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Double-Stage Anaerobic Digestion for Biohydrogen Production: A Strategy for Organic Waste Diversion and Emission Reduction in a South African Municipality

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Abstract: Landfilling of organic waste poses a significant environmental threat, heavily contributing to climate change. The diversion of waste is imperative, but pathways to implementing alternative waste management strategies are needed. Double-stage anaerobic digestion has been identified as a potential technique that can reduce greenhouse gas emissions and diminish the amount of waste landfilled. Still, further research is needed before its implementation at the municipal level. This paper explored the potential insertion of double-stage anaerobic digestion into the portfolio of alternative treatment methods using the case study of the eThekwini Municipality in Durban, South Africa, by proposing a source-separation waste management scheme and forecasting the organic waste generation for a 24-year timeframe until 2050. The WROSE model has been identified as the ideal tool for the analysis. A new scenario, including double-stage anaerobic digestion, has been introduced in WROSE after developing a country-specific emission factor. The technology has been assessed against similar techniques, namely anaerobic digestion and composting, according to the environmental indicators included in WROSE. Compared with the business-as-usual scenario and three other alternatives, the new scenario proved to be the second-most effective (−282% versus business-as-usual) after anaerobic digestion (−291%) in reducing climate-altering emissions, achieving analogous waste diversion rate (10.09%), landfill airspace (1,653,705 m^3), and monetary savings (3.8 billion Rand) compared to composting and anaerobic digestion.

Keywords: biohydrogen; organic waste; double-stage anaerobic digestion; greenhouse gas (GHG) emissions; municipal solid waste (MSW); waste diversion; WROSE

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1. Introduction

Landfilling of municipal solid waste (MSW) is a significant contributor to climate change. It has been estimated that solid waste management is responsible for 1.6 $GtCO_{2eq}$ worldwide, accounting for 5% of global carbon emissions, primarily due to landfilling without gas-capturing systems [1]. Additionally, it has been predicted that, by 2050, waste-related emissions will increase to 2.6 $GtCO_{2eq}$ without proper mitigation measures [1]. For these reasons, reducing the impact of MSW management systems is paramount.

The organic fraction of municipal solid waste (OFMSW) is, along with paper, the waste fraction with the highest amount of degradable organic carbon (DOC) and, hence, responsible for most of these emissions [2]. In South Africa, 30.5 million tonnes of organic waste are produced annually [3], 76% of which are currently disposed of in landfills [4]. It has been estimated that the emissions from the national waste sector, 21 $MtCO_{2eq}$, are steadily increasing (+4.4% between 2015 and 2017, +6.2% between 2017 and 2020), while the national carbon footprint is gradually decreasing [5,6].

Furthermore, South Africa is experiencing a widespread waste disposal capacity shortage: in most municipalities, the remaining airspace is scarce, and landfills are promptly reaching the end of their lifespans [7].

Consequently, it is essential to maximise the diversion of organic waste to reduce the carbon footprint determined by its management and extend the active life of landfills. In South Africa, OFMSW is mainly made of garden refuse and food waste, comprising over 40% of MSW [6]. Composting is an alternative disposal method particularly suitable for treating garden waste, given its recalcitrant nature [8]. However, the low commercial value of compost, its main by-product, makes it challenging to create a market to reintroduce it into the South African economy to promote circularity [9]. Anaerobic digestion (AD) is an alternative organic waste treatment method successfully implemented in South Africa at the rural and industrial levels [10–12]. Nonetheless, most of the industrial systems do not provide a boost to the circular economy but focus on producing electricity for internal use or even sold to power individual factories, as in the case of the Bronkhorstspruit AD facility supplying the BMW Rosslyn Plant in Pretoria [12,13].

On the other hand, a novel system called double-stage anaerobic digestion (2S-AD) would achieve the goal of providing proper treatment to organic waste while embodying the circular economy principle [14]. In addition to methane, splitting a conventional AD system into two different stages, a dark fermentation phase followed by standard anaerobic digestion, allows the extraction and recovery of valuable intermediates usually consumed by methanogens during the last stages of AD [15]. While volatile fatty acids (VFAs) are biopolymer precursors, hydrogen is widely used in the refining and fertilising industries. It can power fuel cells in zero-emission electric vehicles or even be mixed with methane to originate biohythane, a high-quality biofuel characterised by better combustion properties and lower emission of pollutants than compressed natural gas [14,16–18].

Several studies explored the possibility of implementing 2S-AD for the combined production of hydrogen and methane using organic fractions (OFMSW, food waste, and garden refuse) comparable to the waste commonly available in South African municipalities [19–22]. However, the pilot scale implementation of 2S-AD is still in the early stages, with plenty of room for further optimisation [23–26]. Additionally, successful examples are found only in industrialised countries, while this new technology has not been tested in low- and middle-income countries having different environmental targets and available infrastructure [13].

For these reasons, this paper aims to explore the potential valorisation of municipal organic waste through 2S-AD using a life-cycle assessment (LCA) approach, the first step before testing a prototype at a pilot scale. The eThekwini Municipality of Durban, South Africa, has been selected as a case study, and the potential impacts deriving from the implementation of the new technology have been evaluated using a South African model. The Waste to Resource Optimisation and Scenario Evaluation (WROSE) model has been developed by the South African Research Chair (SARCHI) in Waste and Climate Change over the last decade [15,27–29]. This paper focuses on the assessment using the environmental indicators included in WROSE, while the techno-economic, social, and institutional indicators will be investigated at a later stage.

Additionally, this research aims to assist the Department of Forestry, Fisheries, and Environment (DFFE) in developing a comprehensive mitigation strategy for greenhouse gas (GHG) emissions from the waste sector in South Africa. Currently, the country relies on a Tier 1 approach of the United Nations Framework Convention on Climate Change (UNFCCC) methods to set the Nationally Determined Contributions (NDCs) through the Mitigation Potential Analysis (MPA), which is based on non-country-specific models and emission factors [4,30]. However, this study aims to transition towards a more advanced Tier 3 approach, integrate country-specific emission factors in a South African-based model such as WROSE, and enhance the accuracy and effectiveness of the national mitigation efforts. Therefore, in addition to exploring the use of 2S-AD as a waste management technology, this paper highlights its potential as a mitigation technology to reduce the carbon footprint of the waste sector.

2. Materials and Methods

2.1. Case Study: The eThekwini Municipality

The eThekwini Municipality in Durban was selected as the case study for the application of the WROSE model within the specific context of a South African Metropolitan Municipality. This decision was informed by the availability of waste data and the critical need for mitigation measures, particularly considering the city's vulnerability to extreme weather events unquestionably related to climate change [31].

The eThekwini Municipality is situated on the south-eastern shores of the KwaZulu-Natal province of South Africa. It extends for 2297 km^2 and has a population of around 3.8 million people, distributed across rural (45%), peri-urban (30%), and urban (25%) areas [32].

The total MSW generation of eThekwini was quantified at 873,000 tonnes in 2020, corresponding to a 12% increase compared to 2000 levels (782,000 tonnes). Projections for 2050 estimate that, thanks to an average annual growth rate of 1.05% between 2020 and 2050, MSW production will surpass 1 million tonnes per year, reaching 1,193,000 tonnes in 2050, equating to a per capita production of 239 kg/year (0.65 kg/day) [29].

Regarding waste composition, the most recent data (Figure 1) shows that the biogenic fraction constitutes almost half of the total refuse: food waste makes up 29% of MSW, while garden refuse accounts for 18% of municipal waste [2].

