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Life Cycle Assessment of Methanol Production from Municipal Solid Waste: Environmental Comparison with Landfilling and Incineration

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Abstract: Inadequate waste management strategies play a significant role in exacerbating environmental challenges, such as increased greenhouse gas emissions, resource depletion, and other adverse ecological impacts. These issues are aggravated by the global rise in municipal solid waste (MSW) generation, surpassing the rate of population growth. Simultaneously, there is an urgent demand for sustainable energy solutions to combat climate change and its wide-ranging impacts. In response, this study addresses a critical question: is methanol production from MSW, a waste-to-chemical (WtC) alternative based on circular economy principles, a more environmentally sustainable approach compared to traditional waste-to-energy (WtE) methods like landfilling with biogas recovery and incineration? To answer this, this study evaluates the environmental performance of MSW-to-methanol technologies using life cycle assessment (LCA), focusing on key indicators such as global warming potential, resource depletion, and impacts on human health and ecosystem quality. The results reveal that methanol production from MSW significantly reduces global warming potential (GWP) by 87% compared to landfilling and 56% compared to incineration. Additionally, the process demonstrates high energy efficiency in electricity generation, achieving 80% of the output of incineration. These findings position MSW-to-methanol as a promising alternative for advancing sustainable waste management and renewable energy transitions. While the technology is still in its developmental stages, this research highlights the need for further advancements and policy support to enhance feasibility and scalability. By providing a comparative environmental analysis, this study contributes to identifying innovative pathways for addressing pressing waste management and energy sustainability challenges.

Keywords: circular economy; biomethanol; refuse-derived fuel (RDF); waste management; waste-to-energy

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1. Introduction

The proper disposal of MSW has been an issue of concern for large cities worldwide due to the large per capita volume generated and the increase in the waste generation rate. It is estimated that by 2050, Brazil will see an increase of almost 50% in the amount of MSW compared to the base year of 2019 [1]. For the same period, the population growth projection is 12% [2]. The inadequate disposal in many Brazilian cities aggravates this scenario. According to an ISWA Report [3], MSW generation is expected to increase worldwide under the usual scenario, from around 2 billion tons/year generated in 2016 to 3.4 billion tons in 2050.

Brazil generates approximately 78 million tons of MSW annually, with a per capita generation rate of 380 kg/person/year. Approximately 38.9% of this waste is inadequately disposed of, including in open dumps and non-compliant landfills that fail to meet regulatory standards for air and soil protection. The remaining waste is deposited in sanitary landfills [4]. While considered a better alternative disposal for MSW in Brazil, landfills pose significant environmental and health challenges. In the short term, landfills release toxic gases and odors, negatively affecting air quality and exposing nearby communities to health risks. In the long term, they contribute to broader environmental problems such as smog, acid rain, and methane emissions. Methane, responsible for about one third of global warming caused by greenhouse gases, is of particular concern. Recent satellite-based studies suggest that uncontrolled methane emissions from landfills are severely underestimated, often exceeding reported figures by up to 200% [5]. These findings underscore the urgent need for enhanced monitoring and mitigation technologies to address landfills' climate impacts.

Beyond air pollution, landfills also threaten soil and water systems. Leachate, the liquid byproduct waste decomposition, often contains toxic substances, heavy metals, and organic pollutants, contaminating groundwater and surrounding ecosystems [6]. Additionally, landfills are emerging as reservoirs of microplastics, which leach into the environment, with potential implications for biodiversity and human health [7].

Despite these challenges, adoption of waste-to-energy (WtE) incineration technologies in Brazil remains limited, particularly compared to countries like Japan and the European Union, where such technologies are well established. In Brazil, incineration primarily targets hazardous and medical waste, with negligible application to MSW [4]. However, studies estimate an economically viable potential of 4.43 TWh/year for energy recovery from MSW [8]. Environmental analyses, including LCAs, suggest that incineration offers significant advantages over landfilling by reducing waste volume and greenhouse gas emissions [9]. Nevertheless, widespread implementation is hindered by challenges such as high initial investment costs, lenient regulatory standards compared to developed nations, and public skepticism about incineration's environmental safety [10].

One promising alternative is the production of methanol from MSW via refuse-derived fuel (RDF) gasification. Methanol is an essential component of Brazil's biodiesel industry, yet it is largely imported and derived from fossil-based feedstocks, contributing to carbon emissions and dependence on external sources. By producing renewable methanol from sustainable materials like MSW, Brazil could reduce both its biodiesel carbon footprint and reliance on imports, supporting its renewable energy goals. However, there is a notable lack of studies comparing the environmental impacts of methanol production from MSW with those of traditional methods such as landfilling and incineration.

Biomethanol produced from MSW is particularly relevant in the context of the urgent need to explore more sustainable alternatives for the global energy matrix, addressing both climate change and the need to preserve land for food production and natural ecosystem biodiversity. A 2022 report by the International Renewable Energy Agency (IRENA) underscores that bioenergy constitutes two-thirds of global renewable energy consumption and 12% of final energy consumption, reaching 25% of total primary energy availability by 2050 [11]. However, achieving this requires an increased share of new bioenergy sources by 2030, with a focus on biomass and biogas for electricity, as well as biomethane and liquid biofuels for transportation. While the global share of bioenergy has been rising, it is still growing at a rate insufficient to heavily contribute to meet the goal of zero net carbon emissions and limiting global warming to 1.5 °C. According to [12], in an ideal scenario, it would be possible to produce twenty-one times the current primary bioenergy supply and even to supply all global primary energy demand in 2050, primarily using energy crops.

The land use issue for biofuel production has been a focal point of recent discussions, eliciting criticism regarding bioenergy sustainability, especially concerning competition with food production [13]. This underscores the importance of valorizing and improving techniques for utilizing sustainable bioenergy sources, including MSW [14]. In this context, the Brazilian government has been investing in renewable energy through initiatives such as the National Program for Biodiesel Production and Use (PNPB), established in 2005, which mandates progressively increasing percentages of biodiesel to be blended with diesel oil over the years. Renewables comprised almost half (46%) of Brazil's total energy supply in 2019. Around 70% of the renewable energy supply is from biomass [15,16].

Methanol is a critical component in biodiesel production through its use in transesterification. Brazil, renowned for its robust ethanol industry and significant biodiesel production, has emerged as the third world's largest biodiesel producer via the methyl route [17]. This position has made Brazil an essential player in the global methanol market. However, despite being a significant consumer, Brazil does not produce methanol domestically. Since 2016, the country has relied entirely on imports to meet its substantial methanol demand, with Trinidad and Tobago, Chile, and Venezuela being the primary sources [18]. According to a report by ChemAnalyst [19], Brazil's methanol demand was approximately 730.22 thousand tons in 2020. This demand is projected to increase significantly, reaching an estimated 1112.3 thousand tons by 2030.

Global methanol production is primarily dependent on fossil fuels. Methanol is typically produced through a catalytic process that utilizes fossil feedstocks, such as natural gas or coal. This reliance on fossil fuels for methanol production raises sustainability concerns, particularly in biodiesel production. The IRENA and the Methanol Institute [20] highlight the potential of renewable methanol as a low-carbon and net-carbon-neutral liquid chemical and fuel. Produced from sustainable biomass or captured carbon dioxide and hydrogen from renewable electricity, renewable methanol could significantly reduce fossil fuel use and greenhouse gas emissions compared to conventional methanol production.

It is estimated that, on average, each cubic meter of biodiesel produced requires approximately 115 L of methanol [21]. Thus, considering solely the demand for biodiesel production in the Brazilian market, the methanol market could reach around 500,000 cubic meters per year, assuming the growth in the transportation sector (increased diesel consumption and an expansion of the biodiesel percentage on diesel). The Fuel of the Future Law, recently enacted in Brazil increases the limits for blending biodiesel, with biodiesel accounting for 15% of diesel oil in 2025 and 20% in 2030. The law also increases the margin for blending ethanol into gasoline from 22% to 27%, with the possibility of reaching 35%. The blend can reach 27.5%, with at least 18% ethanol. For biodiesel, which has been blended with fossil diesel at a 14% rate since March 2024, the law mandates an annual increase of one percentage point in blending until it reaches 20% in March 2030. Additionally, the law creates national programs for sustainable aviation fuel (SAF), green diesel, and biomethane [22].

Beyond raw materials, it is well established that utilizing energy from renewable sources enhances the environmental profile of the final product. In a study by Chen et al. [23] assessing three methanol production routes in China using coal, coke oven gas (COG), and natural gas, the authors found significant environmental impacts, with electricity consumption being the most sensitive parameter. When reassessed under a scenario of 100% renewable energy production, there was an 82.2%, 66.5%, and 83.5%

reduction in impacts for the three routes, respectively. The study concluded that clean energy adoption can bring substantial benefits for sustainable development, particularly in regions abundant in renewable energy, such as South America. Given its predominantly hydropower-based electricity generation matrix, Brazil has a competitive advantage in environmentally sound fuel production.

Dong et al. [24] assessed air emissions across three waste-to-energy (WtE) distinct scenarios: (i) a gasification-based plant in Finland, (ii) mechanical grate incineration in France, and (iii) circulating fluidized bed incineration in China. The findings revealed that the gasification system exhibits superior overall environmental performance compared to incineration. Notably, the parameters with the most substantial influence on LCA results include electricity recovery, CO_2 emission, and NO_x emission.

Similarly, Jeswani & Azapagic [25] juxtaposed the impacts of incineration with landfill biogas recovery in the UK, evaluating scenarios with both electricity production and co-generation of heat and electricity. The assessment, based on the life cycle of two functional units (disposal of 1 ton of MSW and generation of 1 kWh of electricity), concluded that incineration energy, when credited for recovered electricity and recyclable materials, exhibits lower environmental impacts than landfill biogas in all categories except for human toxicity.

Afzal et al. [26] explore the conversion of mixed plastic waste (MPW) into synthesis gas (syngas). They provide a techno-economic analysis and LCA for two gasification pathways generating methanol and hydrogen from MPW. The findings reveal a minimum selling price (MSP) of USD 0.70/kg for methanol and USD 3.41/kg for hydrogen. Despite achieving significant reductions (52% for methanol and 56% for hydrogen) in total supply chain energy use compared to fossil-fuel-derived pathways, GHG from MPW gasification is projected to increase by 166% and 36% for methanol and hydrogen, respectively, in contrast to current production methods. The article highlights syngas yield and waste plastic feedstock price as pivotal factors influencing the MSP in MPW gasification processes.

