energies

MDPI

Article

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

Angelika Sita Ouedraogo, Robert Scott Frazier and Ajay Kumar *

Biosystems and Agricultural Engineering, Oklahoma State University, 111 Agriculture Hall, Stillwater, OK 74078, USA; angelika.ouedraogo@okstate.edu (A.S.O.); robert.frazier@okstate.edu (R.S.F.)
* Correspondence: ajay.kumar@okstate.edu; Tel.: +1-405-744-5431

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

check for updates

Citation: Ouedraogo, A.S.; Frazier, R.S.; Kumar, A. Comparative Life Cycle Assessment of Gasification and Landfilling for Disposal of Municipal Solid Wastes. *Energies* **2021**, *14*, 7032. https://doi.org/10.3390/en14217032

Academic Editor: Antonis A. Zorpas

Received: 17 September 2021
Accepted: 22 October 2021
Published: 27 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

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, polychrorinated 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 (H_2S), 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 landfilling 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 landfilling 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 landfilling 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 landfilling, 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 landfilling. 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	
5	Freshwater Ecotoxicity Potential for	Urban Air Emissions	Comparative Toxicity Unit eco (CTU-eco)
		Rural Air Emissions	
		Freshwater Emissions	
		Seawater Emissions	
		Natural Soil Emissions	
		Agricultural Soil Emissions	
	Human Health Impact		
6	Human Health Particulate Potential for Air Emissions		PM2.5 equivalent
7	Human Health Cancer Potential for	Urban Air Emissions	Comparative Toxicity Unit cancer (CTU-cancer)
		Rural Air Emissions	
		Freshwater Emissions	
		Seawater Emissions	
		Natural Soil Emissions	
		Agricultural Soil Emissions	
8	Human Health Non-Cancer Potentials for	Urban Air Emissions	Comparative Toxicity non-cancer (CTUnon-cancer)
		Rural Air Emissions	
		Freshwater Emissions	
		Seawater Emissions	
		Natural Soil Emissions	
		Agricultural Soil 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_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.

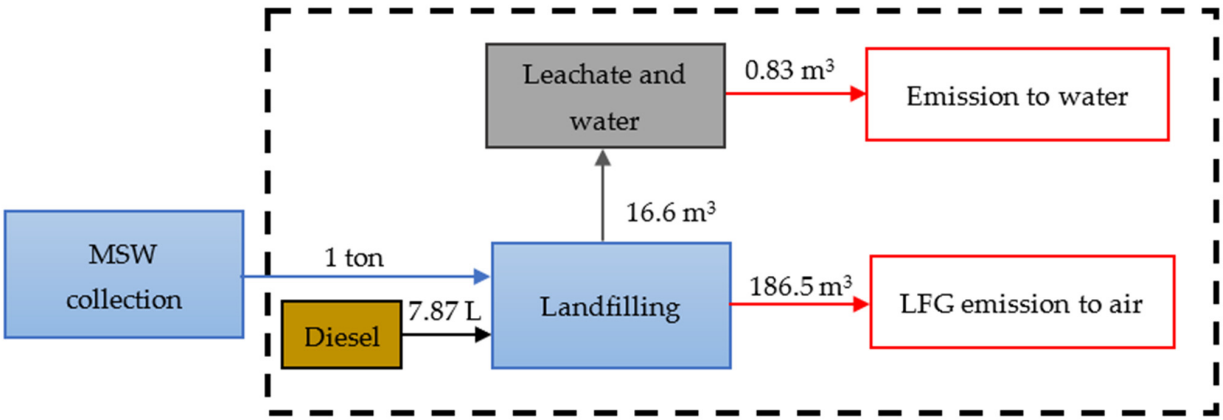


Figure 1. Landfilling process flow diagram.

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^3 of LFG. Figure 2 shows the landfill gases (LFG, CH_4 and CO_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.