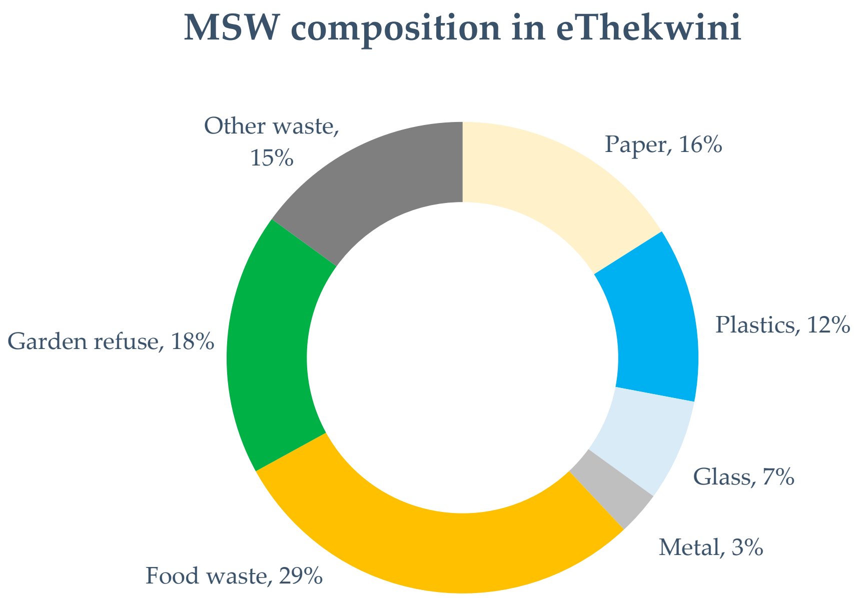

Figure 1. Average MSW composition in eThekwini (adapted from Friedrich and Trois, 2013 [2]).

The eThekwini Municipality operates four general waste landfill sites, of which only two remain active: Buffelsdraai and Lovu (Table 1). Commissioned in 2006, the Buffelsdraai landfill has an estimated operational lifespan of 60 years and encompasses 100 hectares of land with a total capacity of over 43 million m^3. The Lovu landfill site, situated south of Durban, started its operational life in 2014 and has an estimated airspace of about 9.6 million m^3 [33].

Table 1. Features of active sanitary landfill facilities in the eThekwini Municipality (adapted and modified from Trois et al., 2023, and Moodley et al., 2019 [29,33]).

Features	Buffelsdraai	Lovu
Opening year	2006	2014
Accepted waste fractions	MSW, garden refuse, C and D waste	MSW, garden refuse, C and D waste
Type of facility/ Baseline scenario	Sanitary landfill with gas recovery and flaring	Sanitary landfill with gas recovery and flaring
Average waste received	2135 tonnes/day	770 tonnes/day
Landfill footprint	100 ha	52 ha
Rehabilitated areas	23.2 ha	0.85 ha
Design airspace availability	43,026,691 m^3	9,660,000 m^3
Approximate remaining airspace availability	40,185,392 m^3	8,786,615 m^3
Remaining design life (2020)	52 years	32 years

The two closed facilities of Bisasar Road and Mariannhill (Table 2) still accept construction and demolition (C and D) waste and garden refuse. Both landfills boast a landfill gas recovery system with electricity generation.

Table 2. Features of closed sanitary landfill facilities in the eThekwini Municipality (adapted and modified from Trois et al., 2023, and Moodley et al., 2019 [29,33]).

Features	Bisasar Road	Mariannhill
Opening year	1980	1986
Year of closure	2015	2019
Accepted waste fractions	Since closure, only garden refuse, sand, C and D waste	Since closure, only garden refuse, sand, C and D waste
Type of facility/ Baseline scenario	Sanitary landfill with gas recovery and gas-to-energy facility for the generation of electricity (6 MW)	Sanitary landfill with gas recovery and gas-to-energy facility for the generation of electricity (1 MW)
Average waste received (before closure)	1000 tonnes/day	300 tonnes/day
Landfill footprint	44 ha	53 ha
Rehabilitated areas	36 ha	19.3 ha
Design airspace availability	25,000,000 m^3	4,400,000 m^3
Approximate remaining airspace availability	330,000 m^3	102,500 m^3
Remaining design life (2020)	1 year	1 year

In the early 2000s, the Bisasar Road landfill was used to dispose of up to 80% of the yearly MSW production in eThewkini, while the Mariannhill landfill only played a secondary role. However, as Bisasar Road quickly reached capacity, the opening of the two new disposal sites of Buffelsdraai (2006) and Lovu (2014) profoundly modified the allocation of waste into each facility (Figure 2). As of 2020, Buffelsdraai receives approximately 75% of the municipal refuse, while the remaining waste is sent to the Lovu landfill after the closure of both Bisasar Road and Mariannhill landfills.

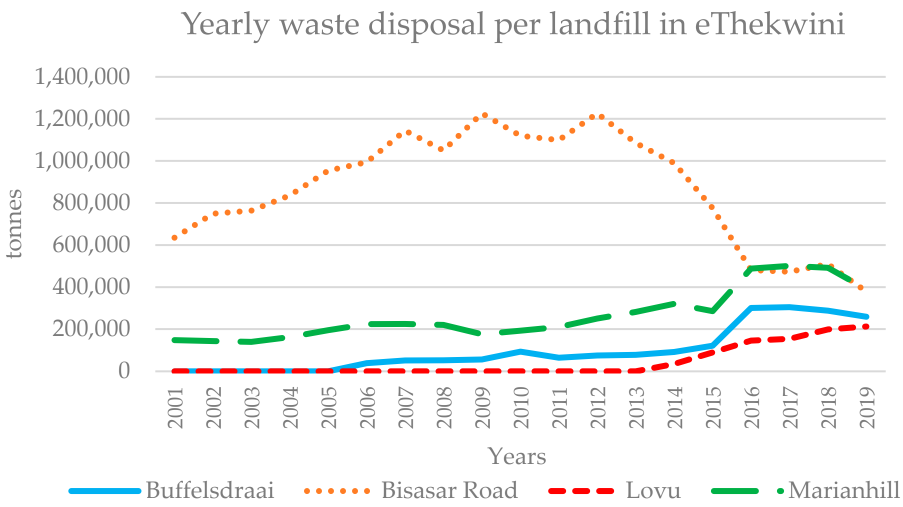

Figure 2. Yearly waste disposal per landfill in eThekwini between 2001 and 2019 (adapted and modified from Trois et al., 2023 [29]).

Two additional landfills, Wyebank and Shallcross, are specifically used for the garden refuse produced in the eThekwini Municipality. Additionally, twenty-one transfer stations (seven dedicated to MSW and fourteen for garden refuse) are part of the municipal waste system. Domestic waste collection is carried out once per week exclusively by the municipal provider, Durban Solid Waste (DSW). In contrast, the commercial and industrial refuse collection is shared between DSW and community-based contractors (CBCs) [34].

2.2. Forecasting of Future Waste Generation

The estimation of future waste generation has been carried out using waste collection and disposal statistics obtained from DSW for 2000–2020. The historical data have been projected until 2050 based on future population estimates from Statistics South Africa (2022–2031) and then on the growth rate reported by the United Nations Department of Economic and Social Affairs (UNDESA) in its World Urbanisation Prospects report [29,35–37]. The results of the projections are represented in Table 3 below.

Table 3. Population, municipal, and per capita waste generation in eThekwini: historical data (2000–2020, data from Trois et al., 2023 [29]) and projections (2021–2050).

Year	Population	Municipal Waste Generation [t/y]	Waste Generation per Capita [kg/cap/day]
2000	3,021,363	781,958	0.71
2005	3,215,478	1,148,743	0.98
2010	3,479,351	1,405,270	1.11
2015	3,727,139	1,272,151	0.94
2020	3,975,049	873,236	0.61
2025	4,188,225	915,045	0.60
2030	4,429,044	1,006,712	0.62
2035	4,592,371	1,028,568	0.61
2040	4,743,168	1,085,441	0.63
2045	4,878,405	1,141,169	0.64
2050	4,995,733	1,193,657	0.65

2.3. Implementation of Alternative Waste Management Strategies

The eThekwini Municipality does not carry out separate organic waste collection. Biodegradable waste is mixed with the non-recyclable fractions and sent to the municipal landfills. Even the fruit and vegetable market wastes are currently disposed of in the Lovu landfill after being stored in the transfer station located in the Durban Fresh Produce Market (DFPM) in Clairwood. Additionally, the separate collection of recyclables in orange (paper, plastic, cardboard, and polystyrene) and clear bags (glass and tin), which guaranteed an estimated segregation of 15% of recyclables [33], stopped after the onset of the 2020 coronavirus pandemic, further increasing the load on the already strained municipal landfill sites.