Liu et al. [27] observed a 30% reduction in total potential environmental impact associated with carbon dioxide capture when analyzing municipal solid waste incineration methods in China. Zaman [28] compared MSW disposal scenarios, favoring gasification over landfill and incineration regarding the impacts of global warming potential (GWP).

Leme et al. [9] conducted an LCA to compare incineration with landfills (both with and without energy recovery) in a case study. The authors concluded that incineration is more environmentally advantageous than landfills in all aspects except for human toxicity potential. Cherubini et al. [29] also conducted a life cycle analysis and classified landfills as the worst environmental option for MSW disposal.

Brazil's historical reliance on open dumps and improper waste disposal methods has led to significant environmental and public health challenges. While there has been progress, including improved waste collection rates and a reduction in open dumps, landfilling remains the primary environmentally sound disposal method in the country. WtE incineration, however, is increasingly being considered as a viable alternative to reduce waste volume and generate energy, particularly as Brazil works to transition toward a circular economy [30]. At the same time, methanol production from MSW RDF gasification presents a promising alternative to conventional waste management practices, as it is a vital component for Brazil's biodiesel industry, which is currently imported and produced from fossil feedstocks, leading to carbon emissions and reliance on foreign sources.

The objective of this study is to evaluate the environmental impacts of methanol production from MSW using LCA, focusing on key indicators such as global warming potential, resource depletion, human health and ecosystem quality. By analyzing MSW-to-methanol technologies, a waste-to-chemical (WtC) approach grounded in circular economy principles, this research seeks to determine its environmental performance relative to traditional WtE management methods, including incineration and landfill with biogas recovery. This comparative analysis aims aim to provide critical insights to support Brazil's transition toward sustainable waste management and renewable energy systems.

This paper advances waste management science by evaluating the utilization of MSW for energy generation and biofuel production through WtE and WtC processes. These approaches are particularly relevant to addressing contemporary global environmental challenges, as they prioritize efficient energy conversion from waste while minimizing associated environmental impacts. Technologically, the research highlights the potential of innovative waste valorization pathways, such as methanol production and its subsequent conversion to electricity, positioning them as sustainable alternatives to traditional practices like incineration. Notably, the study introduces a novel approach by assessing the use of methanol in engines for power generation, emphasizing its environmental benefits and energy efficiency.

This analysis tackles critical issues, including greenhouse gas emissions, fossil resource depletion, and energy recovery, while identifying key opportunities for advancements in waste-to-energy systems. By challenging conventional waste disposal practices in Brazil, particularly landfilling, and exploring alternative destinations for MSW, the study offers a valuable framework for policymakers, researchers, and industry stakeholders. Its insights aim to optimize waste management practices and significantly reduce environmental impacts on a global scale.

2. Methodology

The LCA methodology was chosen to achieve the study's objectives, as it provides a robust and systematic framework for evaluating the environmental impacts of waste management options across diverse contexts [31]. To address the paper's goals, three municipal solid waste (MSW) disposal alternatives in the Brazilian context are assessed: landfilling with biogas recovery (S1), incineration with energy recovery (S2), RDF gasification for methanol production (S3A), and methanol-to-electricity (S3B). LCA comprehensively compares these scenarios by analyzing key environmental indicators, including greenhouse gas emissions, energy consumption, resource utilization, and other ecological effects. This approach allows for an in-depth understanding of each disposal method's environmental benefits and trade-offs, such as the mitigation of methane emissions from landfills, the reduction of air pollution from incineration, and the decreased reliance on fossil fuels for biomethanol production.

The decision to evaluate these scenarios was based on the relevance and applicability of each option within the Brazilian context. Landfilling was chosen because it remains the most common waste management method in Brazil, despite its environmental challenges. WtE incineration was included as it is the most widely adopted WtE technology globally, and there is ongoing discussion in Brazil about its potential for large-scale implementation. Lastly, RDF gasification for methanol production was selected due to its promising nature (being implemented in few pilot and industrial plants in different countries), as an alternative waste management solution, particularly given Brazil's need for methanol as a key fuel for biodiesel production. This scenario also addresses the country's growing interest in sustainable energy solutions and the potential for reducing fossil fuel dependency. By comparing these three alternatives, the study aims to provide a comprehensive analysis of the environmental impacts and offer insights into waste management strategies.

2.1. Goal and Scope Definition

This paper aims to evaluate and compare the environmental impacts of three MSW disposal alternatives—landfill, incineration, and RDF/methanol production—to identify each solution's most significant environmental aspects. The assessed systems are designed to manage one ton of MSW, involving generating electricity and methanol as the final output products for the technosphere.

The selected methodology adheres to a gate-to-grave approach, involving the analysis from the waste's entry into the treatment system (post-collection) to its ultimate disposal.

For all scenarios, the distances from the MSW collection and transportation points to the landfill, incineration plant, and RDF/methanol production plant are assumed to be identical. Consequently, fuel consumption and air emissions associated with waste transportation to the sites are considered the same for all three alternatives and can thus be excluded from the inventory. This assumption is made to enhance the generalizability of this work, broadening its potential application to diverse cases and studies.

In Scenario 3, concerning the transportation of recyclable waste to respective recycling plants, a fixed distance of 100 km from the RDF plant to each recycling plant (glass, aluminum, and steel) was defined. It is also assumed that the methanol production plant is adjacent to the RDF production plant, thereby excluding the impacts related to the transportation of materials between these facilities. The scenarios under evaluation are depicted in Figure 1 below.

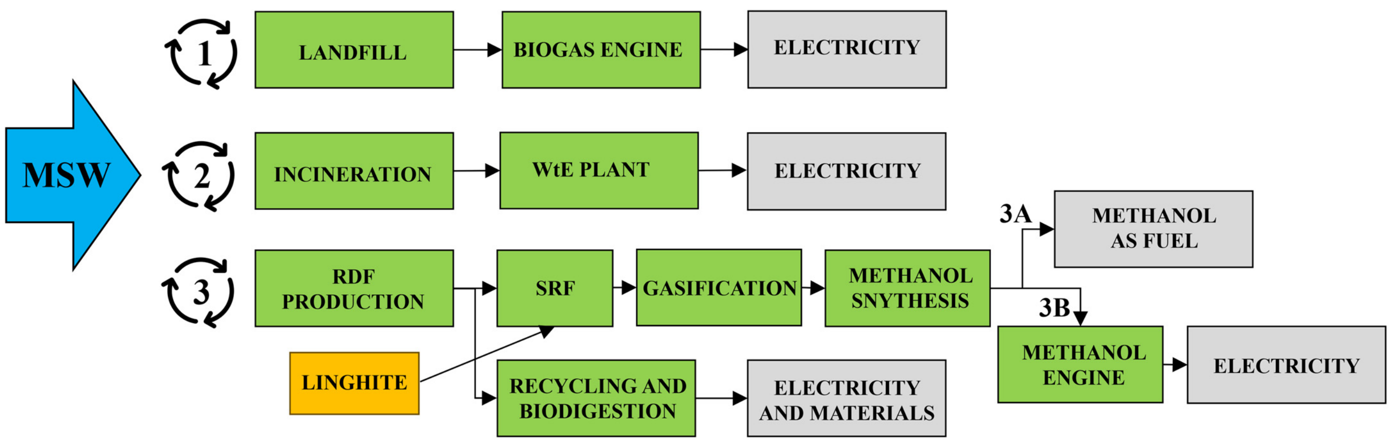

Figure 1. MSW disposal scenarios.

The assessment does not consider the environmental burdens of producing and consuming goods that lead to MSW generation. However, since the carbon present in MSW is composed of a mix of fossil and biogenic sources, the emitted CO_2 from MSW processing should be classified as either biogenic or fossil to ensure an accurate evaluation of its environmental impact.

The infrastructure for transport, handling equipment, and processing plants is also neglected in the assessment. This omission is justified by the consideration that these components involve long-lived assets, and their inclusion would introduce intangible variables into the analysis that are not considered in the current evaluation.

Electricity and methanol production will be evaluated using an LCA substitution approach to avoid allocation. The produced electricity will replace the Brazilian grid electricity, while the produced methanol will substitute the commonly imported methanol used in Brazil.

The environmental impact assessment was conducted through the utilization of SimaPro® v. 9.5 (Pré-Sustainability B.V, Utrcht, The Netherlands.) software the Ecoinvent database and the ReCiPe Midpoint H method applied to assess midpoint impacts. As emphasized by [32,33], this method has consistently yielded positive results in evaluations involving solid waste and has found widespread application among researchers conducting LCAs related to MSW disposal. Notable examples include studies by [34–36], all of whom employed the ReCiPe method to compare various MSW management options. A detailed explanation of the LCIA RECIPE method can be found in [37].

This study adhered to the ISO 14044 [38] guidelines for classifying, characterizing, and normalizing the LCI results. The characterization phase of this study encompassed 18 midpoint impact categories: global warming (GW), stratospheric ozone depletion (OD), ionizing radiation (IR), fine particulate matter formation (FPMF), ozone formation affecting human health (OF-H), ozone formation affecting terrestrial ecosystems (OF-T), terrestrial acidification (TA), freshwater eutrophication (EUT-F), marine eutrophication (EUT-M), human carcinogenic toxicity (HT-C), human non-carcinogenic toxicity (HT-NC), terrestrial ecotoxicity (ECO-T), freshwater ecotoxicity (ECO-F), marine ecotoxicity (ECO-M), land use (LU), water consumption (WC), mineral resource scarcity (SCA-M), and fossil resource scarcity (SCA-F). Following the acquisition of the LCIA results, only the categories with the most substantial environmental impacts were selected for further analysis.

This study did not include long-term emissions from landfills due to several challenges. First, landfills can emit harmful substances for thousands of years, far exceeding the typical time frame used in life cycle assessments. Second, accounting for all future landfill emissions could make them the dominant contributor to the system's environmental impact, overshadowing other life cycle stages and complicating an accurate assessment. Lastly, the uncertainty surrounding if and when toxic materials in landfills will be released into the environment further complicates their inclusion [39,40].