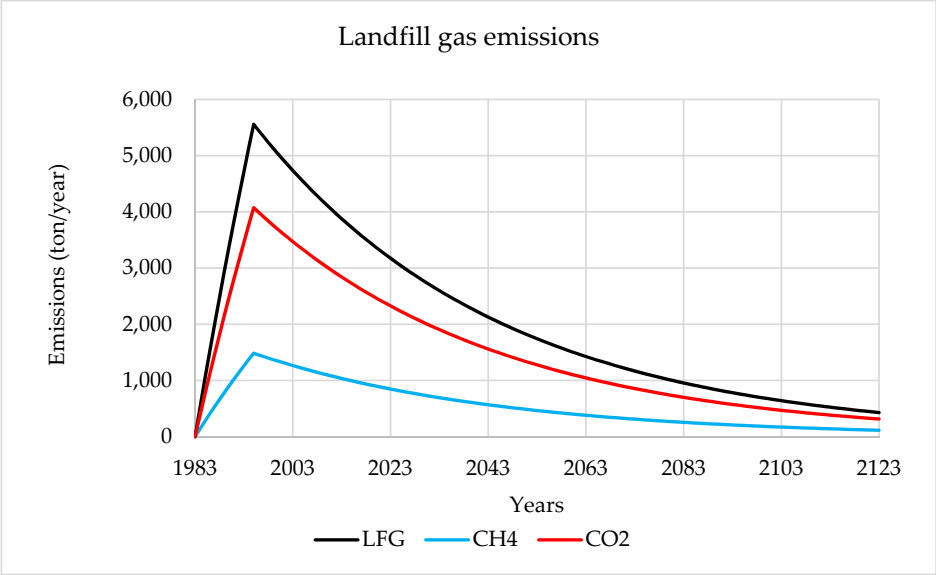


Figure 2. Landfill gas generation using LandGEM.

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	m^3	LandGEM [32]
Methane	61.29	kg	
Carbon dioxide	184.71	kg	
Annual average Leachate generated	0.166	m^3/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].

