilling for Disposal of Municipal Solid Wastes

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Abstract: Disposal of municipal solid wastes (MSW) remains a challenge to minimize its impacts on the environment and human health. Landfilling, currently the most common method used for MSW disposal, occupies land space and leads to soil and air emissions. Gasification, an alternative MSW disposal method, can convert waste to energy, but can also lead to soil and air emissions and is a more extensive operation. In this study, life cycle assessments (LCA) of the two disposal methods (landfilling without energy recovery and gasification) were compared to understand impacts on environment and health. The LCA was conducted following the ISO 14040 standards with one ton of MSW as the functional unit. The life cycle inventory was obtained from published journals, technical reports, LandGEM, HELP and GREET database. The impact assessment was done using TRACI 2.1 and categorized into eight groups. The LCA revealed that landfilling is a higher contributor in global warming, acidification, smog formation, eutrophication, ecotoxicity and human health cancer and non-cancer categories. The negative environmental impacts of MSW landfilling can be primarily attributed to the fate of leachate loss and landfill gas, while those of the MSW gasification can be attributed to the disposal of its solid residues.

Keywords: life cycle assessment; gasification; landfill; impact assessment; MSW; GREET; TRACI

1. Introduction

Development of sustainable waste management and clean energy production technologies have become a growing worldwide challenge to protect the environment and human health. Landfilling, the most common method to dispose of MSW (50% of US MSW is landfilled), is the third largest source of human-related methane emissions, accounting for 16% of the total US methane emissions [1,2]. Methane emission is one of the major causes of global warming, air quality and human health-related issues [3]. In addition, landfills cause severe toxicological risks and odor nuisances to the surrounding environment (air and soil), animals and residents due to chemical exposure such as benzene, vinyl chloride monomer, polychlorinated dibenzo-p-dioxins/furans, dioxins and polycyclic aromatic hydrocarbons [3]. These hazardous compounds have been reported to cause reproductive disorders, pulmonary, gastrointestinal, renal, liver and dermatologic-related diseases, lung, skin and bladder cancer, bone marrow alteration, and leukemia [3–7]. Mataloni, et al. [8] investigated the effect of MSW landfills on the health of residents living near landfill sites. The study found that hydrogen sulfide (H₂S), an airborne contaminant released during MSW landfilling, was linked to lung cancer and respiratory diseases mortality, along with respiratory diseases morbidity, especially for children (<14 years). Conclusions of Vinti, et al. [9] were in agreement with Mataloni, et al. [8] findings. The authors added that landfilling caused mental health issues (mood states) and births with congenital anomalies [9–11].

Alternative MSW treatment techniques such as gasification have been proposed as a sustainable method to convert waste to energy [12–14]. Gasification is a thermal decomposition of biomass or MSW into syngas, ash and slag, conducted in a partial oxidative...
atmosphere. Syngas, composed of CO, CO$_2$, H$_2$, and CH$_4$, can then be converted into electricity through internal combustion engine and generator combinations [15]. Gasification of MSW is an emerging waste management method. However, little research provides a comparative analysis of the US MSW gasification and landfilling effects on sustainability, the environment and human health.

Life cycle assessment (LCA) has been used to evaluate the sustainability of waste management techniques and implement clean MSW management strategies [16,17]. The LCA is developed following the ISO 14040 standards which stipulates that an LCA report consists of a goal and scope, life cycle inventory (LCI), impact assessment (impact on environment and human health) and results interpretation [18]. Some studies have reported a comparative LCA of MSW landfills and thermal treatments. In Sweden, a study compared the LCA of MSW landfilling with energy recovery, incineration and gasification-pyrolysis using SimaPro and CML2, and concluded that landfilling had a lower impact on the environment than incineration and gasification-pyrolysis [19]. However, the report concluded that gasification is a better waste treatment option because landfills presents socio-economic challenges such as land usage and difficult emission control. Conversely, a study in Australia compared landfilling of several classes of waste to gasification of combustible waste with energy recovery [20]. The study concluded that gasification had lower environmental and human health impact compared to landfilling. Another research in Australia focused on landfilling, incineration and gasification-pyrolysis of mixed papers and mixed plastics using the ecoinvent database [21]. In the UK, a study conducted a comparative LCA of MSW landfills with energy recovery, incineration and gasification using GaBi. Technologies such as two-stage gasification and plasma process, two-stage fast pyrolysis and combustion process, and gasification and syngas combustion were also investigated [22]. In the US, another comparative LCA analysis using LandGEM and TRACI focused on landfills, advanced thermal recycling and gasification [23]. However, these studies [19,21–23] did not consider the human health impact and only Coventry, Tize and Karunanithi [23] used operational data of waste treatment in the US. In addition, most comparative studies on landfilling assume that LFG and or energy is recovered from landfilling. In actual fact, 46% of the total landfill sites reported in the US do not have an LFG collection system nor energy recovery system [24].