This manuscript aims to propose an alternative organic waste management scheme, following the footsteps of previous research based on the dry/wet model, which combines drop-off, kerbside collection, and central sorting, first presented by Matete and Trois in 2008 [38].

According to the new plan, effective organic waste management will be promoted following different steps implemented between 2027 and 2035 in different city areas. Initially, the fruit and vegetable waste originating at the municipal fresh produce markets will be collected at the transfer station situated in DFPM, where the placement of a pilot double-stage anaerobic digestion system is proposed. The pilot stage of the project will be carried out starting in 2027. It has been estimated that 5831 tonnes/year of clean fruit and vegetable market waste, accounting for 2.2% of all eThekwini's OFMSW, will be diverted from landfilling and fed to the pilot digester [37]. This amount of vegetable market waste is assumed to be steady during the duration of the project due to the space constraints of the municipal markets.

From 2029 to 2035, the four phases of the household separate collection scheme will be carried out in selected areas, increasing the number of neighbourhoods involved in the project every five years. The wards taking part in each phase have been selected based on the presence of formal dwellings, weekly waste collection (informal settlements not regularly served by DSW have not been included at this stage), and proximity to the future organic waste treatment site based at DFPM.

Phase 1, starting in 2029, will see the involvement of the central neighbourhood of Chatsworth, increasing the amount of OFMSW diverted and sent to the pilot digester to 4% of the municipal biowaste production.

Phase 2 will commence in 2031 and be limited to the city centre, accounting for 6.3% of OFMSW.

Since 2033, Phase 3 will include most southern and western neighbourhoods, bringing the diversion rate of OFMSW to over 9.6%.

Finally, the project will be extended to the northern coastal areas of the municipality in 2035, with a potential intercept of 13.1% of the OFMSW produced in eThekwini.

The geographical distribution and the characteristics of the areas involved in the new household separate collection scheme are highlighted in Figure 3 and Table 4 below.

Table 4. Characteristics of the areas involved in the proposed organic waste management scheme.

Phase	Start Date	Estimated OFMSW Production [t/y]	Estimated OFMSW Recovery [t/y]	%	Total Population Served	Neighbourhoods Added in Phase
Pilot	2027	275,996	5831	2.1%	N/A	Fresh produce markets of eThekwini
Phase 1	2029	286,630	11,549	4.0%	196,580	Chatsworth
Phase 2	2031	293,214	18,454	6.3%	422,443	City centre (Bellair, Berea, Bluff, Carrington Heights, Essenwood, Glenmore, Montclair, Mount Vernon, Woodlands, Yellow Wood Park)
Phase 3	2033	295,749	28,397	9.6%	751,569	Southern (Amanzimtoti, Athlone Park, Isipingo Hills, Isipingo Rail, Kingsburgh, Lotus Park) and western suburbs (Everton, Gillitts, Hillcrest, Kloof, Pinetown, Reservoir Hills, Sherwood, Sparks, Waterfall, Westville)
Phase 4	2035	298,285	39,030	13.1%	1,095,248	Northern suburbs (Athlone, Beachwood Mangroves, Broadway, Glen Anil, Glen Ashley, Glen Hill, Hambanathi, La Mercy, Mount Edgecombe, Park Hill, Phoenix, Prospect Hall, Tongaat, Tongaat Beach, Umdloti, Umgeni Park, Umhlanga, Verulam, Virginia, Westbrook)

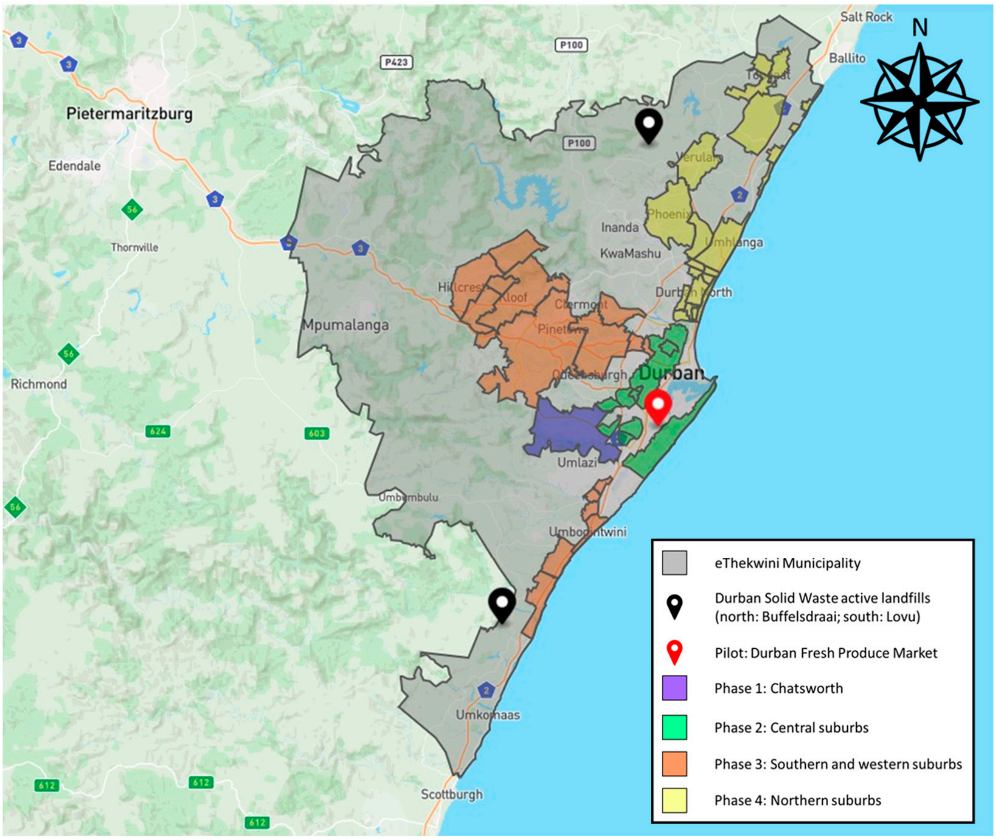

Figure 3. Geographical distribution of the areas involved in the proposed scheme for the separate collection of household organic waste.

For each neighbourhood, it is assumed that only 50% of the potentially available biowaste will be effectively separated at the source, while the remaining half is not expected to be intercepted by the source separation program. This number is a prudential estimate based on European experiences, where the best source-separation programs intercepted at most 70–80% of OFMSW [39,40]. Regrettably, similar optimal conditions are not expected in South Africa.

2.4. Waste Management Scenarios

The tool used for the analysis is the Waste to Resource Optimisation and Scenario Evaluation (WROSE) model. WROSE has been developed since 2009 by the South African Research Chair (SARCHI) in Waste and Climate Change at the University of KwaZulu-Natal (UKZN) in Durban, South Africa [27,41].

The initial goal of the tool was to identify and evaluate zero waste strategies using a dry-wet waste diversion model, with the aim of preventing the disposal of recoverable or biodegradable waste fractions into landfills [27,41]. The scenarios were generated by combining several waste diversion strategies and treatment methods to incorporate South Africa's existing waste disposal practices with potential alternative waste management techniques.

WROSE performs the assessment by analysing input data such as waste quantity and composition. Following a Life Cycle Assessment (LCA) approach, the model evaluates the mass of waste disposed of or diverted for each combination of strategies and treatment methods. The quantification of results is guided by a specific set of indicators: environmental, techno-economic, and, since 2018, social and institutional [15,27–29,42]. For instance, the assessment of a scenario's carbon footprint relies on the quantity of each waste fraction and its corresponding carbon emission factor, which varies across fractions. The US EPA emission factors initially embedded in WROSE have subsequently been replaced with updated factors that depict the South African context with a higher degree of accuracy [2,43].