Regarding geographical and temporal boundaries, the analysis is limited to specific data sourced from Brazil, particularly from the study of Leme et al. [9] for primary information. Furthermore, various secondary inventories were utilized, which will be elaborated upon in the inventory section.

2.2. Life Cycle Inventory Analysis

LCIs were gathered from peer-reviewed scientific literature and other LCA studies. The investigated technological pathways require the compilation of input and output datasets, spanning raw material consumption, energy utilization, direct emissions, and resulting product generation. Detailed descriptions of data sources for each scenario are provided below.

2.2.1. Landfill with Biogas Recovery (Scenario 1)

Scenario 1 involves the landfill disposal of one ton of MSW, which inherently leads to air, water, and soil emissions. It is assumed that 75% of the biogas generated during the landfill process can be captured, with a 25% loss to the atmosphere due to cell cover failure, as documented by [41]. Within the captured biogas, 62% is allocated for use in internal combustion engines (ICEs) for electricity generation, while the remaining portion is burned in flare stacks, as reported by [9].

The consumption of electrical energy (14.6 MJ) includes both the operation of landfill facilities and the biogas supplying system, along with diesel usage for the compaction machines and the soil used to cover the landfill waste. Emissions to air come from diesel-powered compaction machines, flare stacks, internal combustion engines (ICEs), and uncontrolled biogas releases. Water emissions result from the treatment of landfill sludge and leachate. Input and emissions data were primarily sourced from [9], with additional emissions to water and soil obtained from the Ecoinvent v3 database via SimaPro. Figure 2 illustrates the system boundaries for this scenario.

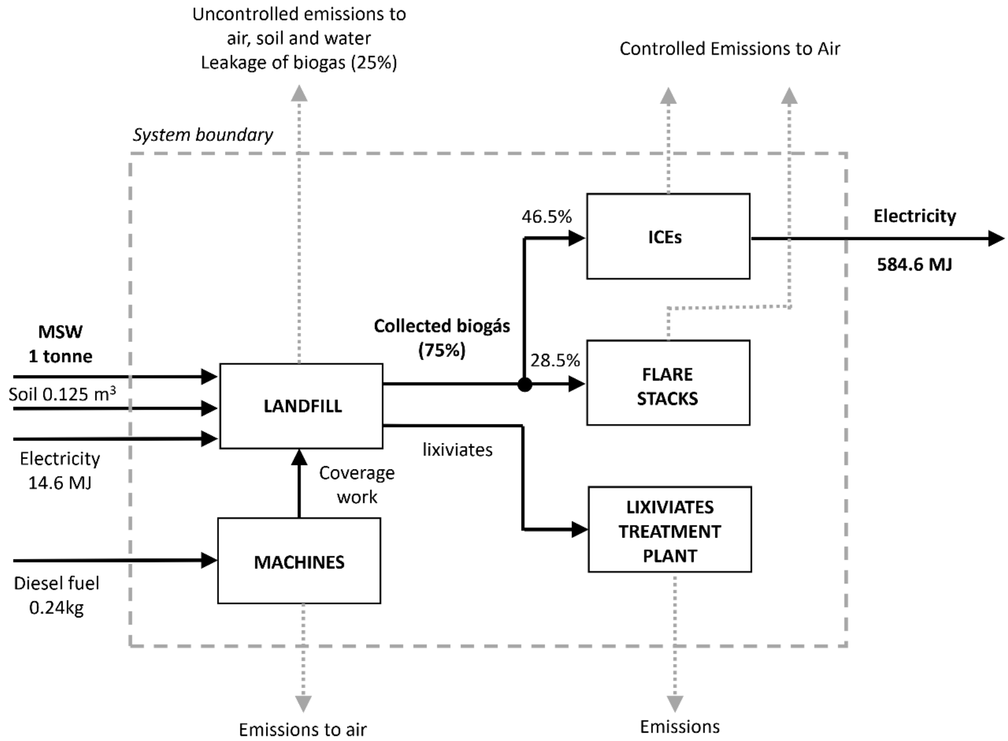

Figure 2. System boundaries for Scenario 1—landfill.

2.2.2. WtE Incineration (Scenario 2)

In this scenario, the utilization of a combustion system employing mass-burning technology was assessed. This system incorporates a grate mechanism facilitating the mixture of residue alongside the injection of combustion air, obviating the necessity for auxiliary fuel. Furthermore, the solid byproducts are directed to an inert landfill situated 50 km distant from the incineration facility. Electricity generation is carried out through a Rankine cycle.

At the system boundaries, the inputs include 1 ton of MSW, reagents for treating effluent gases, and diesel for transporting solid byproducts. Outputs comprise emissions released into the atmosphere, ashes and slag resulting from incineration, and the generated electric energy (1756 MJ), as illustrated in Figure 3. The data were sourced from [9], considering a lower heating value (LHV) for the waste of 7981 kJ/kg and a moisture content of 35% (w.b.). The WtE facility focuses exclusively on electricity generation, with a gross % electricity conversion efficiency of 22% [42]. Emissions into water and soil were acquired from the Ecoinvent v3 database. The reagents utilized for waste gas treatment included urea, activated carbon, and sodium carbonate, as documented by [43]. Air emissions data were sourced from [44]. According to [9], one ton of Betim MSW contains 280 kg of carbon, with 39.3% of fossil origin and 60.7% of biogenic origin. Consequently, incinerating one ton of this waste is expected to emit 403 kg of fossil CO_2 into the atmosphere. Figure 3 illustrates the system boundaries for this scenario.

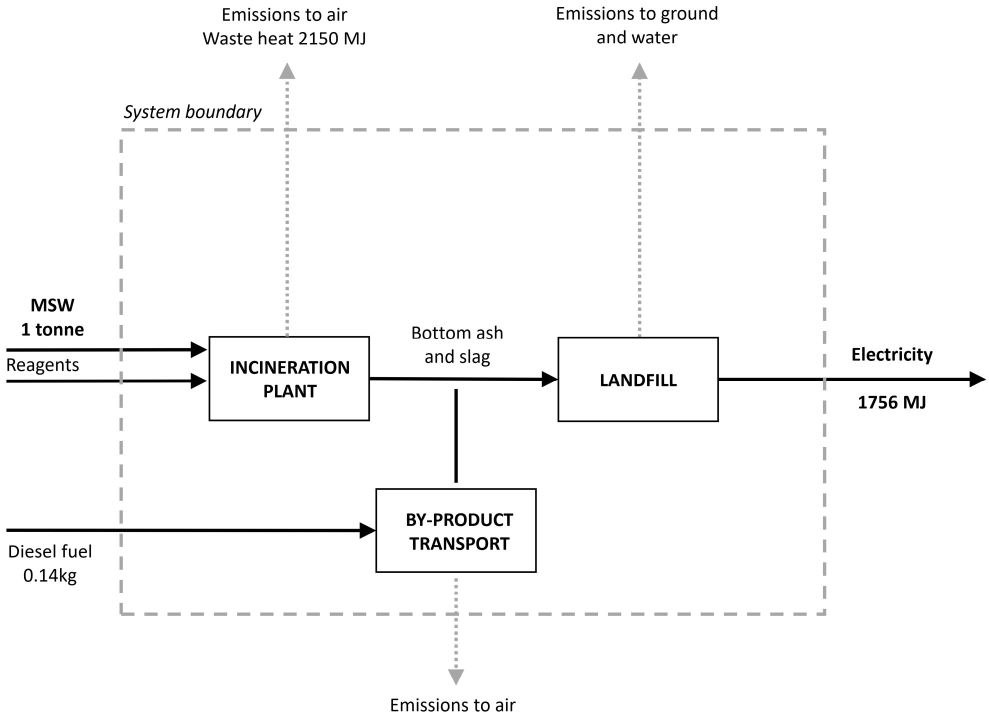

Figure 3. System boundaries for Scenario 2—incineration.

2.2.3. MSW Methanol Production (Scenario 3A)

Scenario 3A corresponds to the methanol production from MSW, and the resulting methanol is classified as an avoided product. This requires adopting a substitution approach, which involves avoiding the importation of methanol commonly used in Brazil. According to [21], Brazil imports 39.8% of methanol from Chile, 33.2% from Trinidad and Tobago, 18.7% from Venezuela, 4.3% from Argentina, and 3.8% from the USA. Consequently, an average maritime freight distance of 6117 km was incorporated into the analysis for conventional methanol importation.

Two distinct routes are required to produce methanol from MSW. Firstly, waste separation in the source and RDF production are undertaken. Secondly, methanol is produced from SRF, as described below.

Route 1—The production of RDF is a complex process that separates MSW materials with high calorific value, such as paper, plastics, fabrics, packaging, tires, and other suitable components. Recyclable glass and metals are diverted toward recycling facilities, while organic material collected through selective collection undergoes composting. The remaining organic materials are directed to a biodigester, where electricity is generated from biogas via generator sets. Materials unsuitable for recycling and inert components are disposed of in a landfill. Additionally, the production processes associated with recycling the aforementioned materials were inventoried, and their impacts were considered avoided in the LCIA. As it is uncommon for all materials to be recycled in Brazil due to varying sorting efficiencies and material values, residual materials that cannot be recycled are directed to landfill disposal. This aligns with the common practice of waste sorting in Betim municipality, as described [45]. The same principle applies to inert materials that cannot be utilized in other processes. Figure 4 illustrates the segregation of MSW components within this process route.