The objective of this study was to investigate and compare the environmental and human health impacts of two MSW disposal methods: gasification and landfilling without energy or LFG recovery, using an open access and freely available US-based database. Unlike research reported in the literature, the LCA model of MSW gasification was based on data collected from a self-sustaining fixed bed downdraft gasifier available at Oklahoma State University and suitable for small-scale decentralized waste-to-energy operation. This technical report can guide waste management planners and city authorities in choosing technologies to mitigate environmental and health-related challenges. The LCI was developed using the Greenhouse Gases Regulated Emissions and Energy Use in Technologies model (GREET) developed by Argonne. GREET is an accessible analytical tool sponsored by the US Department of Energy and is able to provide the emission outputs of energy-based technologies [25]. The Landfill Gas Emissions Model (LandGEM) and Hydrologic Evaluation of Landfill Performance tool (HELP) were used to estimate landfill gases and leachate yield, respectively. The impact assessment was completed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI version 2.1). TRACI evaluates the contribution of chemicals released by processes on the environment through global warming, acidification, eutrophication, tropospheric ozone formation (smog), ecotoxicity, and human health criteria-related effects [26].

2. Methods

2.1. Goal and Scope

This study is intended to compare the emission, environmental and human health impact of two municipal waste management methods: (1) gasification and (2) landfilling
without energy recovery. These findings will help support the choice of MSW management methods in the US. The functional unit of this study is 1 ton of the US average MSW. The LCA was completed according to the ISO 14040 standard. First, the life cycle inventory (LCI) was finalized using GREET to define the emissions. GREET, LandGEM, and HELP were used to complete the LCI of MSW landfills. Subsequently, the LCI and database were used in TRACI 2.1 (2014) to provide the impact assessment of both processes. The impact assessment was categorized in two major groups: the impact on environment, and impact on human health. The impact on environment comprises global warming (kg CO$_2$ equivalent), acidification (kg SO$_2$ equivalent), eutrophication (kg N equivalent), smog (kg O$_3$ equivalent) and ecotoxicity (CTU-eco). The impact on human health, on the other hand, was classified as HH particulate (PM2.5 equivalent), cancer and non-cancer effects (Table 1).

**Table 1. Environmental and human health impact categories.**

| №   | Environmental Impact                          | Unit              |
|-----|-----------------------------------------------|-------------------|
| 1   | Global Warming Potential for Air Emissions    | kg CO$_2$ equivalent |
| 2   | Acidification Potential for Air Emissions     | kg SO$_2$ equivalent |
| 3   | Smog Formation Potential for Air Emissions    | kg O$_3$ equivalent |
| 4   | Eutrophication Potential for Air Emissions    | kg N equivalent   |
|     | Water Emissions                              |                   |
|     | Urban Air Emissions                          |                   |
|     | Rural Air Emissions                          |                   |
| 5   | Freshwater Ecotoxicity Potential for          | Comparative Toxicity Unit eco |
|     | Urban Air Emissions                          | (CTU-eco)         |
|     | Rural Air Emissions                          |                   |
|     | Freshwater Emissions                         |                   |
|     | Seawater Emissions                           |                   |
|     | Natural Soil Emissions                       |                   |
|     | Agricultural Soil Emissions                  |                   |
| 6   | Human Health Particulate Potential for Air Emissions | PM2.5 equivalent |
|     | Urban Air Emissions                          |                   |
|     | Rural Air Emissions                          |                   |
| 7   | Human Health Cancer Potential for Urban Emissions | Comparative Toxicity Unit cancer (CTU-cancer) |
|     | Freshwater Emissions                         |                   |
|     | Seawater Emissions                           |                   |
|     | Natural Soil Emissions                       |                   |
|     | Agricultural Soil Emissions                  |                   |
| 8   | Human Health Non-Cancer Potentials for        | Comparative Toxicity non-cancer (CTUnon-cancer) |
|     | Urban Air Emissions                          |                   |
|     | Rural Air Emissions                          |                   |

2.2. *Waste Management Scenarios and Boundaries*

The MSW life, generally, starts from the domestic garbage. Prior to the gasification or landfilling process, the MSW gets collected from the domestic garbage with a truck, then transported to the landfill site or the gasification plant. However, the collection and transportation methods were assumed to be the same for both scenarios, hence, this comparative LCA study did not include the LCA and impact of transportation and collection
processes. For this LCA study, MSW life starts at the gate of the waste management site (landfill or gasification plant).

2.2.1. Scenarios 1: Landfilling

Landfill sites are spaces designed to receive waste materials. The MSW is buried to allow degradation of its biological materials in an oxygen-free environment. The MSW undergoes anaerobic decomposition which consists of breaking down organic matters into biogas [27,28]. Two products from the MSW decomposition are landfill gas (LFG) and leachate (liquid). Landfill gasses are essentially composed of methane (>50%), CO\textsubscript{2} (~40%), and less than 1% of non-methane organic compounds (NMOC). NMOC composition was evaluated using the landfill gas emission model (LandGEM). The leachate composition is given in the EPA’s report on leachate from MSW characterization [29]. According to the Landfill Methane Outreach Program database (LMOP), 46.7% of the reported landfill sites do not have an LFG collection or energy recovery system [24]. This study assumed that the LFG produced from 1 ton of MSW is released in the air. The title 40 of the Code of Federal Regulations (CFR) part 258 requires that landfills prevent leachate from leaking into groundwater by installing liner systems [30]. However, Paladino and Massabò [31] explained that liners are not totally impermeable and can lead to leachate loss. Hence this study assumed that 5% of the total leachate contaminated the groundwater. The collected leachate was treated in a municipal sewage treatment plant. However, the related emissions were disregarded. The process boundaries and steps are shown in Figure 1.