The scenarios considered are based on the original WROSE scenarios but adapted to the current situation and the goals of this study, which focuses primarily on the valorisation of clean organic waste [29]. Therefore, systems such as recycling or material recovery facilities (MRF), whose output is not a clean biodegradable fraction, are not taken into consideration in this research.

The scenarios developed for this investigation are represented in Figure 4 and listed below.

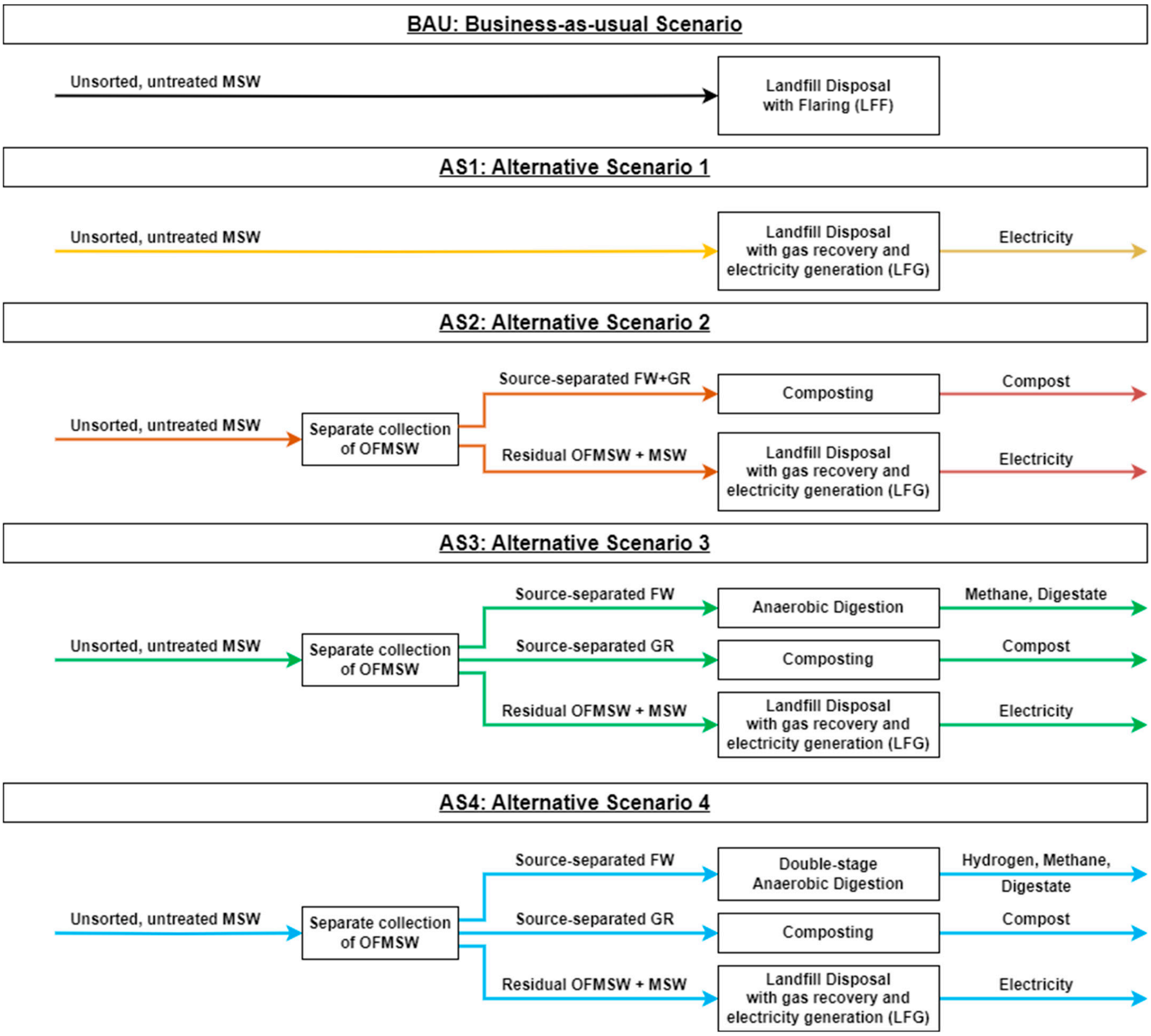

Figure 4. Proposed waste management scenarios based on WROSE scenarios (adapted and modified from Dell'Orto and Trois (2022) and Trois and Jagath (2011) [15,27]).

2.4.1. Business-as-Usual (BAU) Scenario: Landfilling with Gas Recovery and Flaring (LFF)

The baseline scenario consists in the landfilling of MSW in the two active municipal landfills, Buffelsdraai and Lovu, which are equipped with a landfill gas extraction and flaring system (LFF). This configuration corresponds to Scenario 2A of the WROSE model [29].

2.4.2. Alternative Scenario 1 (AS1): Landfilling with Gas Recovery and Electricity Generation (LFG)

The first alternative scenario corresponds to the current situation in the two closed municipal landfills, Bisasar Road and Mariannhill. The biogas extracted from the two landfills is burned to produce electricity, which is fed into the municipal grid. The same configuration is proposed for the two active landfills, where the current flaring system would be replaced with biogas-to-electricity generators, aiming to reduce waste-related GHG emissions. Such configuration corresponds to Scenario 2B of the WROSE model [29].

Although this alternative does not achieve any separation of organic waste, the scenario is included in the analysis as the most likely to be implemented in the immediate future by the eThekwini Municipality.

2.4.3. Alternative Scenario 2 (AS2): Landfilling with Gas Recovery and Electricity Generation (LFG) and Composting

This configuration optimises scenario AS1, thanks to the diversion of organic waste achieved through the plan discussed in Section 2.3 above. The source-separated food waste is sent to a composting facility (to be built) along with the garden refuse separated at the source by the eThekwini Municipality, which equates to approximately 35% of the garden waste produced in Durban [44]. The non-segregated food waste and garden refuse are disposed of in the two active municipal landfills of Buffelsdraai and Lovu. The amount of landfilled food waste depends on the ongoing phase of the proposed organic waste management scheme (e.g., 97.9% between 2026 and 2027).

Although based on Scenario 5 of the WROSE model, this alternative differs from the original due to the lack of a recycling facility for fractions such as glass, metal, paper, and plastic [29]. However, the partial diversion of organic waste reduces the amount of waste landfilled, leading to an extension of the lifespan of the two active municipal landfills.

2.4.4. Alternative Scenario 3 (AS3): Landfilling with Gas Recovery and Electricity Generation (LFG), Anaerobic Digestion (AD), and Composting

In this alternative, the configuration proposed in AS2 is further refined by differentiating the treatment method for food waste and garden refuse. While the latter is still sent to a composting facility, food scraps feed an anaerobic digestion plant to be built in the perimeter of the Durban Fresh Produce Market. The market currently hosts a transfer station, managed by Durban Solid Waste, for temporary storage of fruit and vegetable waste before final disposal into the Lovu landfill. The site selection aims to minimise the transportation costs during the initial stages of the proposed organic waste management scheme.

This scenario, similar to Scenario 4A of the WROSE model, aims to reduce the amount of waste sent to landfills [29]. Additionally, sending food waste to anaerobic digestion instead of composting reduces the carbon emissions caused by the alternative treatment of organic waste while obtaining methane-rich biogas that can be used to produce electricity. However, AS3 does not include any separate collection or treatment of recyclable materials, which are still sent to landfills.

2.4.5. Alternative Scenario 4 (AS4): Landfilling with Gas Recovery and Electricity Generation (LFG), Double-Stage Anaerobic Digestion (2S-AD), and Composting

This configuration improves the previous scenario AS3, where food waste is treated through double-stage anaerobic digestion (2S-AD) instead of single-stage AD. This method's main benefit is the possibility of extracting hydrogen gas from the first stage of 2S-AD. The hydrogen produced by the reactor can be either burned on-site to contribute to the energy demands of the 2S-AD system or, more advantageously, collected and sold for industrial use. Replacing the non-renewable grey hydrogen, currently obtained through high-emission methods based on fossil fuels (steam methane reforming, SMR), with green hydrogen generated through 2S-AD further offsets carbon emissions [45].

