SARDINIA2023 19th INTERNATIONAL SYMPOSIUM ON WASTE MANAGEMENT AND SUSTAINABLE LANDFILLING
9-13 OCTOBER 2023 / FORTE VILLAGE RESORT

POTENTIAL FOR BIO-HYDROGEN PRODUCTION FROM ORGANIC WASTE IN A LARGE SOUTH AFRICAN METROPOLITAN MUNICIPALITY

Andrea Dell'Orto [1a], Cristina Trois [1]

[1] DSI/NRF/CSIR SARChI Research Chair in Waste and Climate Change, School of Engineering, University of KwaZulu-Natal, Howard College Campus, Durban, South Africa.

ABSTRACT: In South Africa, municipal solid waste is most commonly landfilled, leading to significant greenhouse gas emissions into the atmosphere. The organic fraction of municipal solid waste (OFMSW) has an untapped potential for bioenergy production that still needs to be quantified. This study aims to fill this gap, and explores promising avenues for valorisation of OFMSW into bio-methane and bio-hydrogen. The eThekwini Municipality (Durban), one of the largest metropolitan areas of South Africa, is committed to decreasing its carbon footprint and become a more sustainable city. Currently, eThekwini boasts a gas recovery and flaring system that reduces the impact of greenhouse gas emissions from landfills. However, the municipality has the potential to enhance the energy recovery from organic waste by implementing different treatment methods, such as anaerobic digestion, and has therefore been selected as case study.
A preliminary waste stream analysis and characterisation has been carried out on two different available feedstocks. Hand-sorted OFMSW has been identified as the most widespread biomass that can be used for biomethane production in anaerobic digestion. On the other hand, the cleaner source-separated fruit & vegetable market waste has potential for combined biohydrogen and biomethane production in a double-stage anaerobic digester. The data resulting from the waste stream analysis has been processed using the Waste to Resource Optimisation and Scenario Evaluation (WROSE™) model to compare different scenarios, such as business as usual (BAU), anaerobic digestion (AD), and double-stage anaerobic digestion (2S-AD). The results aim to inform the eThekwini Municipality on the best technology pathway for the treatment of organic waste in Durban.

Keywords: double-stage AD, bio-hydrogen, organic waste, WROSE™ model

1. INTRODUCTION

The decomposition of solid waste in sanitary landfills is a significant contributor to the human carbon footprint. In 2020, landfills were responsible for 1.9% of the global greenhouse gas emissions (Our World in Data, 2020). Such an amount is higher in countries such as South Africa, where most municipal solid waste (MSW) is landfilled (DFFE, 2022a, 2022b). The disposal of solid waste into sanitary landfills originated 18,252 Gg CO_{2eq} in 2020, accounting for 3.8% of the national carbon footprint (DFFE, 2022a). Moreover, the contribution of solid waste treatment to climate change has dramatically increased in the last decades (+34.1% since 2000), making it essential to find alternative ways of managing the organic fraction of municipal solid waste (OFMSW), which heavily contributes to the emission of climate-altering compounds due to its high degradable organic carbon (DOC) content (Friedrich & Trois, 2013).

On the other hand, the high biodegradability of OFMSW can be exploited to produce biofuels through several biological methods. Among those, double-stage anaerobic digestion (2S-AD) is one of the most promising technologies that needs to be further investigated, particularly at larger scales than laboratory scale. 2S-AD deviates from conventional AD by splitting the system into two stages to give optimal degradation conditions to both hydrogen-producing and methanogenic bacteria, allowing for the recovery of bio-hydrogen from the first stage.

Metropolitan Municipalities of South Africa generally produce organic waste suitable for 2S-AD. For this reason, this paper aims to pave the way for the implementation of 2S-AD in South Africa by analysing the case study of the eThekwini Municipality of Durban. The potential environmental benefits related to the implementation of AD have been assessed using the Waste to Resource Optimization and Scenario Evaluation (WROSE) model, and the suitable feedstocks available in the eThewkini Municipality have been quantified and characterised.