Life Cycle Inventory

The LCI of MSW landfilling was designed using LandGEM, HELP and GREET [25,32,33]. The MSW life cycle starts when the waste is disposed in the trash. The MSW is collected and transported to the landfill site where compactors are used to layer the waste. The LCI of MSW landfilling includes inputs such as 1 ton of MSW, diesel consumed by compactors and outputs such as landfill gas (LFG) and leachate (Figure 1). The diesel consumption was based on the compactor D6T from Caterpillar. The compactor is able to work a maximum of 50 tons per day with a diesel consumption of 24.7 L/h [34].

Based on the calculations made using LandGEM, 1 ton of landfilled MSW produces 186.5 m\textsuperscript{3} of LFG. Figure 2 shows the landfill gases (LFG, CH\textsubscript{4} and CO\textsubscript{2}) yield over 140 years. The leachate generated was estimated using the Hydrologic Evaluation of Landfill Performance (HELP). The LCI of MSW landfilling is presented in Table 2.

2.2.2. Scenarios 2: Gasification

A scaled-up downdraft gasifier was used for this study. The gasification of MSW yields syngas, and solid residues (tar and biochar). The syngas from gasification was used
to produce electricity via combustion in a natural gas IC engine and the solid residues were landfilled.

![Landfill gas emissions graph](image)

**Figure 2.** Landfill gas generation using LandGEM.

**Table 2.** Life cycle inventory of MSW landfilling.

| Inputs            | Quantity | Unit | References |
|-------------------|----------|------|------------|
| MSW               | 1        | Ton  | -          |
| Diesel            | 7.87     | L    | [34,35]    |

| Outputs            |          |      |            |
|-------------------|----------|------|------------|
| LFG               | 186.5    | m³   | LandGEM [32]|
| Methane           | 61.29    | kg   |            |
| Carbon dioxide    | 184.71   | kg   |            |

| Annual average Leachate generated | 0.166 | m³/ton | HELP [33] |

**Life Cycle Inventory**

The life cycle assessment of 1 ton of MSW gasification was developed based on the scaled-up downdraft gasifier at Oklahoma State University. The model was composed of waste pretreatment, gasification, syngas cleaning, electricity production, and char and tar collection. The system’s boundaries are shown in Figure 3. GREET was used to calculate the emissions based on the process inputs.

**MSW Pretreatment**

MSW pretreatment consisted of sorting, size reduction and shaping (pellets). The LCI of the pretreatment was calculated based on the average composition of MSW landfilled in the US. Overall, MSW landfilled in the US is composed of inorganic wastes (2.24%), paper and paperboard (11.78%), glass (5.17%), metals (9.53%), plastics (18.46%), yard trimmings (7.21%), food (24.14%), wood (8.32%), rubber and leather (3.42%), textiles (7.73%) and other (2.01%) [2]. Prior to the gasification, metals and glasses were removed from the MSW to avoid interferences with the syngas during the gasification. As metals and glasses constitute 14.7% of the MSW, 0.853 ton of MSW was processed after the sorting. The MSW sorting requires 0.059 kWh/ton [36]. The MSW size reduction and shaping consumed 91.5 kWh of electricity [37].
Figure 3. MSW gasification process flow diagram.
MSW Decomposition in Gasifier

The thermal conversion of MSW was carried out in a downdraft gasifier. The gasifier is a self-sustaining reactor. Therefore, it requires a minimum energy input for initial firing with charcoal and propane, and then the process temperature was controlled with the MSW feeding rate and airflow rate [12,38]. The inputs for the MSW decomposition were the pretreated MSW, propane, charcoal, air and electricity (for field devices). The downdraft gasifier was equipped with field devices such as air compressor, electric heaters, chiller, water pump, belt conveyor, air log motor, ash scrapper and ash conveyor that function using 25.58 kWh of electricity per ton of MSW [39].

Syngas, Electricity, and Solid Residue

Tar removal is a crucial step prior to the conversion of syngas into electricity. In this study, the syngas was converted into electricity using an IC engine. As uncleaned syngas contained tar, and IC engines can only run on syngas containing less than 100 mg/m³ of tar, a syngas scrubber was installed between the cyclone and the engine [12,40]. The scrubbing solution was a mixture of acetone and water (20:80 ratio) [41]. Hence, the inputs at the syngas cleaning system were syngas containing tar, acetone and water. The conversion of syngas to electricity was conducted using an internal combustion engine with clean syngas and air as inputs. The conversion of MSW produced 584.3 kWh of electricity [42].