Similar to AS2 and AS3, this scenario does not account for source separation and recycling of glass, metals, paper, and plastics. The inclusion of recycling in the analysis will be evaluated at a later stage of the research.

2.5. Indicators

The WROSE model performs the comparative analysis of scenarios based on a set of environmental, techno-economic, social, and institutional indicators [15,42]. Since the main aim of the research is to assist the South African government in developing a mitigation strategy for GHG emissions originating from the waste sector, this study focuses on the environmental indicators only. On the other hand, the evaluation based on the other indicators (e.g., techno-economic) will be carried out in the future.

2.5.1. Greenhouse Gas (GHG) Emission/Reduction Assessment

The assessment of the carbon emissions or reductions related to implementing a specific scenario, expressed in $MtCO_{2eq}$, have been estimated using Equation (1) below [29].

$$\text{Emissions/reductions } [MtCO_{2eq}] = \text{Waste quantity } [t] \times \text{emission factor } [MtCO_{2eq}/t] \quad (1)$$

Equation (1) has been calculated for each waste fraction in each scenario to determine the emission factor associated with each waste management technology. The emission factors included in the WROSE model have been developed by the researchers of the SARCHI Waste and Climate Change group for LFF, LFG, composting, and AD [2,27,43]. The factor for AD has been adjusted to account for updated transportation emissions, average methane yield for a food waste of standard composition (total solids (TS) = 23%; volatile solids (VS) = 92.5% TS), and average emissions for energy generated [46–51]. The list of calculations and assumptions is presented in Table 5 below.

Table 5. Calculation of emission factor for AD (adapted and modified from Trois and Jagath, 2011 [27]).

Emission Category	Factor [$MtCO_{2eq}/t$]	Assumptions	Reference
Direct emissions	0.00105	Based on the Tier 1 approach from IPCC • 1 g CH_4/kg wet waste • N_2O emissions negligible • 95% methane recovered for electricity generation	 [27,30,52] [27,30,52] [27,30,52]
Transportation emissions	0.01208	• Average fuel efficiency in South Africa: 4.53 L/t • Average emission factor for diesel: 2.6676 $kgCO_{2eq}$/L	[46] [51]
Energy emissions/ reductions	−0.21026	Emissions from combustion: 0.0024 $MtCO_{2eq}$/t Emissions from the substitution of electricity: −0.21266 $MtCO_{2eq}$/t • Average SMP in AD: 0.45 m^3 CH_4/kg VS • Average TS content in Food Waste (FW): 0.23 kg TS/kg FW • Average VS in FW: 0.21275 kg VS/kg FW (92.5% TS) • Average CH_4 yield: 95.7 Nm^3/t • Calorific value of CH_4: 6.39 kWh/m^3 • Energy recovery rate: 40% • Energy required for AD: 18% of energy recovered • Average emission factor per energy generated: 1.06 kg CO_{2eq}/kWh	[27] [48] [49,50] [49,50] [27,53] [27,53] [27,53] [47]
Digestate emissions	−0.04430	Estimated by Trois and Jagath (2011) using European data	[8,27,53]
Emission factor	**−0.24143**		

Additionally, an emission factor for 2S-AD was formulated following the methodology used by Trois and Jagath (2011), adapted from Møller et al. (2009), for the calculation of the factor for AD [27,53]. The estimation was conducted using wet waste weight, which was obtained by assuming an addition of 0.6 m^3 of water per tonne of food waste.

The emission factor is comprised of four separate groups of emissions or reductions.

1. *Direct emissions*. The calculation of direct process emissions followed the IPCC Guidelines for National Greenhouse Gas Inventories and the indications included in the IPCC Emission Factor Database, as used by the United States Environmental Protection Agency (US EPA) in its Waste Reduction Model (WARM) for single-stage AD [30,52,54]. The absence of national data and statistics from South Africa implies that the Tier 1 approach is the optimal strategy for evaluating GHG emissions. According to the guidelines, the emissions factor for the biological treatment of OFMSW is 1 g CH_4 / kg of wet waste. Nitrous oxide emissions are considered negligible, and approximately 95% of the methane produced is recovered for energy generation. Additionally, the direct emissions calculated for single-stage AD have increased by 6.7% by taking into account an enhanced methane yield in 2S-AD (102.1 Nm^3/t vs. 95.7 Nm^3/t) based on an average specific methane production rate (SMP) of 0.48 m^3 CH_4/kg VS for a standard food waste composition (TS = 23%; VS = 92.5% TS) [24,49,50]. The direct emissions amount to 0.00112 $MtCO_{2eq}/t$ wet waste.
2. *Collection and transportation emissions*. The collection and transportation emissions have been estimated by Abera (2022) based on a sample of 18 municipalities in South Africa [46]. It has been calculated that the average fuel consumption of municipal garbage trucks is 4.53 L/t wet waste, while the emission factor for diesel is 2.6676 $kgCO_{2eq}/L$ [51]. Consequently, the average emission factor is 0.01208 $MtCO_{2eq}/t$ wet waste.
3. *Energy emissions/reductions*. Energy-related emissions can be broken down into three components: emissions from the combustion of methane, reductions due to the substitution of electricity produced from fossil fuels, and reductions through the generation of green hydrogen in place of grey hydrogen.
    a. The emissions from combustion have been estimated at 0.0024 $MtCO_{2eq}/t$ of wet waste by Trois and Jagath (2011) [27].
    b. The emission reductions due to the substitution of electricity generation have been estimated for the average methane yield calculated at 102.1 Nm^3/t for standard food waste (TS = 23%, VS = 92.5% TS) [49,50]. Considering that the calorific value of methane is 6.39 kWh/Nm^3, the energy generated through its combustion equates to 652.4 kWh/t [53]. The recovery rate is assumed to be 40%, while the requirement for the digestion process is 36% (18% for each stage) of the recovered energy [27,53]. Consequently, the reduction can be calculated by dividing the available energy by 1.06 kg CO_{2eq}/kWh, the emission factor for energy generated by the South African electricity public utility, Eskom, which relies almost exclusively on coal [47]. The resulting emission reduction from substituting fossil fuel-generated electricity is -0.17704 $MtCO_{2eq}/t$ of wet waste.
    c. The last group of emission reductions examines the impacts of replacing hydrogen generation through carbon-based methods (grey hydrogen) with technologies that do not need fossil fuels and are fully sustainable (green hydrogen) [55]. Around 95% of global hydrogen production relies on fossil fuels, with steam methane reforming (SMR) being the most common technique for industrial hydrogen production [45,56]. Replacing SMR with green hydrogen produced through a sustainable technology such as 2S-AD will have beneficial effects in terms of reduced carbon emissions that have been quantified using the lower heating value (LHV) of hydrogen gas (10.8011 MJ/Nm^3 H_2) [56,57]. The average hydrogen yield has been estimated at 14.9 Nm^3/t, based on a specific hydrogen production (SHP) of 0.07 m^3 CH_4/kg VS for a food waste of standard composition (TS = 23%, VS = 92.5% TS) [24,49,50]. The emission reduction can be calculated by multiplying the LHV of hydrogen by the SHP and then by the emission factor of grey H_2, which is, on a 100-year time horizon (GWP100), equivalent to 33.8 g CO_{2eq}/MJ [45]. The resulting emission factor from substituting grey hydrogen with green hydrogen is -0.0543 $MtCO_{2eq}/t$ of wet waste.

The energy-related emission factor amounts to −0.18008 $MtCO_{2eq}$/t wet waste.