2. MATERIALS AND METHODS

2.1 Methodology

2.1.1 Waste Management Model: WROSE™

The Waste Resource Optimization and Scenario Evaluation (WROSE™) model, developed at the University of KwaZulu-Natal in 2010, is the ideal tool to assess waste management scenarios in the South African context (Dell'Orto & Trois, 2022; Trois et al., 2023). The WROSE™ model processes input data such as waste generation rate and composition to compare and evaluate various scenarios, from a baseline scenario that represents the current situation, to more advanced and optimized solutions (Figure 1). This study has developed an additional scenario (scenario 7) to consider the potential insertion of double-stage anaerobic digestion. All scenarios consider a fixed 5% recycling rate (recyclables) / recovery rate (organic waste).

WROSE™ uses the following indicators to evaluate all the scenarios. (Dell'Orto & Trois, 2022; Kissoon & Trois, 2017, 2019):

- Greenhouse gas emission reduction (in accordance with South Africa's nationally determined contributions, they are determined using both IPCC emission factors and scenario-specific South African emission factors)
- Diversion from landfill (lifespan extension, reduction of airspace and monetary costs)
- Technical feasibility (available feedstocks, development of specific [retreatments for each feedstock, bio-hydrogen and biomethane potential, upscaling of 2-stage AD)
- Economic feasibility (optimal positioning of the plant, cost of investment, profitability of by-products on the market, and potential savings in the near and distant future)
- Job creation potential (tonnes of waste or MW of electricity per job)
- Health risks (factors that pose direct or indirect risks)
- Public acceptance and social perception (individual contribution to separation of waste at the source, participation in environmental impact assessment procedures)
- Institutional indicators (environmental and energy laws, financial and administrative legislation).

In particular, this study focuses on the first two categories of environmental indicators: GHG emission reduction and waste diversion from landfills (landfill airspace savings and waste diversion rates).