The solid residues collected from gasification were landfilled. The LCA of bottom ash landfilling was used in this study based on the data available [43]. The total solid residues collected was 102.4 kg [44]. The inputs and outputs of MSW gasification are shown in Table 3. Table 4 shows the emissions to air and water of gasification per unit process. The electricity consumed emissions and energy generated credit were evaluated using the US electricity mix model in GREET.

| Inventory                              | Quantity   | Unit     | References |
|----------------------------------------|------------|----------|------------|
| Input MSW                              | 1          | Ton      | -          |
| Electricity for MSW sorting            | 0.059      | kWh      | [36]       |
| MSW quantity after sorting             | 0.853      | Ton      | -          |
| Electricity for MSW size reduction and shaping | 91.5      | kWh      | [37]       |
| Electricity for field devices          | 25.58      | kWh      | [39]       |
| Propane                                | 0.013      | Gal      | [39]       |
| Wood charcoal                          | 1.36       | kg       | [38]       |
| Air                                    | -          | -        | -          |
| Acetone                                | 0.85       | Gal      | [41]       |
| Water                                  | 3.41       | Gal      | [41]       |
| Power generated                        | 584.3      | kWh      | [42]       |
| Solid residues                         | 102.4      | kg       | [44]       |
| Emissions                              | Table 4    | -        | GREET      |

Table 3. LCI of MSW gasification per ton of MSW.
### Table 4. Emissions output (in kg) of MSW gasification using GREET.

| Emissions         | Electricity Consumed | Propane   | Charcoal | Acetone | MSW to Electricity [19] | Solid Residues [45] | Total Gasification | Electricity Credit |
|-------------------|----------------------|-----------|----------|---------|-------------------------|---------------------|--------------------|--------------------|
| CO₂ total         | $4.99 \times 10^1$   | $1.64 \times 10^{-2}$ | $6.49 \times 10^{-2}$ | 2.92 | $7.60 \times 10^2$ | - | $8.13 \times 10^2$ | $-2.49 \times 10^2$ |
| CO₂               | $5.04 \times 10^1$   | $1.65 \times 10^{-2}$ | $6.90 \times 10^{-2}$ | 2.92 | - | - | $5.34 \times 10^1$ | $2.52 \times 10^2$ |
| CO₂ Biogenic      | $-5.90 \times 10^{-1}$ | $-2.49 \times 10^{-5}$ | $-3.47 \times 10^{-5}$ | 0.00 | - | - | $-5.90 \times 10^{-1}$ | $-2.93$ |
| VOC               | $5.88 \times 10^{-3}$ | $8.97 \times 10^{-6}$ | $4.49 \times 10^{-5}$ | $2.96 \times 10^{-3}$ | - | - | $8.89 \times 10^{-3}$ | $-2.93 \times 10^{-2}$ |
| CO                | $1.98 \times 10^{-2}$ | $1.54 \times 10^{-5}$ | $1.80 \times 10^{-4}$ | $3.37 \times 10^{-3}$ | - | - | $2.34 \times 10^{-2}$ | $-9.89 \times 10^{-2}$ |
| NOx               | $3.63 \times 10^{-2}$ | $2.85 \times 10^{-4}$ | $4.50 \times 10^{-4}$ | $6.56 \times 10^{-3}$ | $5.84 \times 10^{-1}$ | - | $6.27 \times 10^{-1}$ | $-1.80 \times 10^{-1}$ |
| PM10              | $5.92 \times 10^{-3}$ | $2.28 \times 10^{-6}$ | $2.53 \times 10^{-5}$ | $1.08 \times 10^{-3}$ | - | - | $7.03 \times 10^{-3}$ | $-2.95 \times 10^{-2}$ |
| PM2.5             | $2.64 \times 10^{-3}$ | $1.93 \times 10^{-6}$ | $2.27 \times 10^{-5}$ | $4.30 \times 10^{-4}$ | - | - | $3.09 \times 10^{-3}$ | $-1.32 \times 10^{-2}$ |
| Sox               | $7.93 \times 10^{-2}$ | $1.07 \times 10^{-5}$ | $1.30 \times 10^{-4}$ | $3.64 \times 10^{-3}$ | - | - | $8.30 \times 10^{-2}$ | $-4.00 \times 10^{-1}$ |
| CH₄               | $8.30 \times 10^{-2}$ | $1.10 \times 10^{-4}$ | $9.50 \times 10^{-5}$ | $6.20 \times 10^{-3}$ | - | - | $8.94 \times 10^{-2}$ | $-4.10 \times 10^{-1}$ |
| N₂O               | $7.80 \times 10^{-4}$ | $2.60 \times 10^{-7}$ | $6.23 \times 10^{-5}$ | $2.17 \times 10^{-3}$ | - | - | $3.01 \times 10^{-3}$ | $-3.87 \times 10^{-3}$ |
| BC                | $2.30 \times 10^{-4}$ | $2.70 \times 10^{-7}$ | $1.34 \times 10^{-5}$ | $5.79 \times 10^{-5}$ | - | - | $3.02 \times 10^{-4}$ | $-1.16 \times 10^{-3}$ |
| POC               | $5.50 \times 10^{-4}$ | $4.50 \times 10^{-7}$ | $4.41 \times 10^{-6}$ | $8.97 \times 10^{-5}$ | - | - | $6.45 \times 10^{-4}$ | $-2.74 \times 10^{-3}$ |
| Hydrogen chloride | -                    | -         | -        | -       | $2.73 \times 10^{-2}$ | - | - | $2.73 \times 10^{-2}$ |
| Hydrogen fluoride | -                    | -         | -        | -       | $2.90 \times 10^{-4}$ | - | - | $2.90 \times 10^{-4}$ |
| Mercury           | -                    | -         | -        | -       | $5.89 \times 10^{-5}$ | - | - | $5.89 \times 10^{-5}$ |
| Dioxins and furans| -                    | -         | -        | -       | $4.09 \times 10^{-11}$ | - | - | $4.09 \times 10^{-11}$ |
| Arsenic (As)      | -                    | -         | -        | -       | - | $5.59 \times 10^{-7}$ | - | $5.59 \times 10^{-7}$ |
| Barium (Ba)       | -                    | -         | -        | -       | - | $8.38 \times 10^{-6}$ | - | $8.38 \times 10^{-6}$ |
| Calcium (Ca)      | -                    | -         | -        | -       | - | $4.19 \times 10^{-2}$ | - | $4.19 \times 10^{-2}$ |
| Cadmium (Cd)      | -                    | -         | -        | -       | - | $8.38 \times 10^{-8}$ | - | $8.38 \times 10^{-8}$ |
| Chlorine (Cl)     | -                    | -         | -        | -       | - | $1.63 \times 10^{-1}$ | - | $1.63 \times 10^{-1}$ |
| Chromium (Cr)     | -                    | -         | -        | -       | - | $8.38 \times 10^{-7}$ | - | $8.38 \times 10^{-7}$ |
| Copper (Cu)       | -                    | -         | -        | -       | - | $6.05 \times 10^{-5}$ | - | $6.05 \times 10^{-5}$ |
| Manganese (Mn)    | -                    | -         | -        | -       | - | $1.00 \times 10^{-7}$ | - | $1.00 \times 10^{-7}$ |
| Sodium (Na)       | -                    | -         | -        | -       | - | $1.79 \times 10^{-1}$ | - | $1.79 \times 10^{-1}$ |
| Nickel (Ni)       | -                    | -         | -        | -       | - | $8.38 \times 10^{-7}$ | - | $8.38 \times 10^{-7}$ |
| Lead (Pb)         | -                    | -         | -        | -       | - | $8.38 \times 10^{-7}$ | - | $8.38 \times 10^{-7}$ |
| Sulfate (SO₄)     | -                    | -         | -        | -       | - | $1.30 \times 10^{-1}$ | - | $1.30 \times 10^{-1}$ |
| Zinc (Zn)         | -                    | -         | -        | -       | - | $1.68 \times 10^{-6}$ | - | $1.68 \times 10^{-6}$ |
3. Results