4. *Digestate emissions*. This part includes the emissions from digestate application and the reductions achieved by replacing inorganic chemical fertilisers with compost derived from digestate. Given the lack of information about the production of fertilisers in South Africa, European data was adjusted to determine the South African factor. The different climatic conditions of Durban (higher temperatures and humidity, more intense solar radiation than in northern Europe, leading to faster biological reactions) resulted in lessened emission reductions compared to those assumed for European climates. The South African factor was estimated at −0.0443 $MtCO_{2eq}$/t wet waste by Trois and Jagath in 2011 [27].

The emission factor for 2S-AD, calculated as the sum of the four abovementioned components, is equivalent to −0.21117 $MtCO_{2eq}$/t wet waste (Table 6).

Table 6. Calculation of emission factor for 2S-AD.

Emission Category	Factor [$MtCO_{2eq}$/t]	Assumptions	Reference
Direct emissions	0.00112	Based on the Tier 1 approach from IPCC used for AD • 1 g CH_4/kg wet waste • N_2O emissions negligible • 95% methane recovered for electricity generation • Methane production increased by 6.7% (102.1 Nm^3/t vs. 95.7 Nm^3) in 2S-AD compared to AD • Average SMP in 2S-AD: 0.48 m^3 CH_4/kg VS • Average TS content in FW: 0.23 kg TS/kg FW • Average VS in FW: 0.21275 kg VS/kg FW (92.5% TS) • Average CH_4 yield in 2S-AD: 102.1 Nm^3/t	[27,30,52] [27,30,52] [27,30,52] [24] [49,50] [49,50]
Transportation emissions	0.01208	• Average fuel efficiency in South Africa: 4.53 L/t • Average emission factor for diesel: 2.6676 $kgCO_{2eq}$/L	[46] [51]
Energy emissions/ reductions	−0.18008	Emissions from combustion: 0.0024 $MtCO_{2eq}$/t Emissions from the substitution of electricity: −0.17704 $MtCO_{2eq}$/t • Average CH_4 yield in 2S-AD: 102.1 Nm^3/t • Calorific value of CH_4: 6.39 kWh/m^3 • Energy recovery rate: 40% • Energy required for 2S-AD: 36% of energy recovered (18% × 2 reactors) • Average emission factor per energy generated: 1.06 kg CO_{2eq}/kWh Emissions from the substitution of grey H_2: −0.0543 $MtCO_{2eq}$/t • Calorific value of H_2: 10.8011 MJ/Nm^3 • Average SHP in 2S-AD: 0.07 m^3 H_2/kg VS • Average H_2 yield in 2S-AD: 14.9 Nm^3/t • Emission factor of grey H_2 (GWP100): 33.8 g CO_{2eq}/MJ	[27] [27,53] [27,53] [27,53] [47] [56,57] [24] [45]
Digestate emissions	−0.04430	Estimated by Trois and Jagath (2011) using European data	[8,27,53]
Emission factor	**−0.21117**		

The resulting emission factor shows that, despite displaying a higher methane yield (102.1 Nm^3/t) than AD (95.7 Nm^3/t), 2S-AD does not achieve the same emission reduction of AD (−0.21117 $MtCO_{2eq}$/t versus −0.24143 $MtCO_{2eq}$/t), as the double-reactor configuration of 2S-AD necessary to guarantee ideal conditions to diverse bacterial species and maximise yields leads to higher energy requirements.

The complete list of factors used in the elaborations is listed in Table 7 below.

Table 7. Emission factors used in the WROSE elaborations.

Technology	Waste Fractions	Emission Factor [$MtCO_{2eq}/t$]
Landfilling with gas recovery and flaring (LFF)	Mixed waste	0.1012
Landfilling with gas recovery and electricity generation (LFG)	Mixed waste	−0.1445
Composting	Food waste (FW) and garden refuse (GR)	0.1850
Anaerobic digestion (AD)	Food waste (FW)	−0.24143 *
Double-stage anaerobic digestion (2S-AD)	Food waste (FW)	−0.21117 *

* Updated/new emission factor.

2.5.2. Landfill Airspace Savings

The evaluation of the savings in landfill capacity resulting from waste diversion is determined through empirical calculations. Site-specific conditions and operational practices, particularly waste compaction within landfill cells, directly impact the airspace preserved. The quantification of landfill space savings relies on compaction techniques and the efficiency with which they are implemented.

The landfill airspace savings can be calculated by dividing the amount of waste diverted from the landfill by the average waste compaction rate (Equation (2)). In this study, the density of the compacted waste is assumed to be 1.2 t/m^3 [29].

$$\text{Landfill airspace savings } [m^3] = \text{Waste diverted } [t] / \text{Density of compacted waste } [t/m^3] \tag{2}$$

2.5.3. Landfill Monetary Savings

The financial savings achieved through the diversion of waste from landfills highlight the potential benefit of not paying the landfill gate fees for the diverted waste.

They can be obtained by multiplying the amount of waste diverted by the landfill gate fee for a unit of waste, as shown in Equation (3). The financial savings are expressed in Rand (R), the monetary unit of South Africa, which corresponds to 0.055 US dollars, as of 13 August 2024 [58].

$$\text{Landfill monetary savings } [R] = \text{Waste diverted } [t] \times \text{Landfill gate fee } [R/t] \tag{3}$$

Historical data on landfill gate fees in the eThekwini Municipality has been collected for the quinquennium 2021–2025 and then projected for 2026–2050 based on the inflation rate of 4.5% forecasted for South Africa by the International Monetary Fund from 2024 to 2028 [59,60]. The same inflation rate has been extrapolated and assumed constant until 2050 to enable the execution of the calculations. The list of the actual and predicted gate fees between 2021 and 2050 is shown in Table 8 below.

Table 8. Landfill gate fees for the eThekwini Municipality (2021–2025: actual fees; 2026–2050: predicted fees).

Year	Gate fee	Source	Year	Gate fee	Source	Year	Gate fee	Source
2021	R500	[61]	2031	R901 *	[59,60]	2041	R1399 *	[59,60]
2022	R521	[62]	2032	R942 *	[59,60]	2042	R1462 *	[59,60]
2023	R599	[62]	2033	R984 *	[59,60]	2043	R1528 *	[59,60]
2024	R644	[62]	2034	R1028 *	[59,60]	2044	R1597 *	[59,60]
2025	R692	[62]	2035	R1075 *	[59,60]	2045	R1669 *	[59,60]
2026	R723 *	[59,60]	2036	R1123 *	[59,60]	2046	R1744 *	[59,60]
2027	R756 *	[59,60]	2037	R1174 *	[59,60]	2047	R1822 *	[59,60]
2028	R790 *	[59,60]	2038	R1226 *	[59,60]	2048	R1904 *	[59,60]
2029	R825 *	[59,60]	2039	R1282 *	[59,60]	2049	R1990 *	[59,60]
2030	R862 *	[59,60]	2040	R1339 *	[59,60]	2050	R2080 *	[59,60]

* Forecast based on projected inflation rate (4.5%) from the International Monetary Fund [59,60].

2.5.4. Waste Diversion Rate

The waste diversion rate refers to the total quantity of waste diverted from the landfill when alternative treatment methods are performed. It is expressed in terms of percentage as the ratio between the amount of waste diverted from landfills and the amount of waste produced and collected for each waste stream (Equation (4)).

$$\text{Waste diversion rate [\%]} = \text{Waste diverted [t]}/\text{Waste collected [t]} \tag{4}$$

3. Results and Discussion

The scenario analysis performed using the WROSE model has compared the business-as-usual (BAU) scenario of landfilling with gas recovery and flaring (LFF) with four alternatives:

- AS1: landfilling with gas recovery and electricity generation (LFG)
- AS2: LFG and composting
- AS3: LFG, AD, and composting
- AS4: LFG, 2S-AD, and composting

The performance of the five scenarios has been assessed based on the following four environmental indicators included in WROSE.