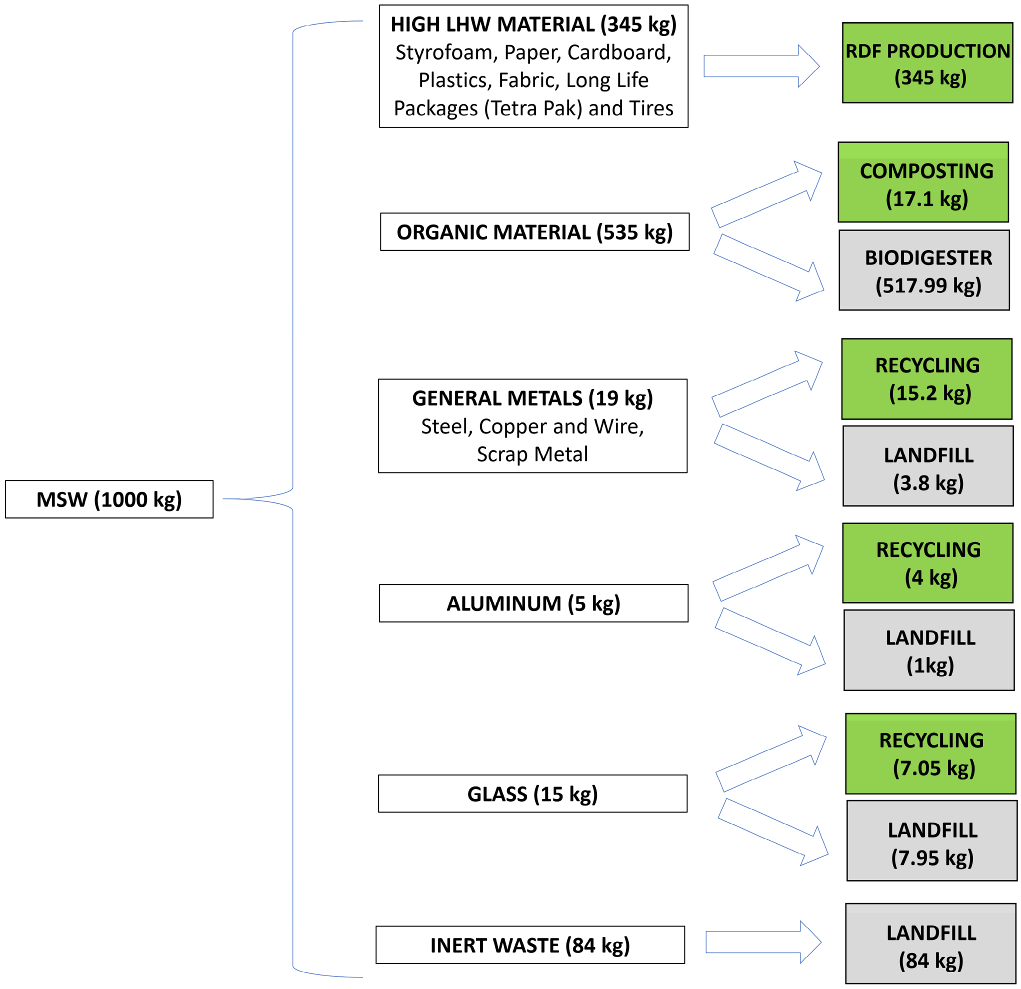

Figure 4. MSW segregation in Scenario 3, Route 1.

The amount of electricity (207.1 MJ) required for processing and drying the RDF was obtained from [46]. Additionally, inputs and electricity utilized for recycling, composting, biodigester operations, landfill processes, and associated air, water, and soil emissions were considered input parameters.

Route 2—Methanol production with RDF: To ensure fuel homogenization, the RDF is blended with 20% dry lignite (132.9 kg) to form SRF. The SRF then undergoes conversion into synthesis gas (syngas) through gasification followed by wet scrubbing (cold scrubbing), water–gas shift ("Shift" reaction), and removal of acid gases. Subsequently, syngas is utilized for methanol synthesis. Data and inventories for this process were obtained from [47,48], encompassing electricity input (514.5 MJ), inputs for various stages, emissions to air, water, and soil, refuse generated, and the final product, methanol (190.7 kg). The residual gases produced by methanol synthesis are sent for destruction in a flare system with 99% efficiency and a scrubber that removes NO_x and SOx with 98% efficiency. Figure 5 depicts the block diagram of the SRF gasification system with lignite.

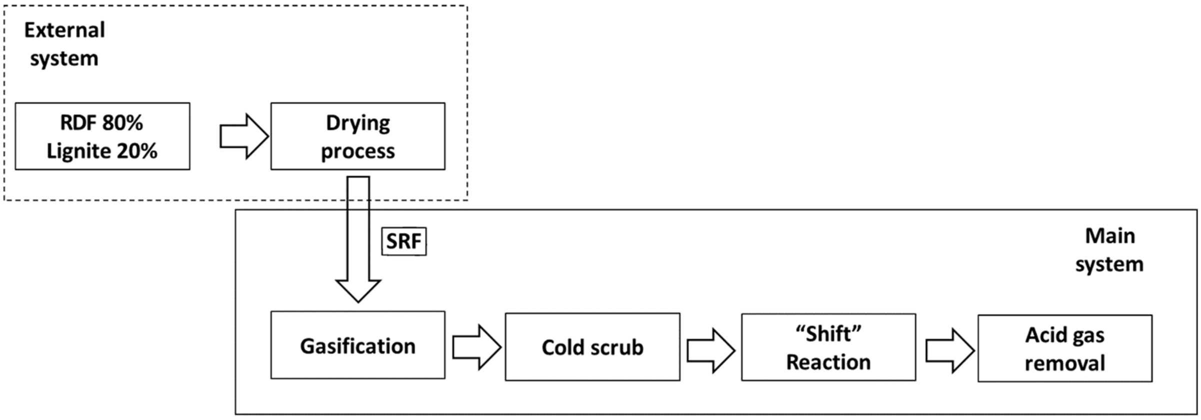

Figure 5. Block diagram of the SRF gasification system with lignite—adapted from [47].

2.2.4. Electricity Production from MSW Methanol (Scenario 3B)

Scenario 3B is a variation of Scenario 3A; however, this case uses the generated methanol for electricity production. To achieve this objective, an additional route is required to convert the energy content of methanol into electricity. Similarly to the other scenarios, a substitution approach is employed for the electricity produced in this process. Figure 6 illustrates the system boundaries for Scenario 3A and 3B.

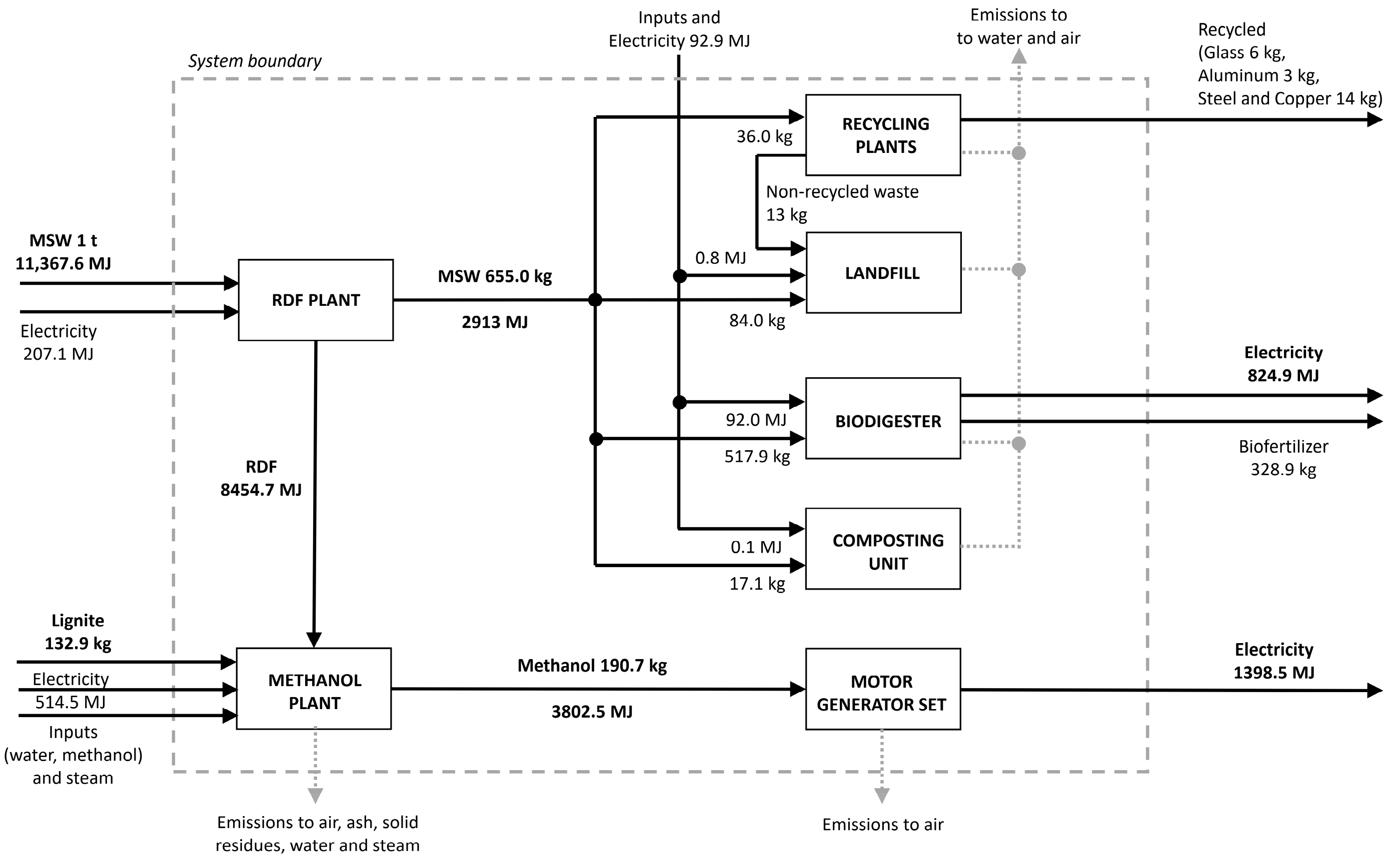

Figure 6. System limits for Scenario 3A and 3B—methanol production.

Route 3—Electricity generation from methanol: the methanol is subsequently combusted in motor generator sets for electricity generation (1398.5 MJ). Efficiency data (41%) and emissions from the engine to air were sourced from [49]. Generator efficiency (89.7%) was obtained from the manufacturer's catalog (WEG synchronous alternator, model 251AI27, with a power rating of 140 kVA at 75% load) [50].

The carbon composition in methanol production reflects that of SRF. Specifically, the RDF within the SRF exhibits a carbon content of 54.30%, comprising 33.48% from fossil sources and 20.83% from biogenic sources. When SRF includes 20% lignite (with a carbon content of 72.50%) and 8000% RDF, the resulting carbon content in methanol produced from SRF consists of 71.25% fossil-derived carbon and 28.75% biogenic carbon.