The impact assessment, a method used to evaluate the environmental and human health impacts of landfilling and gasification, is discussed in this section. The environmental and human health impacts were evaluated using TRACI 2.1.

3.1. Environmental Impact

Table 5 shows the effect of MSW gasification and landfilling on the environment. The environmental impact was organized into five midpoint impact categories including global warming, acidification, eutrophication, smog air (tropospheric ozone formation) and ecotoxicity potentials. Impact categories such as eutrophication and freshwater ecotoxicity potentials emission were calculated based on different types of media. For example, the potency of chemicals for freshwater ecotoxicity was calculated based on the emissions to urban and rural air, fresh and sea water, and natural and agricultural soil. Calculating the impact of a process through different media allows emissions to be evaluated for site-specific locations. Global warming, acidification and smog formation potentials were not affected by locations and were evaluated for air emissions only.

Table 5. Environmental Impact.

| №  | Environmental Impact                      | Landfilling  | Gasification | Unit                      |
|----|------------------------------------------|--------------|--------------|---------------------------|
| 1  | Global Warming Potential for Air emission| 1.72 × 10³   | 5.66 × 10²   | kg CO₂ equivalent         |
| 2  | Acidification Potential for Air Emission | 1.58         | 1.01 × 10⁻¹  | kg SO₂ equivalent         |
| 3  | Smog Formation Potential for Air Emissions| 4.13 × 10¹   | 1.32 × 10¹   | kg O₃ equivalent          |
| 4  | Eutrophication Potential for Air Emissions| 2.54 × 10⁻¹  | 1.82 × 10⁻²  | kg N equivalent           |
|    | Water Emissions                          | 1.66         | 1.20 × 10⁻¹  |                           |
| 5  | Freshwater Ecotoxicity Potential for      |              |              | Comparative               |
|    |                                           |              |              | Toxicity Unit eco         |
|    | Urban Air Emissions                       | 1.82 × 10³   | 2.15         |                           |
|    | Rural Air Emissions                       | 1.84 × 10³   | 2.18         |                           |
|    | Freshwater Emissions                      | 4.29 × 10³   | 4.74         |                           |
|    | Seawater Emissions                        | 3.03 × 10⁻³  | 9.55 × 10⁻¹⁵ |                           |
|    | Natural Soil Emissions                    | 2.31 × 10³   | 2.74         |                           |
|    | Agricultural Soil Emissions               | 2.31 × 10³   | 2.74         |                           |