3.1. Greenhouse Gas (GHG) Emissions

The GHG emissions deriving from the suggested organic waste management scheme in the eThekwini Municipality are shown in Table 9 and Figure 5 below. The cumulative emissions for the 2026–2050 timeframe are set to surpass 2,100,000 $MtCO_{2eq}$ for the current BAU scenario by 2050. On the other hand, operating an electricity generation system to replace flaring in the active landfill sites would completely offset the current emissions, reducing them by over 243% in scenario AS1.

Table 9. Projected 2026–2050 cumulative GHG emissions at 4-year intervals for the eThekwini Municipality.

Scenario	**Projected Cumulative GHG Emissions since 2026 ($MtCO_{2eq}$)**							**2026–2050 Emission Reduction Potential**	
	2026	**2030**	**2034**	**2038**	**2042**	**2046**	**2050**		
BAU	0	321,072	654,744	997,593	1,355,305	1,727,600	2,113,822		
AS1	0	−458,447	−934,886	−1,424,429	−1,935,193	−2,466,780	−3,018,254	**−5,132,077**	**−243%**
AS2	0	−380,073	−758,024	−1,135,480	−1,529,298	−1,939,172	−2,364,379	**−4,478,202**	**−212%**
AS3	0	−614,733	−1,253,610	−1,910,070	−2,594,987	−3,307,828	−4,047,336	**−6,161,158**	**−291%**
AS4	0	−586,203	−1,194,490	−1,818,919	−2,470,417	−3,148,476	−3,851,901	**−5,965,724**	**−282%**

The proposed source-separation scheme for organic waste would achieve the highest emission reduction (−291%) in scenario AS3, which includes composting of garden refuse and anaerobic digestion of food waste. This cutback on GHG emissions is mainly due to the substitution of electricity generation from coal with the energy deriving from the methane produced during AD.

Scenario AS4, which includes 2S-AD, would still achieve significant reductions compared to BAU (−282%) and AS1, although leading to higher emissions than AS3 due to the higher energy demand of the two-reactor system, which is necessary to maximise the hydrogen and methane yields for the different bacterial species in 2S-AD.

Lastly, scenario AS2 (landfilling + composting) proved to be the least effective in reducing the carbon footprint of waste management, even performing worse than scenario AS1, which does not include any source separation of waste. However, while the biogas produced in landfills is captured and burned in scenario AS1, composting is not always carbon-neutral [8]. In South Africa, it has been estimated that composting leads to the net release of GHGs into the atmosphere, negating the benefits of collecting food waste and garden refuse separately [43].

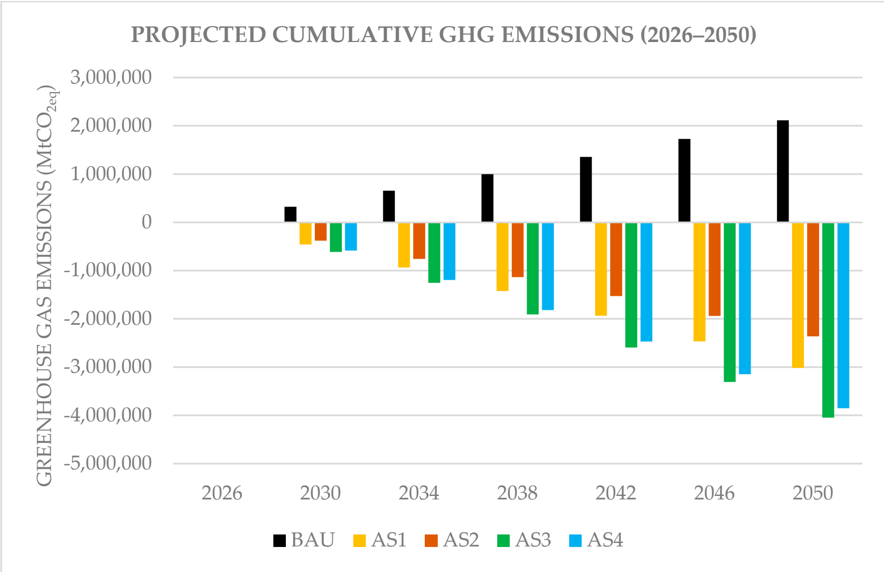

Figure 5. Projected 2026–2050 cumulative GHG emissions at 4-year intervals for the eThekwini Municipality.

3.2. Landfill Airspace Savings

The landfill airspace savings attained by the five different waste management scenarios in eThekwini are represented in Table 10 and Figure 6 below.

Table 10. Projected 2026–2050 landfill airspace savings at 4-year intervals for the eThekwini Municipality.

Scenario	Projected Cumulative Landfill Airspace Savings since 2026 (m^3)						
	2026	2030	2034	2038	2042	2046	2050
BAU	0	0	0	0	0	0	0
AS1	0	0	0	0	0	0	0
AS2	0	198,215	447,298	730,775	1,026,541	1,334,365	1,653,705
AS3	0	198,215	447,298	730,775	1,026,541	1,334,365	1,653,705
AS4	0	198,215	447,298	730,775	1,026,541	1,334,365	1,653,705

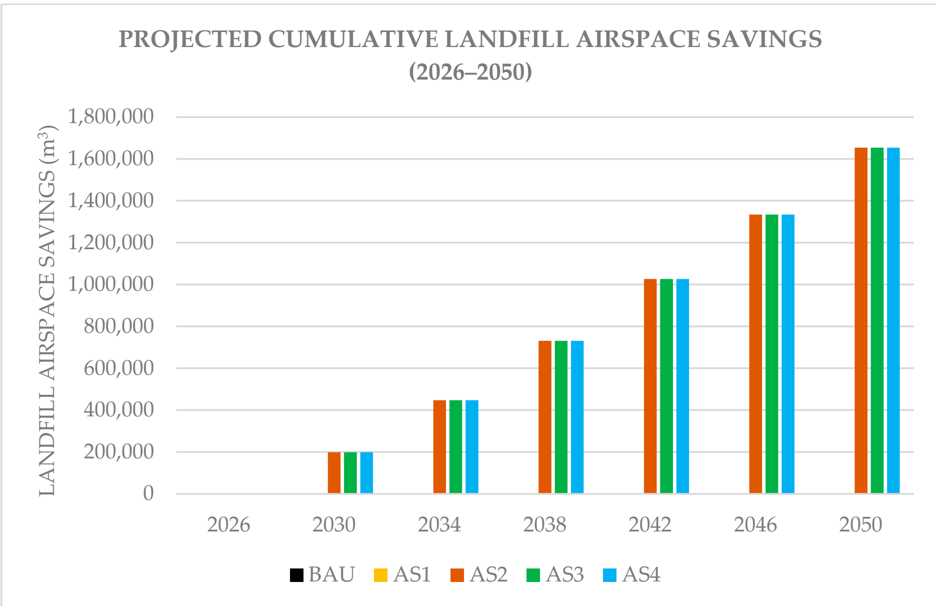

Figure 6. Projected 2026–2050 landfill airspace savings at 4-year intervals for the eThekwini Municipality.

In this analysis, the five strategies can be clustered into two groups. The first group includes scenarios BAU and AS1, which do not achieve any airspace savings since no alternative waste treatment method is implemented.

Conversely, the second class ensures the same airspace savings in each of the three remaining scenarios. All the proposed alternatives divert the same amount of food waste and garden refuse, although these fractions are treated differently in each scenario. The simulation predicts that AS2, AS3, and AS4 can prevent the disposal of over 1.65 million cubic meters of waste into the municipal landfills in the 2026–2050 interval. Furthermore, these savings correspond to the extension of the lifespan of the city landfills by approximately 1.66 years over 24 years (+6.9%), based on the cumulative airspace savings in 2050 (1,653,705 m^3), the density of compacted waste (1.2 m^3/tonne), and the projected municipal waste production in 2050 (1,193,657 tonnes/yr).

3.3. Landfill Monetary Savings

The landfill airspace savings created by alternative waste treatment strategies also result in monetary savings for the municipality, thanks to the avoided landfill gate fees. Based on the predicted gate fees listed in Section 2.5.3, the simulation with the WROSE model anticipates that, between 2026 and 2050, the eThekwini Municipality can potentially save over 3.8 billion Rand in gate fees if the proposed organic management scheme is implemented as part of scenarios AS2, AS3, or AS4 (Table 11).