2.3. Life Cycle Energy Assessment (LCEA)

To complement LCA, a life cycle energy analysis (LCEA) was performed to determine the global system efficiency (GSE). This indicator evaluates the energy balance of each scenario by considering energy inputs from all sources—renewable and non-renewable—and the energy content of products and co-products. The GSE ratio is critical for assessing the overall efficiency and sustainability of biofuel production or energy generation systems. It provides valuable insights into the renewable energy efficiency of each waste management option, guiding decision makers toward sustainable practices and enabling a robust comparative analysis of different approaches.

The GSE indicator was chosen for its comprehensive approach to evaluating energy efficiency, incorporating both renewable and non-renewable energy contributions. This makes it particularly suitable for comparing waste management scenarios, aligning with the study's emphasis on sustainable energy and adopted waste practices in Brazil. To evaluate GSE across the proposed scenarios, the LCEA methodology was applied, as it quantifies all the energy inputs from collection, processing, and recovery activities, as well as outputs such as electricity, heat, and methanol

Given that all scenarios utilize 1 ton of MSW as input, it is crucial to consider the energy conversion rate from MSW into each scenario's net electrical energy output. To facilitate this evaluation, the GSE indicator will be employed, as calculated according to Equation (1) below [51].

$$\mathrm{GSE} = \frac{\mathrm{EB} + \mathrm{EPC}}{\sum \mathrm{ET} + \mathrm{ER}} \quad (1)$$

EB = energy contained in biofuel;

ECP = energy contained in the co-products;

ET = total energy input (renewable + non-renewable);

ER = energy contained in MSW.

To facilitate the application of the GSE indicator across all scenarios for comparative purposes, several considerations were implemented:

(a) Given that all three scenarios (S1, S2, and S3B) have electricity as their final product within the system boundaries, this was designated as the energy contained in the biofuel (EB). In Scenario S3B specifically, the indicator also accounted for the energy contained in methanol (an intermediate product), calculated as its LHV multiplied by its mass;

(b) In Scenario S3B, the electricity generated from biogas in the biodigester was considered as the energy contained in the co-products (ECP);

(c) The total energy input (ET) for all scenarios encompasses the electrical energy consumed across all process stages. Scenario S3B excludes energy used in sorting, recycling, and composting processes, focusing solely on energy used for processing RDF, syngas generation, and methanol synthesis.

These considerations ensure a comprehensive and standardized approach to evaluating the GSE indicator across different scenarios, facilitating meaningful comparisons and insights into biofuel production and energy generation sustainability.

3. Results and Discussion

3.1. Normalization Results of Impact Categories Indicators

After the LCIs for each scenario have been collected, the data representing environmental aspects must be transformed into quantifiable environmental impacts using RECIPE World 2010 normalization parameters. Table 1 and Figure 7 show the normalized values for the 18 environmental impact categories. The eight categories with the greatest environmental impacts of all the scenarios (positive or negative values) were selected in order of relevance: HT-C, TA, OF-H, GW, SCA-F, OF-T, FPMF, and WC.

Table 1. Normalized environmental impact categories in assessed scenarios (green color indicates positive environmental impacts).

Impact Category		S1	S2	S3A	S3B
Human carcinogenic toxicity	HT-C	1.32×10^{-1}	3.25×10^{-2}	-1.54×10^{-1}	-9.69×10^{-2}
Terrestrial acidification	TA	2.42×10^{-1}	8.20×10^{-3}	2.86×10^{-2}	4.27×10^{-2}
Ozone formation. Human health	OF-H	2.99×10^{-2}	4.89×10^{-2}	2.85×10^{-2}	9.43×10^{-2}
Fossil resource scarcity	SCA-F	-7.28×10^{-3}	-1.22×10^{-2}	-1.55×10^{-1}	-1.95×10^{-2}
Global warming	GW	8.40×10^{-2}	4.28×10^{-2}	1.60×10^{-2}	4.74×10^{-2}
Ozone formation: terrestrial ecosystems	OF-T	3.53×10^{-2}	5.66×10^{-2}	-9.68×10^{-3}	6.75×10^{-2}
Fine particulate matter formation	FPMF	1.12×10^{-1}	2.93×10^{-3}	-1.22×10^{-2}	-5.48×10^{-3}
Water consumption	WC	-1.15×10^{-2}	-3.02×10^{-2}	-2.49×10^{-2}	-4.91×10^{-2}
Freshwater eutrophication	EUT-F	5.24×10^{-2}	2.41×10^{-3}	2.13×10^{-2}	3.32×10^{-2}
Marine eutrophication	EUT-M	7.81×10^{-2}	-2.19×10^{-3}	-3.17×10^{-3}	-4.95×10^{-3}
Stratospheric ozone depletion	OD	2.88×10^{-3}	-3.55×10^{-3}	-9.24×10^{-3}	-1.10×10^{-2}
Marine ecotoxicity	ECO-M	6.37×10^{-3}	2.38×10^{-3}	-1.25×10^{-2}	-3.06×10^{-3}
Terrestrial ecotoxicity	ECO-T	-9.01×10^{-4}	1.84×10^{-2}	-3.94×10^{-3}	9.76×10^{-4}
Freshwater ecotoxicity	ECO-F	8.81×10^{-3}	1.50×10^{-3}	-8.71×10^{-3}	7.73×10^{-4}
Ionizing radiation	ID	-4.78×10^{-4}	-1.14×10^{-3}	-2.19×10^{-3}	-2.73×10^{-3}
Land use	LU	-5.89×10^{-4}	-1.35×10^{-3}	-1.43×10^{-3}	-2.50×10^{-3}
Human non-carcinogenic toxicity	HT-NC	2.13×10^{-4}	2.12×10^{-4}	-7.45×10^{-4}	-5.49×10^{-4}
Mineral resource scarcity	SCA-M	-1.92×10^{-7}	1.30×10^{-6}	-1.65×10^{-5}	-1.50×10^{-5}

For the eight selected categories, the landfill (S1) and incineration (S2) scenarios showed predominantly harmful environmental impacts (positive numerical results) that outweighed the positive environmental outcomes (negative numerical results). Specifically, S1 demonstrated the worst performance, showing negative impacts in six analyzed categories (HT-C, TA, GW, OF-H, OF-T, FPMF). Conversely, the methanol scenario (S3A) and methanol-to-electricity (S3B) scenarios exhibited positive environmental impacts in most of the categories. Scenario S3A demonstrated positive impacts in five categories: HT-C, SCA-F, OF-T, FPMF, and WC. S3B showed positive impacts in four categories: HT-C, SCA-F, FPMF, and WC. When compared to S1, the other scenarios significantly reduced environmental impacts. S2 reduced impacts by 78%, S3A by 143%, and S3B by 92%. This quantification indicates that these alternative scenarios, including incineration, are substantially more environmentally beneficial than the landfill scenario.

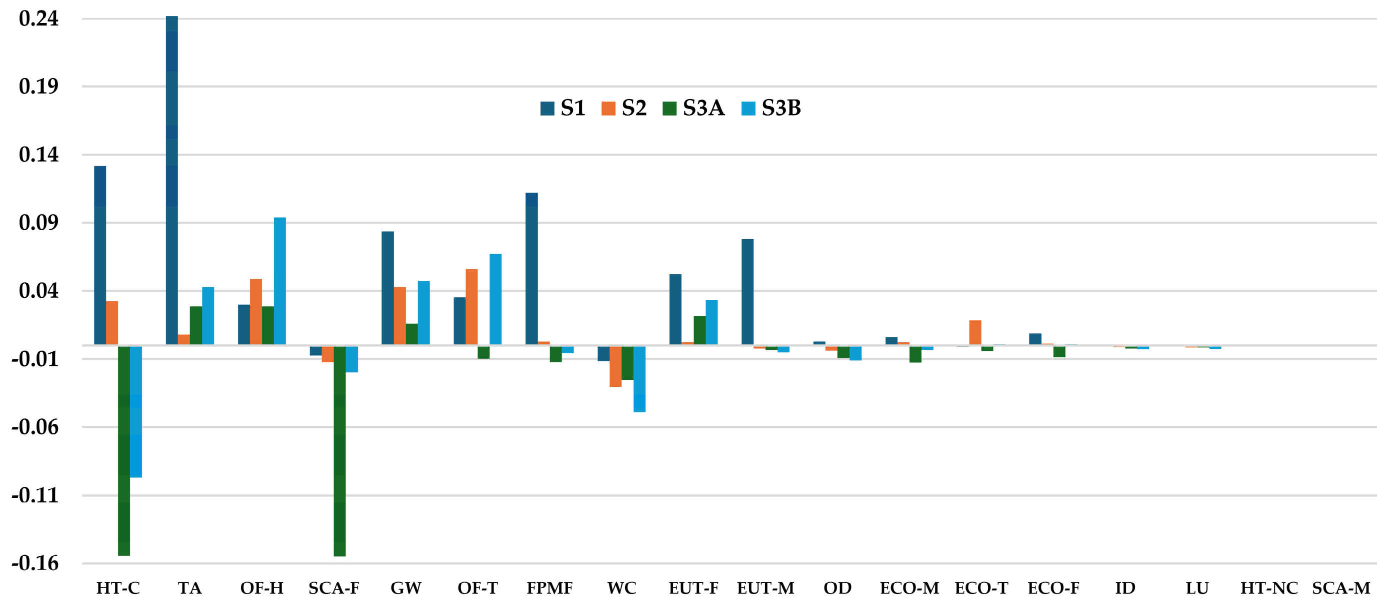

Figure 7. Normalized values of the potential environmental impacts in the 18 impact categories.

WtE incineration is increasingly recognized as a promising solution in developing countries to reduce landfill dependency and generate electricity, while fostering a circular economy and long-term sustainability. When paired with advanced emission controls, incineration can significantly reduce pollutant emissions, aligning with global sustainability goals, as AlMokmesh et al. [52] highlighted.

Landfilling remains one of the most widely used methods of municipal waste management globally, due to its cost effectiveness and technical simplicity, especially in resource-limited regions. While alternative waste management strategies like incineration and composting are gaining traction, landfilling remains indispensable, since some residual waste will always require disposal. However, the environmental risks associated with landfilling are considerable [6]. For example, [7] highlight the urgent need to address the role of microplastics in landfills. These microplastics form through plastic degradation and are transported via air and leachate, carrying pollutants such as heavy metals and endocrine disruptors, which pose significant risks to ecosystems and human health.