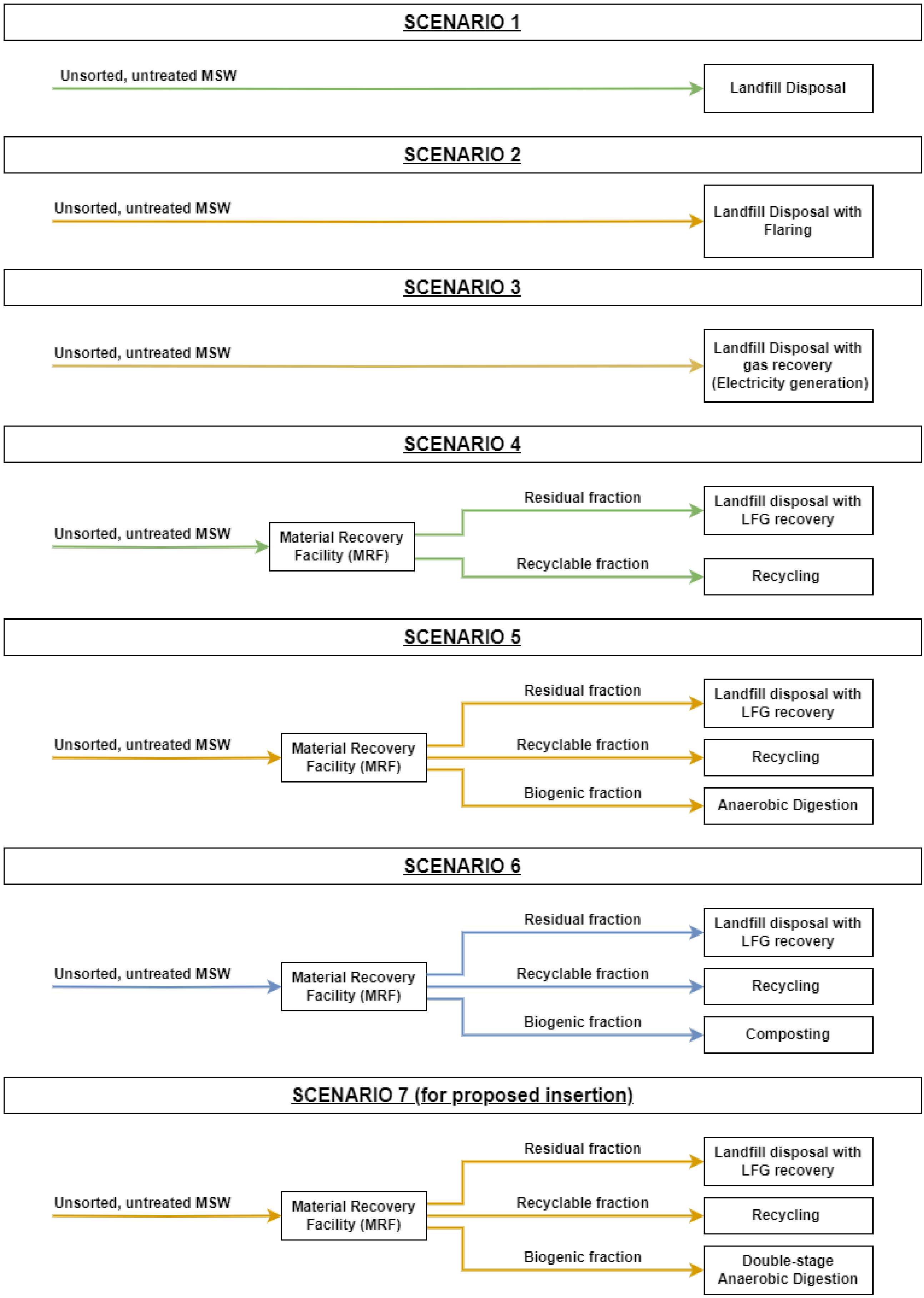

Figure 1. WROSE™ waste management scenarios (adapted and modified from Dell'Orto & Trois, 2022; Trois & Jagath, 2011).

2.1.2 Waste Generation Projections

The estimation of waste generation has been made by utilizing factors such as the quantity of waste disposed of, the rate of collection, and the population and income levels. Statistics South Africa provides national, provincial, and metro population data in their mid-year population estimates 2021 (Statistics South Africa, 2021). The datasets contain population by country, province, and district from 2002 to 2021 and projections from 2022 to 2031 by group, age, and sex. Metropolitan projections to 2050 (Equation 1) assume the same proportion to the total population as in 2031.

$$W_G = \sum (W_{gX} * P_X), \text{ for } X = 1, 2, \ldots, N \tag{1}$$

Where:
W_g = total waste generation (tonnes/year)
W_{gX} = waste generation per capita (tonnes/year)
P_X = population per income level
X = income level category

2.1.3 Greenhouse Gas Emission Assessment

The greenhouse gas emission or reduction potentials were calculated in $MTCO_2eq$ using the waste fractions and emission factors from the IPCC (2006), as quoted in US EPA (2016), following a tier 1 approach, since national data and statistics are not fully available. The emission factor for the biological treatment of OFMSW is 1g CH_4/kg of wet waste (Møller et al., 2009; Trois & Jagath, 2011), while NOx emissions are deemed negligible. The calculation estimates a 95% biogas recovery (methane and hydrogen) towards energy generation.

The effects of GHG emissions are factored in using a gate-to-grave approach, from the moment the waste is discarded until it is disposed of, treated, or recycled into new products (US EPA, 2006). The IPCC (2006) provided a streamlined LCA approach to determine the emissions factors for anaerobic digestion of biogenic MSW (Trois & Jagath, 2011).