3.1.1. Global Warming Potentials for Air Emissions

Global warming (GW), measured in kg CO₂ equivalent, is related to the temperature rise caused by greenhouse gases such as CO₂, CH₄ and nitrous oxides (N₂O). MSW landfilling emitted 1721 kg CO₂ equivalent, compared to 566.5 kg CO₂ equivalent for MSW gasification. The GW potential of landfilling is 75.24% higher than that of gasification (Table 5). MSW landfill gases are composed of 60% methane and 40% CO₂. Hence, landfills are the third largest source of methane emission in the US, which explains its high contribution in GW categories compared to gasification [1]. Landfilling GW was lower than those reported by Yay [36] and Leme, et al. [45]. The difference could be attributed to different potency factors used by the impact assessment tools. The gasification GW in this study was lower than those reported by Zaman [42] and higher than the estimations made by Coventry, Tize and Karunanithi [23]. These studies had different boundaries and resources inputs. For example, Coventry, Tize and Karunanithi [23] included the MSW transportation to the LCA. Furthermore, the startup energy used in Zaman [42] was higher than that used in this study.

3.1.2. Acidification Potentials for Air Emissions

Acidification potentials (AP) for air emissions, expressed in kg SO₂ equivalent, mainly affects the environment acidity and causes the degradation of infrastructures, water resources and living species [26]. MSW landfilling showed higher acidification potential for air emissions (1.58 kg SO₂ equivalent) compared to gasification (1.01 × 10⁻¹ kg SO₂
equivalent). Yay [36] reported lower acidification potential (0.169 kg SO$_2$ equivalent) for landfilling. Acidification potential of gasification in this study was lower than that reported by Zaman [19,42]. The acidification potential for air emissions was caused by chemicals such as hydrogen sulfide (H$_2$S), ammonia nitrogen (NH$_3$-N), NOx and SOx. NH$_3$-N of leachate caused 98.5% of landfilling AP. Gasification AP was caused by NOx emissions (0.45 kg). However, the negative value of SOx emission (−0.32 kg), due to the electricity credit attributed to gasification for the electricity production, reduced the AP impact of gasification.

3.1.3. Eutrophication Potentials for Air and Water Emissions

The eutrophication potential for air emissions, expressed in kg N equivalent, is due to the nitrogen content in the form of ammonium ion (NH$_4$-N), NOx and N$_2$O emissions. The MSW landfilling had more environmental impact in terms of air eutrophication ($2.54 \times 10^{-1}$ kg N equivalent) compared to gasification ($1.82 \times 10^{-2}$ kg N equivalent). The water eutrophication of landfilling was mainly caused by NH$_4$-N, NH$_3$-N, phosphate, and NOx emissions, while that of gasification was due to NOx. Landfilling was found to have a higher water eutrophication impact (1.66 Kg N equivalent) compared to gasification ($1.20 \times 10^{-1}$ kg N equivalent). Eutrophication for air and water emissions were emitted during conversion of MSW to electricity for gasification and from the leachate and diesel combustion. The eutrophication potentials estimated in this study are higher than those reported by Coventry, Tize and Karunanithi [23].

3.1.4. Photochemical Smog Formation Potential for Air Emissions

The photochemical smog formation potential for air emissions, measured in kg O$_3$ equivalent, causes ozone depletion and respiratory diseases, such as bronchitis, asthma and emphysema, and ecological issues, such as ecosystem and crop damage [26]. MSW landfilling emitted 41.3 kg O$_3$ equivalent in terms of smog formation, compared to gasification which emitted 13.23 Kg O$_3$ equivalent. The smog formation for MSW landfilling was due to LFG (CH$_4$ and NMOCs), leachate (chlorine) and diesel combustion (VOC, CO, NOx). Volatile organic compounds (VOC), CO, NOx and CH$_4$ contributed to the smog formation for gasification.

3.1.5. Freshwater Ecotoxicity Potentials

The ecotoxicity, measured in comparative toxicity unit eco (CTU-eco) was evaluated based on six media: urban air, rural air, freshwater, seawater, natural soil and agricultural soil.

Urban and Rural Air Emissions

The freshwater ecotoxicity potentials for air emissions of landfilling and gasification were mainly due to metals, such as Cadmium (Cd), Zinc (Zn), Lead (Pb), Copper (Cu), Nickel (Ni), Chromium (Cr) and Arsenic (As). In addition to the metals, trace components present in LFG contributed to the ecotoxicity of air. Gasification had a minor air ecotoxicity impact (4.33 CTU-eco) compared to landfilling (3665.3 CTU-eco). This high level of landfilling ecotoxicity is due to metals from the leachate and organic trace compounds from the LFG.

Freshwater and Seawater Emissions

The freshwater ecotoxicity potentials for freshwater and seawater emissions of both processes were caused by metals and NMOCs. The gasification emissions to freshwater (4.74 CTU-eco) and seawater (9.55 $\times$ 10$^{-15}$ CTU-eco) were negligible compared to landfilling emissions to freshwater (4287 CTU-eco) and seawater (3 $\times$ 10$^{-3}$ CTU-eco). The high impact of landfilling on freshwater and seawater was mainly due to the toxicity of organic trace compounds emitted by the LFG and heavy metals in leachate.
Natural and Agricultural Soil Emissions

Freshwater ecotoxicity potentials for natural and agricultural soil emissions of land-filling was very high (total of 4616 CTU-eco) compared to those of gasification (total of 5.47 CTU-eco). The high ecotoxicity of land-filling was due to organic trace compounds in the LFG and metals in the leachate.