3.2. Comparison of Environmental Impacts

Table 2 depicts the impact characterization results of 1 ton of MSW for each specified impact category and scenario. Figure 8 illustrates the weighted results, visually representing their relative significance.

The data strongly confirm the environmental superiority of methanol synthesis using MSW (S3A) over landfilling (S1) and incineration (S2). Methanol production emerged as a better option compared to landfilling across all selected impact categories; it outperformed incineration in six out of the eight categories assessed, notably including GW.

Producing electricity with methanol (S3B) does not appear to be a favorable option for the Brazilian context compared to avoiding fossil methanol imports (S3A). The scenario that avoids methanol imports surpasses the scenario where methanol is employed for electricity generation in seven of the eight assessed categories. This outcome results from the substantial mitigation of environmental impacts associated with substituting fossil methanol production. On the other hand, in S3B, using methanol to replace Brazilian electricity production is less appealing because Brazil's electricity is predominantly renewable, primarily generated from hydroelectric power. Additionally, even though burning methanol in engines is significantly cleaner than other conventional fuels, it still produces emissions of fossil CO_2, volatile organic compounds (VOCs), and NO_x, further undermining the attractiveness of this scenario compared to S3A.

Table 2. LCIA characterization results for evaluated scenarios (The green color indicates positive environmental impacts).

Impact Category	Unit	S1	S2	S3A	S3B
Human carcinogenic toxicity	kg 1.4-DCB	1.35	3.35×10^{-1}	-1.59	-9.98×10^{-1}
Terrestrial acidification	kg SO_2 eq	9.93	3.36×10^{-1}	1.17	1.75
Ozone formation: human health	kg NO_x eq	6.15×10^{-1}	1.01	5.87×10^{-1}	1.94
Fossil resource scarcity	kg oil eq	-7.14	-1.20×10^{1}	-1.52×10^{2}	-1.91×10^{1}
Global warming	kg CO_2 eq	6.72×10^{2}	3.42×10^{2}	1.28×10^{2}	3.79×10^{2}
Ozone formation: terrestrial ecosystems	kg NO_x eq	6.27×10^{-1}	1.00	-1.72×10^{-1}	1.20
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.87	7.50×10^{-2}	-3.12×10^{-1}	-1.40×10^{-1}
Water consumption	m^3	-3.07	-8.06	-6.63	-1.31×10

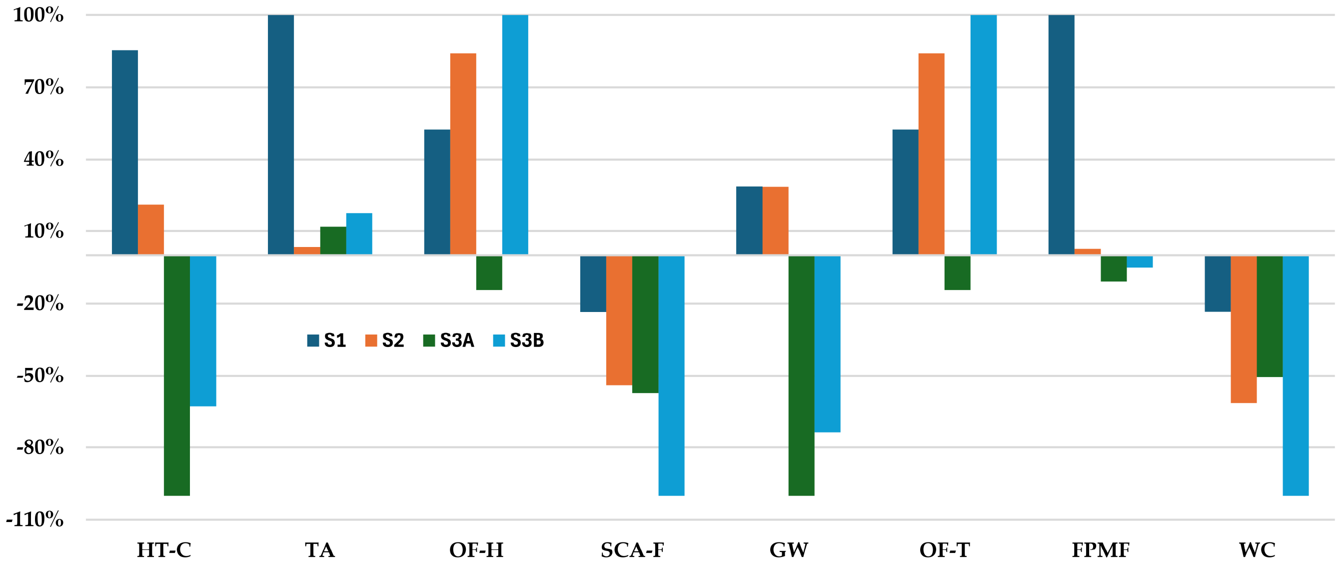

Figure 8. Comparison of characterization impact values in LCIA.

HT-C describes the potential impact of chemical substances released into the environment that may cause human cancer. S1 is the worst scenario due to metal emissions to water in the landfill and VOC emissions to the air. In the S2 scenario, metal emissions to water are also the most relevant factor in the inert residues landfilling. S3A and S3B perform significantly better in this regard, thanks to the avoidance of methanol and electricity production (respectively) and the drastic reduction in the use of landfills compared to the other scenarios.

TA refers to the potential negative impacts on terrestrial ecosystems caused by acidifying emissions (SO_2, NO_x, and NH_3) that can lead to soil acidification when deposited onto the earth's surface. In this case, S1 exhibits significant SO_2 emissions due to landfill biogas burning, as biogas contains sulfur compounds. The methanol scenarios perform poorly compared to S2 due to uncontrolled NO_x emissions resulting from biodigester biogas burning.

OF-H refers to potential impacts on human health due to the formation of ground-level ozone when VOCs and NO_x react in the presence of sunlight. On the other hand, OF-T refers to the potential impacts of ground-level ozone on terrestrial ecosystems. For these two categories, the worst-performing scenario was S3B, primarily due to NO_x emissions from burning methanol in engines and uncontrolled NO_x emissions during biodigester biogas burning. Conversely, in Scenario S3A, the avoidance of methanol-related activities significantly counterbalances this impact, making it the best scenario among these two categories.

SCA-F refers to the potential depletion of nonrenewable fossil resources, such as coal, oil, and natural gas, due to their extraction and use throughout a product or process's life cycle. The main factors related to SCA-F are electricity production and material recycling in each scenario. Scenario S2 produces more electricity than S1, thus avoiding more impacts. Although S3B produces less electricity than S2, it includes significant material recycling of MSW (steel, aluminum, and glass) and compost production. Scenario S3A is the best of all in this impact category, due to the substitution of fossil methanol production.

GW refers to the potential impacts associated with the emission of GHGs throughout the life cycle of a product or process. Scenario S1 is the worst scenario due to significant methane emissions from biogas, as methane's global warming impact of non-fossil origin is 27.2 times greater than that of CO_2 over a 100-year time frame.

Scenario 3A has the lowest environmental impact in this category because it avoids using landfills and importing fossil-based methanol, reducing emissions and reliance on fossil fuels. The low GW impact of S3A is attributed to its high energy utilization rate of municipal solid waste (MSW) compared to the other scenarios. Results show an absolute reduction in GHG emissions of 87% compared to landfill and 56% compared to incineration.

The poor performance of Scenarios S2 and S3B can be attributed to their reliance on the combustion of fossil carbon present in MSW to produce electricity. This process releases fossil-derived CO_2 emissions, which contribute to global warming and diminish the climate change impact advantages of WtE technologies. The most significant contributors to global warming in the surveyed inventories are CH_4 and CO_2. A more effective strategy for enhancing methanol production for electricity generation is to avoid the use of lignite in SRF production; instead, carbon-neutral charcoal derived from sustainable biomass could be utilized. As one of the largest global producers of renewable charcoal, Brazil presents a significant opportunity to support this transition. By leveraging Brazil's extensive biomass resources and well-established renewable charcoal industry, methanol production can be both environmentally sustainable and economically viable [53,54].

Kajaste et al. [55] found emissions with a global warming potential close to −1 for the ICV of methanol production using biomass. Similar results were obtained by [9] when comparing the disposal of the same sample of MSW in a landfill versus the incineration process, both with electricity generation, concluding that incineration is the better solution from both environmental and electricity generation perspectives. Corbett & Winebrake [56] evaluated the LCA of various methanol production routes for use in ships and concluded that for greenhouse gases, methanol compares favorably to conventional fuel and liquefied natural gas only when renewable feedstock, such as forest waste and landfill gas, is used in its manufacture.

FPMF describes the potential impacts of generating fine particulate matter ($PM_{2.5}$). Here, Scenario S1 is the worst due to atmospheric emissions from the landfill. The incineration plant in Scenario S2 incorporates an advanced pollution control system, reducing its impact. In Scenarios S3A and S3B, the potential impacts of this category are mitigated by the substitution of grid electricity and methanol.

WC refers to the potential impacts associated with the withdrawal or consumption of water resources throughout the life cycle of a product or process. This includes the direct use of water in industrial processes and the indirect use of water through irrigation, cooling, and cleaning. The best scenario is S3B, thanks to electricity recovery and material recycling. S3A ranks lower than S3B, as water consumption is more significantly impacted by the substitution of electricity production than by the avoidance of fossil methanol production. This also explains why S2 performs better than S3A.

Incineration performs better than landfilling in almost all categories, except for ozone formation (OF-T and OF-H), which is impacted by NO_x emissions during waste burning. Incineration generates more electricity from waste than landfilling, reducing the need for fossil fuels and improving environmental outcomes through the substitution approach used in this study. Unlike landfills, which produce methane as organic waste decomposes, incineration prevents this issue by burning the waste, thereby reducing greenhouse gas emissions by methane leaks. Also, modern WtE incineration plants are equipped with advanced pollution control systems, which are essential for treating emissions and minimizing the release of harmful pollutants into the environment [57].