Additionally, the GHG emissions of double-stage anaerobic digestion were calculated by adjusting the emission factor used by Trois and Jagath (2011). In particular, the energy reductions element was adapted to double-stage AD by comparing the specific methane production in AD (110 Nm3/tonne) with the specific production of hydrogen and methane in double-stage anaerobic digestion (SMP = 0.5 Nm^3 CH_4 / kg_{VS}; SHP = 0.07 Nm^3 H_2 / kg_{VS}) for a standard composition of food waste (TS = 23%, VS = 92.5% TS) (Dell'Orto et al., 2023; Micolucci et al., 2020; Møller et al., 2009; Mu et al., 2020; Panigrahi et al., 2020; Trois & Jagath, 2011). The result of the analysis shows that, due to the lower heating value of hydrogen gas compared to methane (3 kWh/Nm^3 H_2 versus 6.39 kWh/Nm^3 CH_4) (Møller et al., 2009; Warfsmann et al., 2023), the energy recovery from double-stage AD (697.2 kWh/tonne) is 0.8% less than that from single-stage AD (702.9 kWh/tonne), leading to an adjusted GHG emission factor of -0.26995 $MTCO_{2eq}$/tonne wet weight.

The calculation of emissions produced or reduced was performed over 30 years (2020-2050) for each selected scenario, using the relevant emission factors included in Table 1.

Table 1. GHG emission factors ($MTCO_{2eq}$/tonne ww) used in WROSE

<table>
<tr><th>Type of waste</th><th>Landfilling</th><th>Landfilling with flaring</th><th>Landfilling with gas recovery</th><th>Recycling</th><th>Composting</th><th>Anaerobic digestion</th><th>Double-stage anaerobic digestion</th></tr>
<tr><td>Food waste</td><td rowspan="10">1.0163</td><td rowspan="10">0.1012</td><td rowspan="10">-0.1445</td><td>0</td><td rowspan="2">0.185</td><td>-0.27184</td><td>-0.26995</td></tr>
<tr><td>Garden refuse</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Paper</td><td>-0.5685</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Glass</td><td>-0.2901</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Metals (mixed)</td><td>-2.5869</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Low-density polyethylene (LDPE)</td><td>-0.8594</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>High-density polyethylene (HDPE)</td><td>-0.7194</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Polyethylene-terephthalate (PET)</td><td>-1.8324</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Other Plastics</td><td>-0.98</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Other waste</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

2.1.4 Landfill airspace savings and waste diversion rate

The calculation of landfill space savings resulting from waste diversion is empirical, considering how the specific conditions and on-site activities, particularly the compaction of waste into landfill cells, affect the amount of airspace saved. The actual landfill airspace savings depend on the level and efficiency of compaction.

$$\mathrm{LAS} = \mathrm{t_w} / \mathrm{C_R} \qquad (2)$$

Where:
LAS = total landfill airspace savings
tw = total waste (tonnes)
CR = average density of compacted MSW (assumed at 1.2 tonnes/m3)

The waste diversion rate measures how much waste is being redirected from the landfill and processed through alternative waste treatments. It is defined as the ratio (expressed as a percentage) between the total quantity of waste diverted and the total quantity of waste produced.

2.2 Case study: The eThekwini Municipality

The eThekwini Municipality is situated along the southern and eastern coastline of the KwaZulu-Natal Province of South Africa, covering an approximate area of 2297 km^2. It is home to around 3,158,000 individuals, distributed across different areas: 45% rural, 30% peri-urban, and 25% urban. Within the eThekwini Municipality, there are two closed facilities, the Bisasar Rd and Mariannhill landfills, which still accept construction and demolition waste and garden refuse, and two active landfill sites, namely the Lovu and Buffelsdraai landfill sites (Moodley et al., 2019; Trois et al., 2023). The Buffelsdraai Landfill, established in 2006 over 100 hectares in the northern farming areas of the Municipality, has a total capacity of 43 million m^3 and an estimated lifespan of 60 years. The Lovu landfill site, covering an area of 52 hectares south of Durban, started its operations in 2014. The design capacity of the landfill is about 10 million m^3, and the estimated remaining life is 32 years.