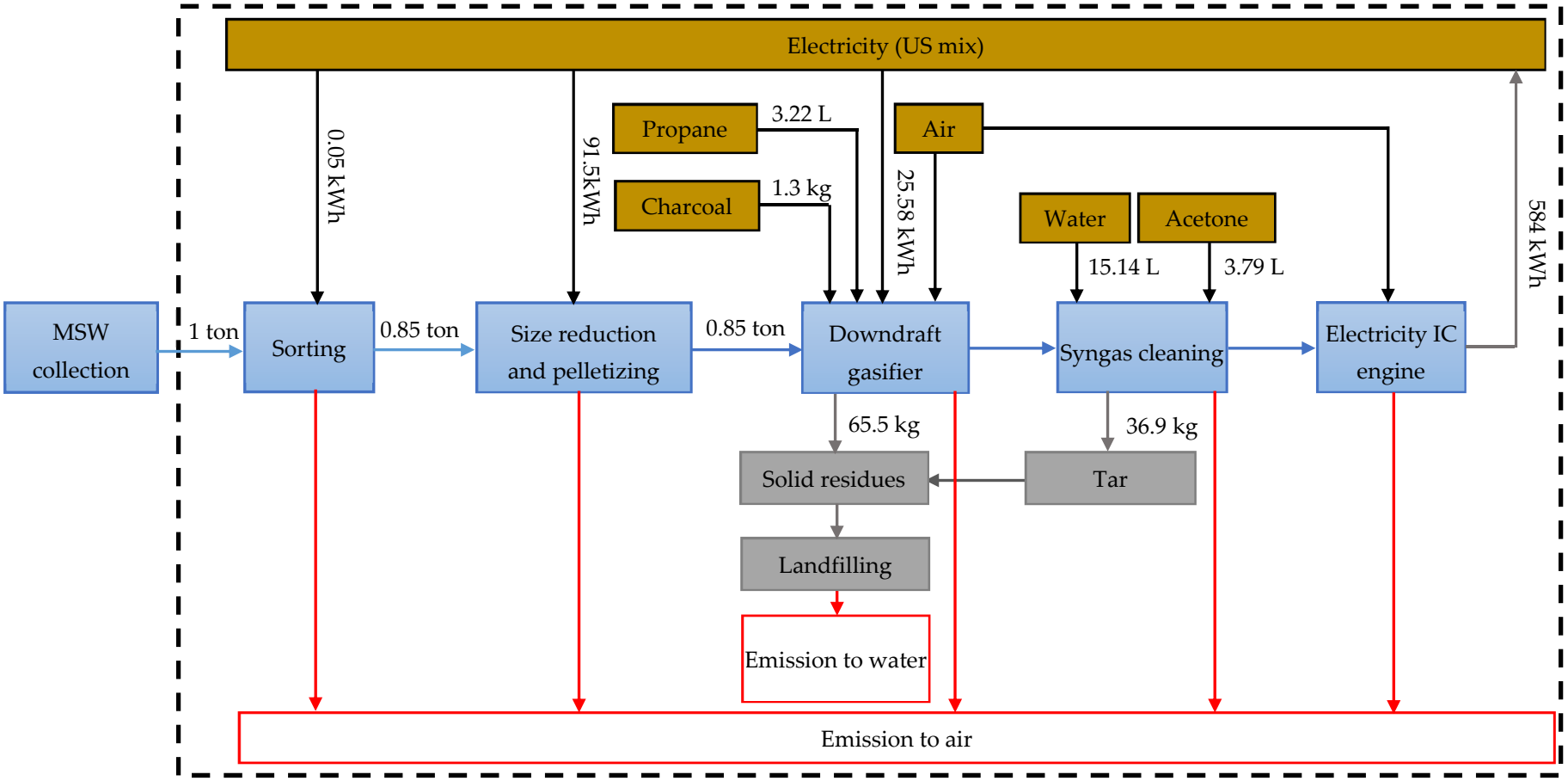


Figure 3. MSW gasification process flow diagram.

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/m^3 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.

Table 3. LCI of MSW gasification per ton of MSW.

	Inventory	Quantity	Unit	References
Inputs	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]
Outputs	Power generated	584.3	kWh	[42]
	Solid residues	102.4	kg	[44]
	Emissions	Table 4	-	GREET

Table 4. Emissions output (in kg) of MSW gasification using GREET.

Emissions	Electricity Consumed	Propane	Charcoal	Acetone	MSW to Electricity [19]	Solid Residues [43]	Total Gasification	Electricity Credit
CO_2 total	4.99×10^{1}	1.64×10^{-2}	6.49×10^{-2}	2.92	7.60×10^{2}		8.13×10^{2}	-2.49×10^{2}
CO_2	5.04×10^{1}	1.65×10^{-2}	6.90×10^{-2}	2.92	-	-	5.34×10^{1}	2.52×10^{2}
CO_2 Biogenic	-5.90×10^{-1}	-2.49×10^{-5}	-3.47×10^{-5}	0.00	-	-	-5.90×10^{-1}	−2.93
VOC	5.88×10^{-3}	8.97×10^{-6}	4.49×10^{-5}	2.96×10^{-3}	-	-	8.89×10^{-3}	-2.93×10^{-2}
CO	1.98×10^{-2}	1.54×10^{-5}	1.80×10^{-4}	3.37×10^{-3}	-	-	2.34×10^{-2}	-9.89×10^{-2}
NOx	3.63×10^{-2}	2.85×10^{-4}	4.50×10^{-4}	6.56×10^{-3}	5.84×10^{-1}	-	6.27×10^{-1}	-1.80×10^{-1}
PM10	5.92×10^{-3}	2.28×10^{-6}	2.53×10^{-5}	1.08×10^{-3}	-	-	7.03×10^{-3}	-2.95×10^{-2}
PM2.5	2.64×10^{-3}	1.93×10^{-6}	2.27×10^{-5}	4.30×10^{-4}	-	-	3.09×10^{-3}	-1.32×10^{-2}
Sox	7.93×10^{-2}	1.07×10^{-5}	1.30×10^{-4}	3.64×10^{-3}	-	-	8.30×10^{-2}	-4.00×10^{-1}
CH_4	8.30×10^{-2}	1.10×10^{-4}	9.50×10^{-5}	6.20×10^{-3}	-	-	8.94×10^{-2}	-4.10×10^{-1}
N_2O	7.80×10^{-4}	2.60×10^{-7}	6.23×10^{-5}	2.17×10^{-3}	-	-	3.01×10^{-3}	-3.87×10^{-3}