3.3. Contribution Assessment of MSW Methanol Production in Scenario S3A

Table 3 presents the LCIA characterization results for methanol production from 1 ton of MSW in Scenario S3A, including each impact category and process. Additionally, Figure 9 illustrates the weighted outcomes of the characterization.

Table 3. LCIA characterization results for evaluated methanol production (S3A) (The green color indicates positive environmental impacts).

Category	Unit	Total	Methanol Synthesis	Recycling	Biodigester	Fossil Methanol [Avoid]	Freight Sea [Avoid]
HT-C	kg 1,4-DCB	−1.59	2.45×10^{-1}	-6.61×10^{-1}	-2.51×10^{-1}	-7.94×10^{-1}	-1.27×10^{-1}
TA	kg SO_2 eq	1.17	2.64×10^{-1}	-5.74×10^{-1}	2.01	-3.55×10^{-1}	-1.71×10^{-1}
OF-H	kg NO_x eq	5.87×10^{-1}	1.80×10^{-1}	-1.92×10^{-1}	1.03	-2.73×10^{-1}	-1.61×10^{-1}
SCA-F	kg oil eq	-1.52×10^{2}	5.34×10^{1}	-4.30×10^{1}	-1.11×10^{1}	-1.49×10^{2}	−2.65
GW	kg CO_2 eq	1.28×10^{2}	4.44×10^{2}	-1.28×10^{2}	-4.21×10^{1}	-1.36×10^{2}	−9.00
OF-T	kg NO_x eq	-1.72×10^{-1}	1.90×10^{-1}	-2.00×10^{-1}	2.92×10^{-1}	-2.92×10^{-1}	-1.63×10^{-1}
FPMF	kg $PM_{2.5}$ eq	-3.12×10^{-1}	8.76×10^{-2}	-1.54×10^{-1}	-6.18×10^{-2}	-1.29×10^{-1}	-5.49×10^{-2}
WC	m^3	−6.63	2.96	−4.78	−3.92	-8.77×10^{-1}	-7.18×10^{-3}

While methanol synthesis exhibits adverse environmental impacts across all selected categories, strategic approaches such as recycling, biodigesters, and avoiding fossil-based methanol balance these effects. Notably, five impact categories—HT-C, SCA-F, OF-T, FPMF, and WC—yield positive environmental outcomes. However, caution is warranted regarding biogas burning from the biodigester, which adversely affects TA, OF-H, and OF-T due to elevated NO_x emissions. In contrast, electricity generation via biogas engines demonstrates favorable environmental results in other categories. Furthermore, recycling has consistently shown positive outcomes in all evaluated categories.

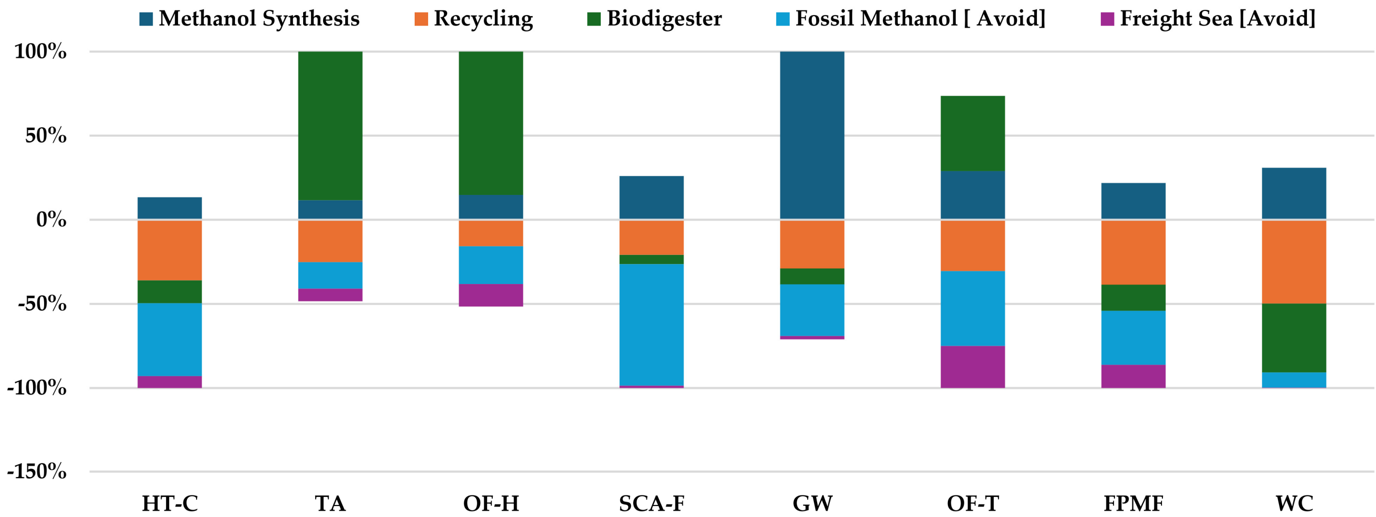

Figure 9. Comparison of characterization impact values in methanol production (S3A).

3.4. Energy Balance and LCEA of MSW Methanol Production

Energy balance assessments were carried out to allow the interpretation of the results for each scenario. Considering all energy inputs and outputs, S1 can produce 584.6 MW of electricity, whereas S2 yields 1756 MJ. The balance between consumption and generation of electricity for Scenario S3B is presented in Table 4.

Table 4. Balance of electric energy in Scenario S3B.

Type	Process	Electricity [MJ/t MSW]
Consumption	RDF processing	69.1
Consumption	RDF drying	138
Consumption	Composting	0.1
Consumption	Landfill facilities (inert material)	0.8
Consumption	Biodigesters	92
Consumption	Syngas to methanol	514.5
Generation	Biodigester biogas engine	824.8
Generation	Methanol engine	1398.5
Net		1408.9

Notably, Scenario S3B produces 80% of the net energy output of a WtE plant (S2) and 2.4 times more than landfill (S1). The input data and results of the GSE indicator calculation are presented in Table 5.

Table 5. Input and output data and GSE indicator calculation results.

Product/Input/Index	S1 (Landfill)	S2 (WtE)	S3A (Methanol)	S3B (Methanol Engine)
Biofuel/Power Output	Electricity	Electricity	Methanol	Electricity
Energy Contained in Biofuel/Electricity (EB)	584.6	1756	3802.6	1398.5
Energy Contained in the Co-products (ECP)			824.8	824.8
Energy Contained in Diesel	10.2	6.0	0	0
Energy Contained in Lignite	0	0	1329	1329
Energy Contained in Electricity	14.7	0	814.5	814.5
Total Energy Input (ET)	24.9	6.0	2143.5	2143.5
Energy Contained in MSW (ER)	11,367.6	11,367.6	11,367.6	11,367.6
Global System Efficiency (GSE)	0.05	0.15	0.34	0.16

The low electricity generation (EB) efficiency in S1 resulted in the lowest GSE indicator among all scenarios. S3B has a GSE that is 7% higher than S2 despite having a higher energy input (ET). This is due to biogas co-product (ECP) generation from the biodigester. The higher GSE indicator value for the methanol synthesis process is based on the greater energy content in methanol than the electricity generated, reflecting the 63.2% losses in the motor generator set.

3.5. Sensitivity Analysis Results

Figure 10 illustrate the sensitivity of the GSE and methanol yield indicators to variations in the gravimetric composition of MSW, specifically reflecting changes in the RDF raw materials.

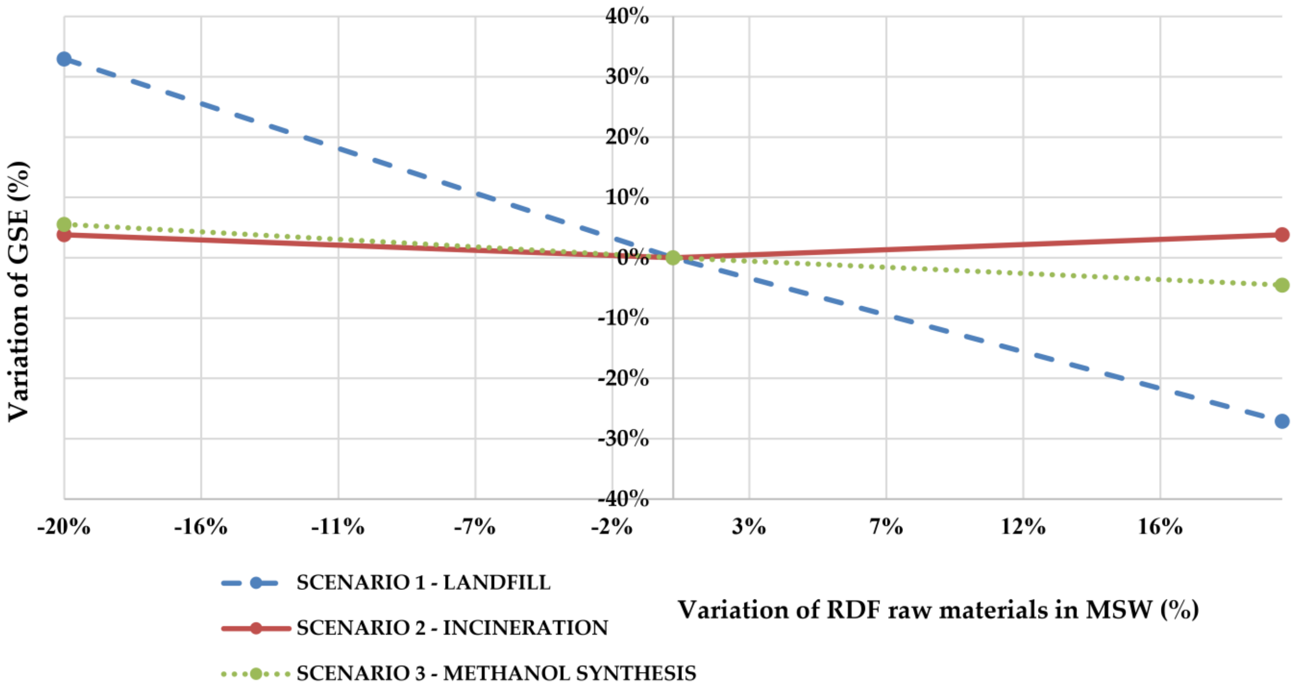

Figure 10. Sensitivity of the GSE indicator to the variation in the MSW's gravimetric composition for the 3 Scenarios.