Waste generation and average composition data (represented in Table 2 and Figure 2, respectively) have been obtained from the municipal sanitation provider, Durban Solid Waste (DSW), for a period between 2002 and 2019 (Durban Solid Waste, 2023) and predicted until 2050 following the methodology detailed in paragraph 2.1.2.

Table 2. Total amount of waste disposed into landfills in the eThekwini Municipality between 2002 and 2019

Year	Waste disposed (tonnes/year)	Year	Waste disposed (tonnes/year)	Year	Waste disposed (tonnes/year)
2002	497,708	2008	700,486	2014	786,309
2003	498,526	2009	699,398	2015	768,946
2004	518,759	2010	688,040	2016	773,470
2005	574,759	2011	730,366	2017	841,720
2006	672,912	2012	805,426	2018	861,022
2007	706,830	2013	798,549	2019	702,997

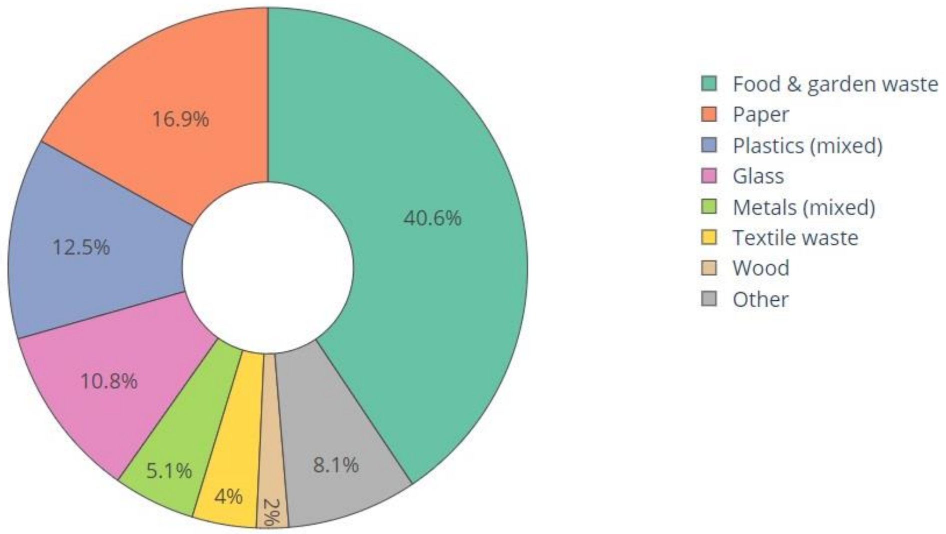

Figure 2. Average waste composition in the eThekwini Municipality

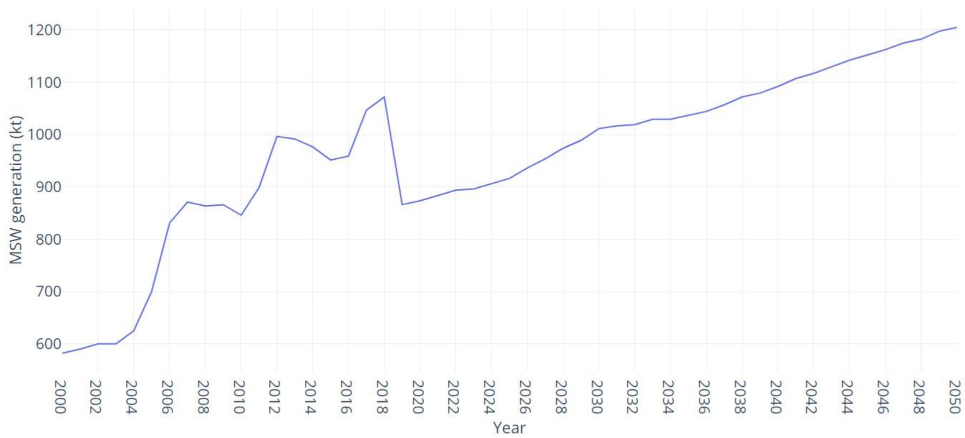

Figure 1. Historical (2000-2019) and predicted (2020-2050) MSW generation in eThekwini.