BC	2.30×10^{-4}	2.70×10^{-7}	1.34×10^{-5}	5.79×10^{-5}	-	-	3.02×10^{-4}	-1.16×10^{-3}
POC	5.50×10^{-4}	4.50×10^{-7}	4.41×10^{-6}	8.97×10^{-5}	-	-	6.45×10^{-4}	-2.74×10^{-3}
Hydrogen chloride	-	-	-	-	2.73×10^{-2}	-	2.73×10^{-2}	
Hydrogen fluoride	-	-	-	-	2.90×10^{-4}	-	2.90×10^{-4}	-
Mercury	-	-	-	-	5.89×10^{-5}	-	5.89×10^{-5}	-
Dioxins and furans	-	-	-	-	4.09×10^{-11}	-	4.09×10^{-11}	-
Arsenic (As)	-	-	-	-	-	5.59×10^{-7}	5.59×10^{-7}	-
Barium (Ba)	-	-	-	-	-	8.38×10^{-6}	8.38×10^{-6}	-
Calcium (Ca)	-	-	-	-	-	4.19×10^{-2}	4.19×10^{-2}	-
Cadmium (Cd)	-	-	-	-	-	8.38×10^{-8}	8.38×10^{-8}	-
Chlorine (Cl)	-	-	-	-	-	1.63×10^{-1}	1.63×10^{-1}	-
Chromium (Cr)	-	-	-	-	-	8.38×10^{-7}	8.38×10^{-7}	-
Copper (Cu)	-	-	-	-	-	6.05×10^{-5}	6.05×10^{-5}	-
Manganese (Mn)	-	-	-	-	-	1.00×10^{-7}	1.00×10^{-7}	-
Sodium (Na)	-	-	-	-	-	1.79×10^{-1}	1.79×10^{-1}	-
Nickel (Ni)	-	-	-	-	-	8.38×10^{-7}	8.38×10^{-7}	-
Lead (Pb)	-	-	-	-	-	8.38×10^{-7}	8.38×10^{-7}	-
Sulfate (SO4)	-	-	-	-	-	1.30×10^{-1}	1.30×10^{-1}	-
Zinc (Zn)	-	-	-	-	-	1.68×10^{-6}	1.68×10^{-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		1.72×10^3	5.66×10^2	kg CO_2 equivalent
2	Acidification Potential for Air Emission		1.58	1.01×10^{-1}	kg SO_2 equivalent
3	Smog Formation Potential for Air Emissions		4.13×10^1	1.32×10^1	kg O_3 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	Urban Air Emissions	1.82×10^3	2.15	Comparative Toxixity Unit eco (CTU-eco)
		Rural Air Emissions	1.84×10^3	2.18	
		Freshwater Emissions	4.29×10^3	4.74	
		Seawater Emissions	3.03×10^{-3}	9.55×10^{-15}	
		Natural Soil Emissions	2.31×10^3	2.74	
		Agricultural Soil Emissions	2.31×10^3	2.74	