In Scenarios 2 and 3A, the system is less sensitive to changes in MSW composition because increasing the proportion of RDF materials raises the energy content of the waste (ER), differently assumed in Table 5. Since the GSE is calculated as the energy in the products (EB) divided by the energy in the waste (ER), a higher input energy (ER) stabilizes the GSE, making it less responsive to efficiency variations. As RDF materials, which contain more energy, increase, they compensate for any changes in efficiency, leading to a smaller impact on the GSE. For instance, increasing RDF content by 20% boosts methanol production by 2.5%, demonstrating how higher energy content in the waste leads to improved energy conversion and more stable GSE values.

Scenario 1 demonstrates the highest sensitivity to variations in MSW composition, with a notable 33.0% increase in the efficiency of converting the energy contained in MSW into electricity when RDF materials are reduced. This is due to a proportional increase in organic matter within the MSW and changes in the ER value. The higher organic content enhances biogas production (EB) during waste decomposition, boosting energy generation in ICEs at the landfill. Additionally, reducing RDF materials in the MSW lowers the ER value, further increasing the GSE.

Figure 11 shows the sensitivity of the emissions with GWP to the variation of MSW gravimetric composition.

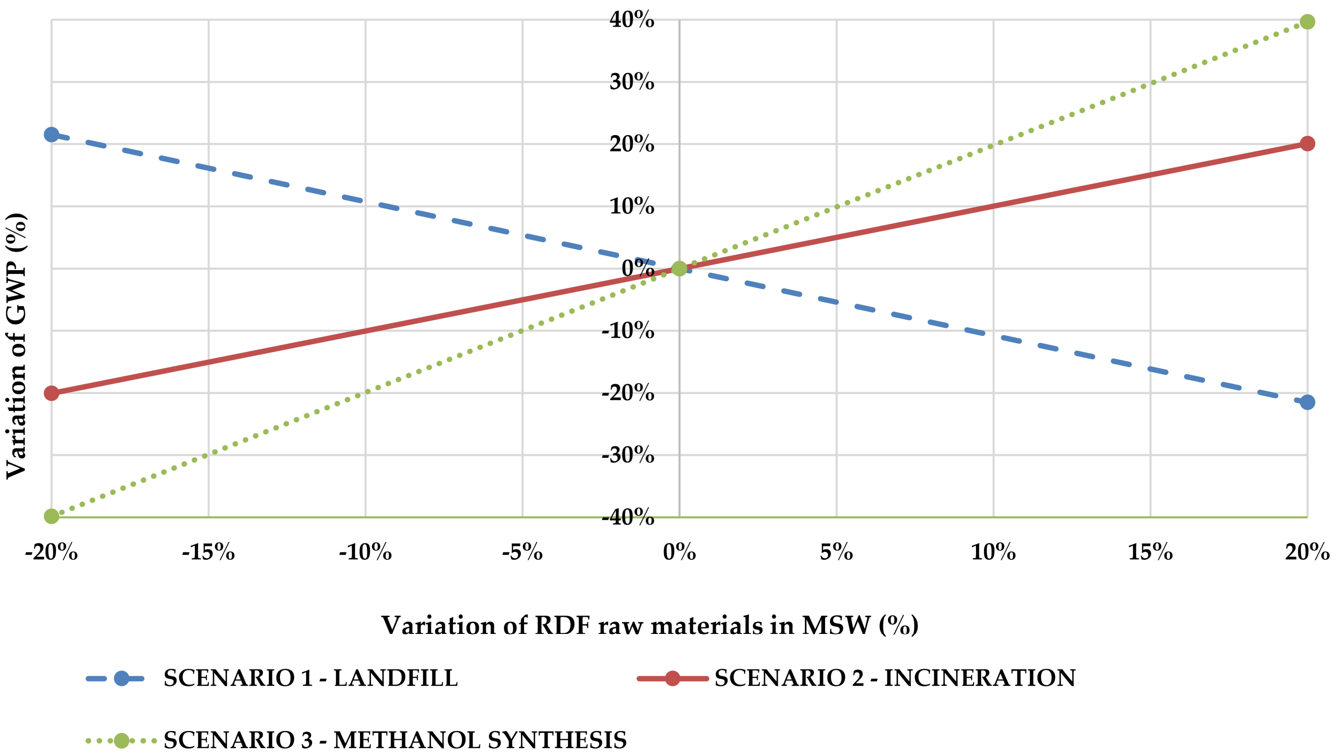

Figure 11. The sensitivity of GWP results in variations in the composition of RDF materials in MSW.

All scenarios examined demonstrate sensitivity to variations in MSW composition regarding their GWP impacts. Scenario 3A exhibits the highest sensitivity due to its low GWP magnitude, meaning that small changes in composition significantly affect its environmental impact. The acid gas removal stage is the most critical in terms of emissions, generating 1.4 kg of CO_2 for every kg of methanol produced. In Scenario 1, emissions are inversely related to the amount of RDF; as RDF increases, less organic matter is landfilled, which reduces biogas generation and atmospheric leakage, ultimately lowering GWP. Conversely, Scenario 2, characterized by a higher concentration of non-organic materials in the MSW, increases fossil CO_2 emissions during incineration. This illustrates how the material composition of MSW directly influences emissions in the different scenarios.

4. Conclusions

This study assesses the environmental impacts and energy efficiency of four municipal solid waste (MSW) management strategies: landfilling with biogas recovery (S1), WtE incineration (S2), methanol production (S3A), and methanol-to-electricity (S3B). S3A emerged as the most environmentally favorable option, reducing normalized impacts by 143% compared to landfilling and 92% compared to incineration. It significantly lowers impacts in categories like human toxicity, global warming, and fossil resource depletion, with an 87% reduction in GWP compared to landfilling and 52% compared to incineration.

Landfilling performed the worst, with high environmental impacts, particularly due to methane emissions, which contribute significantly to global warming. Incineration performed better, reducing emissions by 78%, but still emitted considerable fossil CO_2 from nonorganic MSW combustion.

Methanol-to-electricity conversion (S3B) was less favorable than S3A due to higher impacts in water consumption and ozone formation, but it still reduced impacts by 92%

compared to landfilling. Despite its lower efficiency, S3B generated 80% of the electricity output of WtE incineration, showing its potential as a renewable energy source.

Contrary to current practices in Brazil, which heavily rely on landfills, the LCIA results suggest that methanol production from MSW is an environmentally sound option for waste disposal, followed by incineration. Adopting methanol production could bring substantial environmental and energy benefits. Additionally, concerns such as the extensive land occupied by landfills near urban areas and the competition between biofuel and food production, which are not an issue for biomethanol from MSW, highlight the advantages of this alternative.

5. Notes

This study adheres to ISO 14040/14044 standards [38,58] employing a transparent methodology with clearly defined functional units, system boundaries, and relevant impact categories. The data utilized were sourced from reliable and up-to-date references, which included information on MSW composition, input consumption, emissions, and other critical factors. However, the scarcity of specific data for the analyzed systems and the varying quality of available data introduce inherent uncertainties that could influence the results. These limitations highlight the need for continuous data updates through new publications or, ideally, direct studies and practical measures. Additionally, incorporating advancements in production and energy conversion technologies into future LCA studies is vital for maintaining the validity and applicability of findings to evolving systems. This study employs the recipe LCIA method, which is widely recognized for its robustness and broad applicability in LCA studies, with intermediate environmental results validated through scientifically established assumptions. Despite the inherent uncertainties, the study ensures full transparency by disclosing all assumptions, limitations, and data sources, adhering to ISO recommendations and providing a clear understanding of the scope and reliability of its findings.

Author Contributions: Conceptualization, E.E.S.L.; Methodology, C.Q.C., L.L.P.d.S., E.E.S.L., M.M.V.L. and O.J.V.; Software, C.Q.C., L.L.P.d.S., M.M.V.L. and O.J.V.; Validation, L.L.P.d.S., M.M.V.L. and O.J.V.; Formal analysis, C.Q.C., M.M.V.L., R.M.B. and O.J.V.; Investigation, C.Q.C., L.L.P.d.S., M.M.V.L. and O.J.V.; Resources, E.E.S.L. and O.J.V.; Data curation, L.L.P.d.S.; Writing—original draft, C.Q.C., L.L.P.d.S., E.E.S.L., M.M.V.L., R.M.B. and O.J.V.; Visualization, R.M.B.; Supervision, E.E.S.L. and M.M.V.L.; Project administration, E.E.S.L.; Funding acquisition, E.E.S.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data supporting this study are public and referenced within the article.

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

List of Abbreviations and Acronyms

ABNT:	Brazilian Association of Technical Standards
RDF:	Refuse-Derived Fuel
ECO-F:	Freshwater Ecotoxicity (ECO-F)
ECO-M:	Marine Ecotoxicity (ECO-M), Land Use (LU)
ECO-T:	Terrestrial Ecotoxicity (ECO-T)
EUT-M:	Marine Eutrophication (EUT-M)
EUT-F:	Freshwater Eutrophication (EUT-F)
FPMF:	Fine Particulate Matter Formation
GHGs:	Greenhouse Gases
GSE:	Global System Efficiency
GW:	Global Warming
GWP:	Global Warming Potential
HT-C:	Human Carcinogenic Toxicity
HT-NC:	Human Non-Carcinogenic Toxicity
ICE:	Internal Combustion Engine
IPCC:	Intergovernmental Panel on Climate Change
IR:	Ionizing Radiation
IRENA:	International Renewable Energy Agency
LCA:	Life Cycle Energy Assessment
LCI:	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment
LHV:	Lower Heating Value
MSW:	Municipal Solid Waste
NBR:	Technical Standard created by ABNT
OD:	Stratospheric Ozone Depletion
OF-T:	Ozone Formation Affecting Terrestrial Ecosystems
OH-H:	Ozone Formation Affecting Human Health
PNPB:	National Program of Biodiesel Production and Use
SCA-F:	Fossil Resource Scarcity
SCA-M:	Mineral Resource Scarcity
SRF:	Solid Recovered Fuel
TA:	Terrestrial Acidification
VOCs:	Volatile Organic Compounds
WtC:	Wast to Chemicals
WtE:	Waste to energy
WC:	Water Consumption

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