3. RESULTS AND DISCUSSION

The scenarios selected for the simulation in the eThekwini Municipality case study are listed in Table 3 below. The current waste treatment method in eThekwini is the disposal of unsorted and untreated waste into a landfill equipped with a gas recovery and electricity generation system. This business-as-usual (BAU) scenario is compared with three alternative scenarios, all including recycling the recyclable fractions and recovering the suitable organic fractions: food waste and garden refuse in composting, or only food waste in single- and double-stage anaerobic digestion.

Table 3. Scenario evaluation for the eThekwini Municipality

Code	Scenario #	Description
BAU	Scenario 3	Business as usual: Landfill disposal with gas recovery and electricity generation
AC	Scenario 6	Food waste and garden refuse: Composting Recyclable fraction: Recycling Residual fraction: Landfill disposal with gas recovery and electricity generation
AD	Scenario 5	Food waste: Anaerobic Digestion Recyclable fraction: Recycling Residual fraction: Landfill disposal with gas recovery and electricity generation
2S-AD	Scenario 7	Food waste: Double-stage Anaerobic Digestion Recyclable fraction: Recycling Residual fraction: Landfill disposal with gas recovery and electricity generation

3.1 Greenhouse gas emission assessment

Figure 4 and Table 4 represent the simulation results to determine the greenhouse gas emission reduction of each of the four scenarios. The analysis shows that the current scenario already offsets the GHG emissions originated by landfilling of waste. However, composting can achieve a minor reduction (-4%) of the emissions up to 2050, while single- and double-stage are much more effective (-64% and -62%, respectively) in decreasing the waste-related emissions, thanks to the recovery and utilisation of the methane and hydrogen originated during the biological processes.