3.1.1. Global Warming Potentials for Air Emissions

Global warming (GW), measured in kg CO_2 equivalent, is related to the temperature rise caused by greenhouse gases such as CO_2, CH_4 and nitrous oxides (N_2O). MSW landfilling emitted 1721 kg CO_2 equivalent, compared to 566.5 kg CO_2 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% CO_2. 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 SO_2 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 SO_2 equivalent) compared to gasification (1.01×10^{-1} kg SO_2

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_2S), 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_2O emissions. The MSW landfilling had more environmental impact in terms of air eutrophication (2.54×10^{-1} kg N equivalent) compared to gasification (1.82×10^{-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 (1.20×10^{-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 (9.55×10^{-15} CTU-eco) were negligible compared to landfilling emissions to freshwater (4287 CTU-eco) and seawater (3×10^{-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 landfilling was very high (total of 4616 CTU-eco) compared to those of gasification (total of 5.47 CTU-eco). The high ecotoxicity of landfilling 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).

Table 6. Human Health Impact.

№	Human Health Impact		Landfilling	Gasification	Unit
1	Human Health Particulate Potential for Air Emissions		5.58×10^{-2}	-1.22×10^{-2}	PM2.5 equivalent
2	Human health Cancer Potential for	Urban Air Emissions	1.99×10^{-6}	4.06×10^{-7}	CTU-cancer
		Rural Air Emissions	1.66×10^{-6}	4.25×10^{-7}	
		Freshwater Emissions	1.28×10^{-6}	7.31×10^{-9}	
		Seawater Emissions	1.32×10^{-7}	5.65×10^{-9}	
		Natural Soil Emissions	6.57×10^{-7}	5.12×10^{-9}	
		Agricultural Soil Emissions	3.75×10^{-6}	1.18×10^{-6}	
3	Human health Non-Cancer Potential for	Urban Air Emissions	1.41×10^{-3}	4.80×10^{-5}	CTUnon-cancer
		Rural Air Emissions	1.48×10^{-3}	5.03×10^{-5}	
		Freshwater Emissions	1.18×10^{-4}	8.55×10^{-7}	
		Seawater Emissions	2.79×10^{-5}	6.68×10^{-7}	
		Natural Soil Emissions	6.45×10^{-5}	6.01×10^{-7}	
		Agricultural Soil Emissions	4.04×10^{-3}	1.39×10^{-4}	