3.2. Impact on Human Health

The impact of gasification and landfilling on human health was classified into three groups: human health (HH) particulate, cancer and non-cancer potentials. The non-cancer and cancer effects are expressed as CTU non-cancer and CTU cancer, respectively (Table 6).

| № | Human Health Impact | Landfilling | Gasification | Unit |
|---|---------------------|-------------|--------------|------|
| 1 | Human Health Particulate Potential for Air Emissions | Landfilling | Gasification | PM2.5 equivalent |
|   | Urban Air Emissions | 5.58 × 10⁻² | -1.22 × 10⁻² | |
|   | Rural Air Emissions | 1.99 × 10⁻⁶ | 4.06 × 10⁻⁷ | |
|   | Freshwater Emissions | 1.66 × 10⁻⁶ | 4.25 × 10⁻⁷ | |
|   | Seawater Emissions | 1.28 × 10⁻⁶ | 7.31 × 10⁻⁹ | |
|   | Natural Soil Emissions | 1.32 × 10⁻⁷ | 5.65 × 10⁻⁹ | |
|   | Agricultural Soil Emissions | 6.57 × 10⁻⁷ | 5.12 × 10⁻⁹ | |

3.2.1. Human Health (HH) Particulate Potentials for Air Emissions

The human health (HH) particulate potentials for air emissions, measured in PM2.5 equivalent, were caused by PM2.5, PM10, CO, NOx and NH₃-N emissions. MSW gasification was found to be lower in terms of HH particulate potential for air emissions (PM2.5 and PM10). PM2.5 equivalent emitted into the air were -1.22 × 10⁻² and 5.58 × 10⁻² for gasification and landfilling, respectively. The negative value of HH particulate for gasification was due to the energy credit attributed to the electricity production. PM2.5, PM10, CO and NOx were produced during combustion of fossil fuel and biomass.

3.2.2. Human Health Non-Cancer Potentials

The human health non-cancer potentials, expressed in comparative toxicity cancer (CTU-non-cancer), evaluate the effect of chemicals and pollutants on human health except for cancer. The non-cancer potentials of landfilling and gasification in CTU-non-cancer were 1.41 × 10⁻³ and 4.80 × 10⁻⁵, respectively for urban air, 1.48 × 10⁻³ and 5.03 × 10⁻⁵, respectively for rural air, 1.18 × 10⁻⁴ and 8.55 × 10⁻⁷, respectively for freshwater, 2.79 × 10⁻⁵ and 6.68 × 10⁻⁷, respectively for seawater, 6.45 × 10⁻⁵ and 6.01 × 10⁻⁷, respectively for natural soil, and 4.04 × 10⁻³ and 1.39 × 10⁻⁴, respectively for agricultural soil emission. The total HH non-cancer potential of landfilling was 96.75% higher than that of gasification (Figure 4).

3.2.3. Human Health Cancer Potentials

The human health cancer potential is expressed in comparative toxicity cancer (CTU-cancer). The main source of cancer in both processes was specific metals, such as Cd, Pb, Ni, As and Mercury (Hg) and organic compounds, such as benzene, toluene, dichloromethane, trichloromethane, tetrachloromethane and tetrachloroethene. The total human health cancer potential emission of landfilling was 82.37% higher than that of gasification (Figure 4).
Overall, landfilling has the highest impact on the environment and human health with the following percent contribution: 75.24% for global warming, 94% for acidification, 75.75% for smog formation, 93.3% for eutrophication, 99.9% for ecotoxicity, 82.4 for HH cancer, and 96.7% for HH non-cancer (Figure 4). The conclusions of this study are in agreement with Coventry, Tize and Karunanithi [23] and Dastjerdi, Strezov, Kumar, He and Behnia [20] findings, stipulating that gasification is more favorable to the environment than landfilling. Demetrious and Crossin [21], on the other hand, concluded that mixed paper and mixed plastic landfilling were more favorable than gasification pyrolysis of mixed plastics. The authors conclusions prove that waste composition affects the impact of the waste disposal method on the environment. For example, the LFG generated during plastic landfilling was insignificant due to the material’s slow degradation. Anshassi, et al. [46] also mentioned that waste composition is a considerable factor in the investigation of the impact of waste management techniques on the environment.

4. Opportunity for Improvements in Impacts

The impact of gasification on the environment and human health was mainly due to emissions from conversion of MSW to electricity, electricity from US grid, and solid residue disposal. The landfilling of solid residues from gasification leached metals such as cadmium, nickel, arsenic and lead. In TRACI, these substances resulted in ecotoxicity and human health-related impacts. The ecotoxicity affects drinking water, meat, milk and fish, which could lead to cancer and non-cancer potential [21]. The utilization of solid residues in road construction (asphalt mixture and road filling) and concrete aggregate (bricks and blocks) can reduce metal leaching and hence its impacts [47].