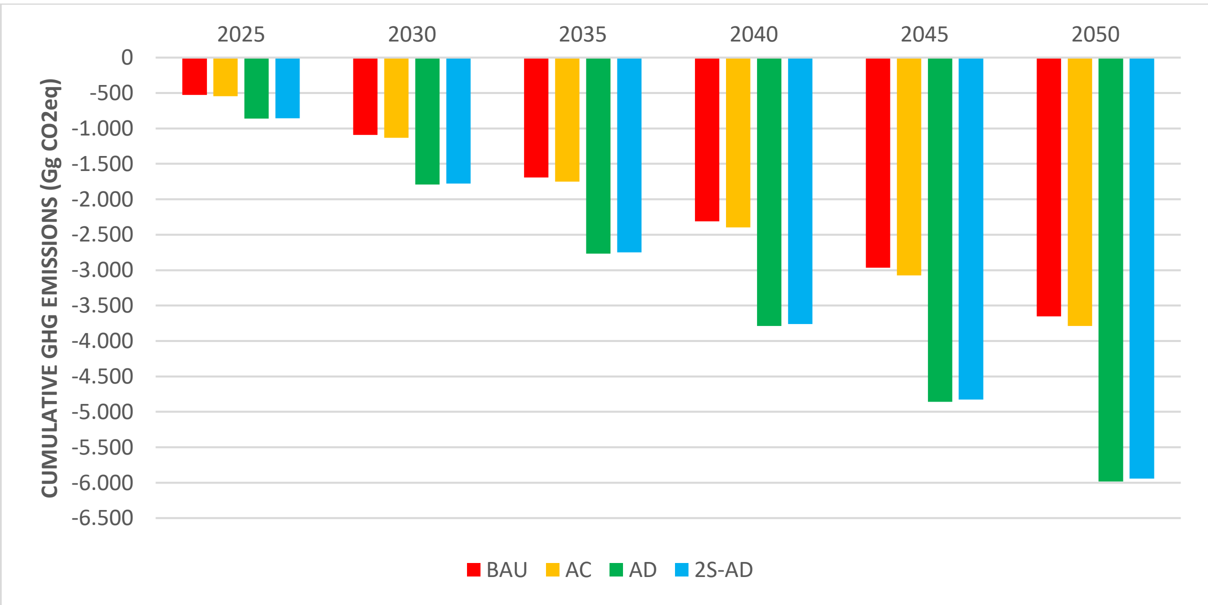

Figure 4. Cumulative GHG emissions 2020-2050 at a fixed 5% recovery rate in the eThekwini Municipality.

Table 4. Cumulative GHG emissions (Gg CO_{2eq}) 2020-2050 at a fixed 5% recovery rate in the eThekwini Municipality

Scenario	Projected Cumulative GHG Emissions since 2020 (Gg CO_{2eq})							2020-2050 Emission reduction potential	
	2020	2025	2030	2035	2040	2045	2050		
BAU	0	-526	-1,093	-1,690	-2,312	-2,967	-3,653	-	-
AC	0	-545	-1,133	-1,752	-2,397	-3,075	-3,787	-134	-4%
AD	0	-861	-1,791	-2,768	-3,786	-4,859	-5,982	-2329	-64%
2S-AD	0	-855	-1,778	-2,749	-3,761	-4,826	-5,942	-2289	-62%

3.2 Landfill airspace savings and waste diversion rate

Figure 5 and Table 5 represent the landfill airspace savings originated by the diversion of solid waste from landfills, compared to the current BAU scenario that does not achieve any diversion. According to the simulation, composting is the most effective method for saving airspace, as it can treat both food waste and garden refuse, corresponding to a 4.3% waste diversion rate. On the other hand, food waste is the only suitable feedstock for single- and double-stage anaerobic digestion, which leads to a 3.4% diversion rate.

Despite the low recovery rates, the prevented landfilling due to the implementation of alternative treatment methods on the diverted fractions can extend the municipal landfills' lifespan by 1.2 – 1.5 years. Therefore, it is advisable to progressively increase the recovery rates to further benefit from waste diversion.