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 NH_3-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 (CTUnon-cancer), evaluate the effect of chemicals and pollutants on human health except for cancer. The non-cancer potentials of landfilling and gasification in CTUnon-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).

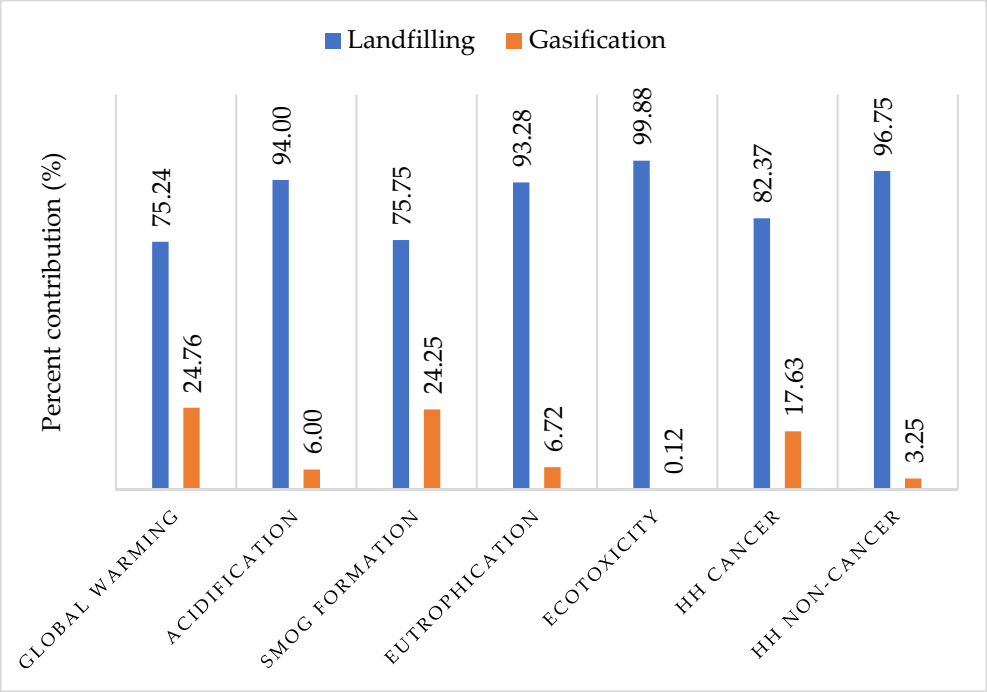


Figure 4. Comparative impact assessment of MSW gasification and landfilling.

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, NH_3-N and NH_4-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			Most Impactful Process	Effects [26]	Proposed Measures
Impacts	**Emission Components**	**Emission Sources**			
Global warming	CO_2, CH_4, NOx, N_2O	Landfilling: landfill gas Gasification: electricity, thermal conversion	Landfilling	• Earth temperature increases • Global warming	• Covert LFG to power • Use gasification
Acidification	NH_3-N, NOx and SOx	Landfilling: Leachate and diesel Gasification: electricity, thermal conversion	Landfilling	• Increases the environment acidity (rain, snow, fog, dust, smoke) • Affects soil concentrations, species, and plant growth	• Reduce ammonia concentration in leachate • Gasification
HH particulate	NH_3-N, CO, NOx, PM2.5, PM10	Landfilling: Leachate and diesel Gasification: electricity, thermal conversion	Landfilling	• Respiratory illness • Increases mortality rate	• Adopt alternative waste management method: gasification
Eutrophication	NOx, N_2O, NH_4-N, NH_3-N	Landfilling: Leachate and diesel Gasification: electricity, thermal conversion	Landfilling	• Fast enrichment of ecosystem with nutrients • Promotes growth of undesired species	• Reduce leachate pollutants concentration
Smog formation	Organic compounds, VOC, CO, NOx, CH_4	Landfilling: LFG and diesel Gasification: electricity, acetone production	Landfilling	• Ozone depletion • Respiratory issues: bronchitis, asthma, and emphysema • Ecological issues: ecosystem and crop damage	• Adopt alternative waste management
Ecotoxicity	Metals and organic compounds	Landfilling: LFG and Leachate Gasification: Solid residues	Landfilling	• Affects drinking water, meat, milk, and fish • Illness related to basic aliments	• Reduce leachate pollutants concentration • Design lining systems with 100% impermeability • Adopt alternative waste management
Human health non-cancer	Metals	Landfilling: LFG and Leachate Gasification: Solid residues	Landfilling	• Non-cancer related illness	
Human health cancer	Cadmium, Lead, Nickel, Arsenic, Mercury, benzene, toluene, trichloromethane, tetrachloromethane, tetrachloroethene	Landfilling: LFG and Leachate Gasification: Solid residues	Landfilling	• Cancer potentials through inhalation, ingestions of drinking water, produce, meat, milk, and fish	