The major issues raised by MSW landfilling were related to the LFG releases into the atmosphere, the odor nuisance, and metals, NH₃-N and NH₄-N from leachate. LFG increased global warming, acidification, ecotoxicity and smog formation potentials, promoting ozone depletion and respiratory illnesses [26]. Proper LFG management through efficient collection and conversion systems (flaring, LFG to heat or electricity) can attenuate their environmental and human health impacts [48]. Leachate, a liquid derived from MSW degradation, releases strong odors and constitute a danger for underground water, aquatic life, soils, crops and animals [49]. Human health is indirectly affected by the ingestion
of polluted goods such as water, fish, meat, milk and agricultural products [26,49]. The leachate management through collection, covered storage, treatment and reutilization (recirculation) is insufficient. Despite the drastic measures put in place to reduce leachate leakage, landfills remain a springboard for groundwater pollution. Hence, gasification is a potential candidate for a clean and environmentally friendly waste treatment method. Table 7 summarizes the cases of impacts and proposed solutions. Both landfilling and gasification have shown environmental and human health concerns. However, gasification is a safer waste treatment method as landfilling presents socio-economic challenges, such as land utilization and pollution, difficult emissions control, costly gas recovery and leachate collection systems, and long lifespan of the site.

Table 7. Impact assessment causes and proposed solutions.

| Causes               | Emission Components | Emission Sources | Most Impactful Process | Effects [26]                                      | Proposed Measures                     |
|----------------------|---------------------|------------------|------------------------|--------------------------------------------------|---------------------------------------|
| Global warming       | CO₂, CH₄, NOₓ, N₂O | Landfilling: landfill gas | Landfilling           | • Earth temperature increases                     | • Covert LFG to power                 |
|                      |                     | Gasification: electricity, thermal conversion |                       | • Global warming                                   | • Use gasification                    |
| Acidification        | NH₃-N, NOₓ and SOₓ  | Landfilling: Leachate and diesel | Landfilling           | • Increases the environment acidity (rain, snow, fog, dust, smoke) | • Reduce ammonia concentration in leachate |
|                      |                     | Gasification: electricity, thermal conversion |                       | • Affects soil concentrations, species, and plant growth | • Gasification                         |
| HH particulate       | NH₃-N, CO, NOₓ, PM2.5, PM10 | Landfilling: Leachate and diesel | Landfilling           | • Respiratory illness                              | • Adopt alternative waste management method: gasification |
|                      |                     | Gasification: electricity, thermal conversion |                       | • Increases mortality rate                         |                                       |
| Eutrophication       | NOₓ, N₂O, NH₄-N, NH₃-N | Landfilling: Leachate and diesel | Landfilling           | • Fast enrichment of ecosystem with nutrients      | • Reduce leachate pollutants concentration |
|                      |                     | Gasification: electricity, thermal conversion |                       | • Promotes growth of undesired species             |                                       |
| Smog formation       | Organic compounds, VOC, CO, NOₓ, CH₄ | Landfilling: LFG and diesel | Landfilling           | • Ozone depletion                                  | • Adopt alternative waste management |
|                      |                     | Gasification: electricity, acetone production |                       | • Respiratory issues: bronchitis, asthma, and emphysema |                                       |
|                      |                     |                                               |                       | • Ecological issues: ecosystem and crop damage   |                                       |
| Ecotoxicity          | Metals and organic compounds | Landfilling: LFG and Leachate | Landfilling           | • Affects drinking water, meat, milk, and fish    | • Reduce leachate pollutants concentration |
|                      |                     | Gasification: Solid residues                  |                       | • Illness related to basic ailments                | • Design lining systems with 100% impermeability |
| Human health non-cancer | Metals             | Landfilling: LFG and Leachate | Landfilling           | • Non-cancer related illness                      | • Adopt alternative waste management |
|                      |                     | Gasification: Solid residues                  |                       |                                                  |                                       |
| Human health cancer  | Cadmium, Lead, Nickel, Arsenic, Mercury, benzene, toluene, trichloromethane, tetrachloromethane, tetrachloroethylene | Landfilling: LFG and Leachate | Landfilling           | • Cancer potentials through inhalation, ingestions of drinking water, produce, meat, milk, and fish | • Design lining systems with 100% impermeability |
|                      |                     | Gasification: Solid residues                  |                       |                                                  |                                       |

5. Conclusions

Life cycle assessment of MSW gasification and MSW landfilling was studied. The life cycle inventory was completed using GREET, LandGEM, HELP, reports and technical journals. The emissions to air and water of both processes were reported. TRACI was used to evaluate the environmental and human health impacts. In terms of environmental impact, the LCA revealed that landfilling led to higher global warming (75.2%), acidification (94%), smog formation (75.75%), eutrophication (93.3%) and ecotoxicity (99.9%) potentials. The organic trace compounds, CH₄, and CO₂ in LFG and NH₃-N, NH₄-N and phosphate in leachate mainly caused the large environmental impact of landfilling. Gasification led to lower impacts in terms of human health particulates, human health cancer and human health non-cancer, compared to landfilling. The organic compounds (LFG) and metals (leachate) produced during MSW landfilling were more toxic to human health than
MSW gasification. Overall, landfilling showed the highest impact on the environment and human health. The LFG and leachate from landfilling are susceptible to cause odor nuisance, cancer, leukemia, and respiratory diseases to residents in the surrounding area.

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