Table 11. Projected 2026–2050 landfill monetary savings at 4-year intervals for the eThekwini Municipality.

Scenario	Projected Cumulative Landfill Monetary Savings since 2026 (R)						
	2026	2030	2034	2038	2042	2046	2050
BAU	0	0	0	0	0	0	0
AS1	0	0	0	0	0	0	0
AS2	0	R192m	R517m	R1008m	R1688m	R2617m	R3868m
AS3	0	R192m	R517m	R1008m	R1688m	R2617m	R3868m
AS4	0	R192m	R517m	R1008m	R1688m	R2617m	R3868m

3.4. Waste Diversion Rate

The WROSE simulations highlight that scenarios BAU and AS1 do not benefit from any diversion from landfills (Table 12). On the other hand, AS2, AS3, and AS4, which divert the same typologies of refuse (food waste and garden refuse), achieve a waste diversion rate that increases depending on the separation efficiency of the organic fractions. While the recovery rate of garden refuse is assumed to be constant at 35% for the whole 24-year interval, the amount of source-segregated food waste increases along with the extension of the organic waste management scheme to a broader area of the eThekwini Municipality. As a result, the diversion rate is 6.91% during the pilot phase, reaching a maximum of 10.09% between 2035 and 2050. These values are admittedly low since they are calculated based on the totality of the municipal waste production of eThekwini, including recyclable fractions and residual waste, which do not benefit from any alternative treatment. However, when considering only the organic fractions, comprising 47% of the total waste, the organic waste diversion rates are higher, achieving a maximum separation of 21.48% between 2035 and 2050.

Table 12. Projected 2026–2050 waste diversion rates for the eThekwini Municipality.

Scenario	Projected Waste Diversion Rates since 2026 (%)					
	2026	2027–2028	2029–2030	2031–2032	2033–2034	2035–2050
BAU	0.00	0.00	0.00	0.00	0.00	0.00
AS1	0.00	0.00	0.00	0.00	0.00	0.00
AS2	0.00	6.91	7.47	8.13	9.08	10.09
AS3	0.00	6.91	7.47	8.13	9.08	10.09
AS4	0.00	6.91	7.47	8.13	9.08	10.09

3.5. Comparative Analysis by 2050

The analysis of the performance of the business-as-usual scenario (BAU) versus each of the alternative scenarios, evaluated using the environmental indicators included in WROSE, is summarised in Table 13 below.

Table 13. Comparative analysis of scenarios based on environmental performance in 2050.

Scenario	GHG Emissions ($MtCO_{2eq}$)	GHG Emission Reduction (%)	Landfill Airspace Savings (m^3)	Landfill Lifespan Extension (Years)	Landfill Monetary Savings (R)	Waste Diversion Rate (%)
BAU	2,113,822	N/A	0	0	0	0
AS1	−3,018,254	−243%	0	0	0	0
AS2	−2,364,379	−212%	1,653,705	+1.66	R3868m	10.09
AS3	−4,047,336	−291%	1,653,705	+1.66	R3868m	10.09
AS4	−3,851,901	−282%	1,653,705	+1.66	R3868m	10.09

The comparison shows that business-as-usual is the worst-performing scenario, directly contributing to waste-related emissions while not achieving any benefit in the other indicators. Therefore, it is highly recommended that municipal leaders take prompt action to decrease the carbon footprint of eThekwini's waste management system and promote waste diversion.

The most immediate measure is represented by scenario AS1, which consists in the implementation of energy recovery in the active landfills of Buffelsdraai and Lovu, where a flaring system is already in operation. Using landfill gas to produce electricity would completely offset the current carbon emissions and help align with the targets set by the government in the Nationally Determined Contributions.

The consequent step to minimise the impact of waste management is to focus on the separate collection and specific treatment of organic waste. Scenarios AS2 (composting), AS3 (AD + composting), and AS4 (2S-AD + composting) all achieve a complete offset of the GHG emissions observed in the BAU scenario. Additionally, they all perform identically in terms of landfill indicators, achieving landfill airspace savings of around 1.6 million cubic meters over 24 years, corresponding to an extension of the lifetime of the current landfills of 1.66 years (+6.9%) and a saving of over 3.8 billion Rand until 2050 for the eThekwini Municipality, thanks to a waste diversion of 10.09%.

Nevertheless, the three scenarios manifest different levels of effectiveness in curbing carbon emissions. The composting scenario (AS2) does not achieve the same level of GHG emission reduction as scenario AS1, which does not account for the separate collection and treatment of organic waste due to the high release of carbon dioxide in composting. Conversely, combining the composting of garden waste with the anaerobic digestion of food waste results in the highest carbon emission offset (−291%) for scenario AS3. In scenario AS4, replacing AD with 2S-AD to allow for the recovery of hydrogen results in slightly diminished GHG emission reductions due to the higher energy demand of the double-stage configuration. Therefore, 2S-AD is not recommended when only environmental aspects are considered.

4. Conclusions

Diversion of organic waste is paramount to reducing the climate-altering emissions from landfilling and assisting countries in developing an effective climate action plan through their Nationally Determined Contributions. In South Africa, the Mitigation Potential Analysis is still based on a Tier 1 approach, and this study aims to help the transition towards a Tier 3 approach that relies on country-specific emission factors and models.

The environmental impact of the business-as-usual scenario has been compared to four alternative scenarios that include standard technologies, such as electricity generation from landfill gas, composting, and anaerobic digestion, to compare these waste management strategies as mitigation technologies. However, the analysis was not limited to established technologies, but included several elements of innovation. Firstly, double-stage anaerobic digestion, a promising technique yet to be implemented at the municipal level, has also been explored. Moreover, a South African-based emission factor for 2S-AD has been developed, and a new scenario inserting 2S-AD in a municipal setting has been introduced into the WROSE model to facilitate the shift towards a Tier 3 approach, surpassing the limitations of the methodology currently used by the South African government in the national Mitigation Potential Analysis.

Additionally, a novel 24-year (2027–2050) waste management scheme proposed for the implementation in the eThekwini Municipality has been assessed using the above-mentioned strategies. The analysis shows that 2S-AD can potentially result in substantial environmental benefits: significant reductions (−282%) of GHG emissions compared to the business-as-usual scenario, substantial landfill airspace and monetary savings (over 1.6 million m^3 and 3.8 billion Rand, respectively), and a 10.09% waste diversion rate that can extend the lifespan of the active municipal landfills by 1.66 years over the next 24 years.

The comparison among the five identified scenarios showed differences between two clusters of scenarios: two positive scenarios (AS3 and AS4), and two moderately effective scenarios (AS1 and AS2). In contrast, the business-as-usual scenario, landfilling with gas recovery and flaring, proved to be detrimental to the environment. Moreover, the results highlight that the difference among the scenarios increases with the amount of waste collected at the source, showing the importance of maximising source-separation rates to achieve the highest environmental benefits, particularly in the comparable AS3 and AS4 scenarios, which include AD and 2S-AD, respectively.

However, it is worth noting that, due to its higher energy demand, 2S-AD achieves marginally worse carbon emission reductions than conventional AD, while waste diversion, landfill airspace, and monetary savings are identical for 2S-AD, AD, and even composting. Therefore, a techno-economic analysis of the new technology is needed to assess the cost-benefits of 2S-AD compared to AD and determine the potential electricity production and if the revenues deriving from the sale of hydrogen to industrial partners can offset the additional energy costs.

Nevertheless, understanding and quantifying the environmental benefits deriving from the application of 2S-AD to organic waste management represents a ground-breaking perspective. Local decision-makers can capitalise on cutting-edge insights and improved guidance, while national legislators have the ability to expand the Mitigation Potential Analysis and address the lack of mitigation measures for the "Biological treatment of solid waste" sector, reducing the carbon footprint of organic waste management.

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