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, CH_4, and CO_2 in LFG and NH_3-N, NH_4-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.

Author Contributions: Conceptualization, A.S.O., R.S.F. and A.K.; methodology, A.S.O.; software, A.S.O.; validation, R.S.F., and A.K.; formal analysis, A.S.O.; investigation, A.S.O.; resources, A.K. and R.S.F.; data curation, A.S.O.; writing—original draft preparation, A.S.O.; writing—review and editing, A.K., and R.S.F.; visualization, A.S.O., R.S.F. and A.K.; supervision, A.K. and R.S.F.; project administration, A.K..; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded in part by the OSU Research Foundation, Oklahoma Agricultural Experiment Station, and the USDA National Institute of Food and Agriculture, Hatch project 1019511.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: This work was supported, in part, by the OSU Research Foundation and Oklahoma Agricultural Experiment Station.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. US Environmental Protection Agency. *Report on the Environment*; EPA: Washington, DC, USA, 2018.
2. US Environmental Protection Agency. *National Overview: Facts and Figures about Materials, Waste and Recycling*; EPA: Washington, DC, USA, 2021.
3. Palmiotto, M.; Fattore, E.; Paiano, V.; Celeste, G.; Colombo, A.; Davoli, E. Influence of a municipal solid waste landfill in the surrounding environment: Toxicological risk and odor nuisance effects. *Environ. Int.* **2014**, *68*, 16–24. [CrossRef] [PubMed]
4. Wilbur, S.B.; Keith, S.M.S.; Faroon, O.; Wohlers, D. *Toxicological Profile for Benzene*; Centers for Disease Control and Prevention: Atlanta, GA, USA, 2007.
5. Gehle, K. *Toxicity of Polycyclic Aromatic Hydrocarbons (PAHs)*; Centers for Disease Control and Prevention: Atlanta, GA, USA, 2009.
6. Feron, V.; Hendriksen, C.; Speek, A.; Til, H.; Spit, B. Lifespan oral toxicity study of vinyl chloride in rats. *Food Chem. Toxicol.* **1981**, *19*, 317–333. [CrossRef]
7. Til, H.; Feron, V.; Immel, H. Lifetime (149-week) oral carcinogenicity study of vinyl chloride in rats. *Food Chem. Toxicol.* **1991**, *29*, 713–718. [CrossRef]
8. Mataloni, F.; Badaloni, C.; Golini, M.N.; Bolignano, A.; Bucci, S.; Sozzi, R.; Forastiere, F.; Davoli, M.; Ancona, C. Morbidity and mortality of people who live close to municipal waste landfills: A multisite cohort study. *Int. J. Epidemiol.* **2016**, *45*, 806–815. [CrossRef]
9. Vinti, G.; Bauza, V.; Clasen, T.; Medlicott, K.; Tudor, T.; Zurbrügg, C.; Vaccari, M. Municipal Solid Waste Management and Adverse Health Outcomes: A Systematic Review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4331. [CrossRef]
10. Heaney, C.D.; Wing, S.; Campbell, R.L.; Caldwell, D.; Hopkins, B.; Richardson, D.; Yeatts, K. Relation between malodor, ambient hydrogen sulfide, and health in a community bordering a landfill. *Environ. Res.* **2011**, *111*, 847–852. [CrossRef]
11. Palmer, S.R.; Dunstan, F.D.; Fielder, H.; Fone, D.L.; Higgs, G.; Senior, M.L. Risk of congenital anomalies after the opening of landfill sites. *Environ. Health Perspect.* **2005**, *113*, 1362–1365. [CrossRef] [PubMed]
12. Indrawan, N.; Thapa, S.; Bhoi, P.R.; Huhnke, R.L.; Kumar, A. Electricity power generation from co-gasification of municipal solid wastes and biomass: Generation and emission performance. *Energy* **2018**, *162*, 764–775. [CrossRef]
13. Gang, X.; Jin, B.-S.; Zhong, Z.-P.; Yong, C.; Ni, M.-J.; Cen, K.-F.; Rui, X.; Huang, Y.-J.; Huang, H. Experimental study on MSW gasification and melting technology. *J. Environ. Sci.* **2007**, *19*, 1398–1403. [CrossRef]
14. Panepinto, D.; Tedesco, V.; Brizio, E.; Genon, G. Environmental performances and energy efficiency for MSW gasification treatment. *Waste Biomass Valorization* **2015**, *6*, 123–135. [CrossRef]
15. Kumar, A.; Jones, D.D.; Hanna, M.A. Thermochemical biomass gasification: A review of the current status of the technology. *Energies* **2009**, *2*, 556–581. [CrossRef]
16. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]
17. Nabavi-Pelesaraei, A.; Kaab, A.; Hosseini-Fashami, F.; Mostashari-Rad, F.; Chau, K.-W. Life Cycle Assessment (LCA) approach to evaluate different waste management opportunities. In *Advances in Waste-to-Energy Technologies*, 1st ed.; Taylor & Francis Group: London, UK, 2019; pp. 195–216.
18. International Organization for Standardization. *Environmental Management: Life Cycle Assessment; Principles and Framework*; ISO: Geneva, Switzerland, 2006; Volume ISO 14044, p. 20.

19. Zaman, A.U. Comparative study of municipal solid waste treatment technologies using life cycle assessment method. *Int. J. Environ. Sci. Technol.* **2010**, *7*, 225–234. [CrossRef]
20. Dastjerdi, B.; Strezov, V.; Kumar, R.; He, J.; Behnia, M. Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia. *Sci. Total Environ.* **2021**, *767*, 144355. [CrossRef]
21. Demetrious, A.; Crossin, E. Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 850–860. [CrossRef]
22. Evangelisti, S.; Tagliaferri, C.; Clift, R.; Lettieri, P.; Taylor, R.; Chapman, C. Life cycle assessment of conventional and two-stage advanced energy-from-waste technologies for municipal solid waste treatment. *J. Clean. Prod.* **2015**, *100*, 212–223. [CrossRef]
23. Coventry, Z.A.; Tize, R.; Karunanithi, A. Comparative life cycle assessment of solid waste management strategies. *Clean Technol. Environ. Policy* **2016**, *18*, 1515–1524. [CrossRef]
24. US Environmental Protection Agency. *Landfill Methane Outreach Program (LMOP): Landfill Technical Data*; EPA: Washington, DC, USA, 2021.
25. Argonne National Laboratory. *Energy Systems*; US Department of Energy: Argonne, IL, USA, 2021.
26. Bare, J.; Young, D.; Qam, S.; Hopton, M.; Chief, S.A.B. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*; US Environmental Protection Agency: Washington, DC, USA, 2012.
27. US Environmental Protection Agency. *LMOP: Basic Information about Landfill Gas*; EPA: Washington, DC, USA, 2021.
28. Bhoi, P.; Ouedraogo, A.; Soloiu, V.; Quirino, R. Recent advances on catalysts for improving hydrocarbon compounds in bio-oil of biomass catalytic pyrolysis. *Renew. Sustain. Energy Rev.* **2020**, *121*, 109676. [CrossRef]
29. US Environmental Protection Agency. *Characterization of MWC Ashes and Leachates from MSW Landfills, Monofills, and Co-Disposal Sites*; EPA: Washington, DC, USA, 1987.
30. US Environmental Protection Agency. *Municipal Solid Wate Landfills*; EPA: Washington, DC, USA, 2021.
31. Paladino, O.; Massabò, M. Health risk assessment as an approach to manage an old landfill and to propose integrated solid waste treatment: A case study in Italy. *Waste Manag.* **2017**, *68*, 344–354. [CrossRef]
32. Pelt, R.; White, C.; Blackard, A.; Bass, R.L.; Burklin, C.; Heaton, R.E.; Reisdorph, A.; Thorneloe, S.A. *User's Manual Landfill Gas Emissions Model-Version 2.0*; US Environmental Protection Agency: Washignton, DC, USA, 1998; p. 94.
33. US Environmental Protection Agency. *Hydrologic Evaluation of Landfill Performence: HELP 4.0 User Manual*; EPA: Washington, DC, USA, 2020.
34. Caterpillar. Caterpillar Equipment Selection and Application Guide. Caterpilar: Deerfield, IL, USA, 2008; p. 37.
35. Lambertson, G. *Industry Begins Grappling With Rising Fuel Costs*; ContructionEquipmentGuide.Com: Fort Washington, PA, USA, 2006.
36. Yay, A.S.E. Application of life cycle assessment (LCA) for municipal solid waste management: A case study of Sakarya. *J. Clean. Prod.* **2015**, *94*, 284–293. [CrossRef]
37. Khoo, H.H. Life cycle impact assessment of various waste conversion technologies. *Waste Manag.* **2009**, *29*, 1892–1900. [CrossRef] [PubMed]
38. Bhoi, P.R.; Huhnke, R.L.; Kumar, A.; Thapa, S.; Indrawan, N. Scale-up of a downdraft gasifier system for commercial scale mobile power generation. *Renew. Energy* **2018**, *118*, 25–33. [CrossRef]
39. Indrawan, N.; Simkins, B.; Kumar, A.; Huhnke, R.L. Economics of distributed power generation via gasification of biomass and municipal solid waste. *Energies* **2020**, *13*, 3703. [CrossRef]
40. Milne, T.A.; Evans, R.J.; Abatzaglou, N. *Biomass Gasifier"tars": Their Nature, Formation, and Conversion*; US Department of Energy: Oak Ridge, TN, USA, 1998.
41. Indrawan, N.; Thapa, S.; Bhoi, P.R.; Huhnke, R.L.; Kumar, A. Engine power generation and emission performance of syngas generated from low-density biomass. *Energy Convers. Manag.* **2017**, *148*, 593–603. [CrossRef]
42. Zaman, A.U. Life cycle assessment of pyrolysis–gasification as an emerging municipal solid waste treatment technology. *Int. J. Environ. Sci. Technol.* **2013**, *10*, 1029–1038. [CrossRef]
43. Birgisdottir, H.; Bhander, G.; Hauschild, M.Z.; Christensen, T.H. Life cycle assessment of disposal of residues from municipal solid waste incineration: Recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. *Waste Manag.* **2007**, *27*, S75–S84. [CrossRef]
44. Gladding, T.; Thurgood, M. *Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes*; Department for Environment, Food and Rural Affairs: London, UK, 2004.
45. Leme, M.M.V.; Rocha, M.H.; Lora, E.E.S.; Venturini, O.J.; Lopes, B.M.; Ferreira, C.H. Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. *Resour. Conserv. Recycl.* **2014**, *87*, 8–20. [CrossRef]
46. Anshassi, M.; Sackles, H.; Townsend, T.G. A review of LCA assumptions impacting whether landfilling or incineration results in less greenhouse gas emissions. *Resour. Conserv. Recycl.* **2021**, *174*, 105810. [CrossRef]
47. Sakai, S.-I.; Hiraoka, M. Municipal solid waste incinerator residue recycling by thermal processes. *Waste Manag.* **2000**, *20*, 249–258. [CrossRef]
48. Damgaard, A.; Manfredi, S.; Merrild, H.; Stensøe, S.; Christensen, T.H. LCA and economic evaluation of landfill leachate and gas technologies. *Waste Manag.* **2011**, *31*, 1532–1541. [CrossRef]
49. Sriuttha, M.; Tengjaroenkul, B.; Intamat, S.; Phoonaploy, U.; Thanomsangad, P.; Neeratanaphan, L. Cadmium, chromium, and lead accumulation in aquatic plants and animals near a municipal landfill. *Hum. Ecol. Risk Assess. Int. J.* **2017**, *23*, 350–363. [CrossRef]