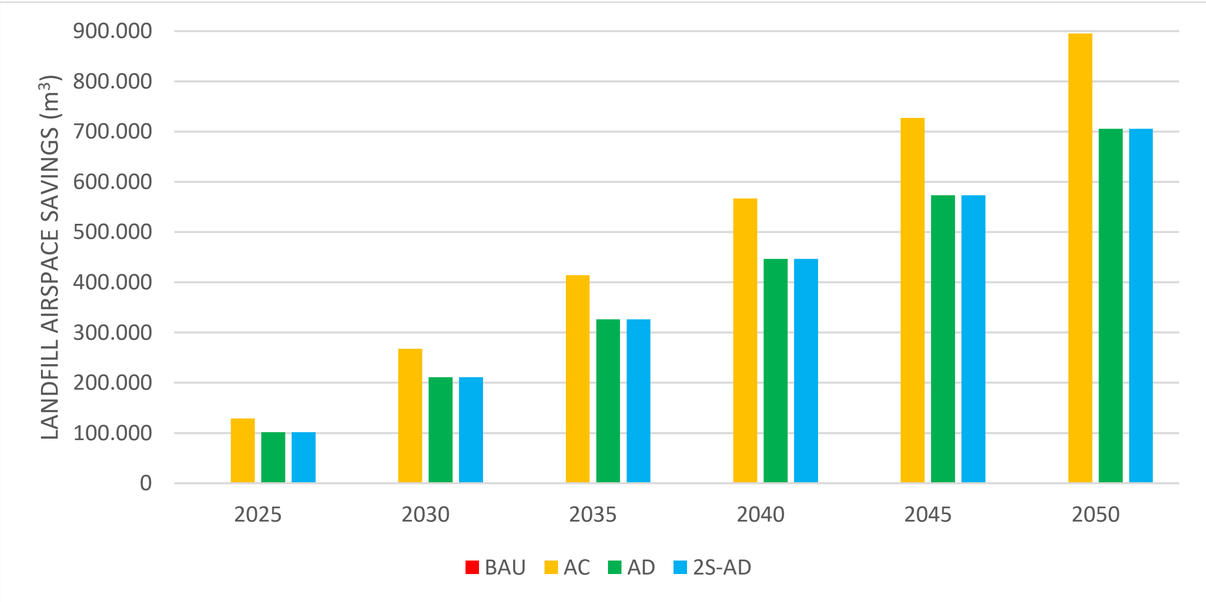

Figure 5. Landfill airspace savings 2020-2050 at a fixed 5% recovery rate in the eThekwini Municipality.

Table 5. Projected landfill airspace savings (m^3) 2020-2050 at a fixed 5% recovery rate in the eThekwini Municipality

Scenario	Projected Cumulative landfill airspace savings since 2020 (m^3)							Estimated landfill lifespan extension
	2020	2025	2030	2035	2040	2045	2050	
BAU	0	0	0	0	0	0	0	-
AC	0	101,566	211,242	326,546	446,697	573,200	705,784	1.2 years
AD	0	128,853	267,994	414,275	566,705	727,194	895,397	1.5 years
2S-AD	0	128,853	267,994	414,275	566,705	727,194	895,397	1.5 years

4. CONCLUSIONS

The decomposition of solid waste in sanitary landfills significantly contributes to the human carbon footprint, particularly in countries like South Africa, where landfilling is the most common disposal method. Alternative waste management strategies are needed to minimise the carbon emissions from the most polluting fractions, such as the organic fraction of municipal solid waste. Double-stage anaerobic digestion (2S-AD) is a promising technique that can achieve climate stabilisation and the production of valuable by-products such as hydrogen, but still needs to be further investigated.

This paper focuses on assessing the environmental benefits of double-stage anaerobic digestion using the case study of the eThekwini Municipality of Durban, South Africa.

The results from simulations performed using the WROSE model reveal that, while the current waste treatment method offsets GHG emissions to some extent, alternative scenarios involving recycling and recovery of organic fractions can lead to significant reductions in emissions. In particular, single- and double-stage anaerobic digestion can potentially reduce carbon emissions by 64% and 62%, respectively.

Furthermore, these alternative treatment methods can contribute to landfill airspace savings and extend the lifespan of municipal landfills by 1.2 – 1.5 years, even with low recovery rates. Therefore, it is recommended to progressively increase recovery rates to maximize the benefits of waste diversion.

In conclusion, this study provides valuable insights into the potential environmental benefits of implementing alternative waste treatment methods like double-stage anaerobic digestion in South Africa, paving the way for more sustainable waste management practices and contributing to global efforts to mitigate climate change.

ACKNOWLEDGEMENTS

We acknowledge the South African Department of Science and Innovation and the National Research Foundation for funding the SARChI Chair in Waste and Climate Change (UID 115447) through the Council for Scientific and Industrial Research (CSIR) Waste RDI Roadmap. We also acknowledge SANEDI and Durban Solid Waste for their contribution. This study forms part of the SANEDI/UKZN Waste-to-Energy Roadmap for South Africa.

REFERENCES

Albini, E., Pecorini, I., & Ferrara, G. (2019). Improvement of Digestate Stability Using Dark Fermentation and Anaerobic Digestion Processes. Energies, 12(18), Article 18. https://doi.org/10.3390/en12183552

Atelge, M. R., Krisa, D., Kumar, G., Eskicioglu, C., Nguyen, D. D., Chang, S. W., Atabani, A. E., Al-Muhtaseb, A. H., & Unalan, S. (2020). Biogas Production from Organic Waste: Recent Progress and Perspectives. Waste and Biomass Valorization, 11(3), 1019–1040. https://doi.org/10.1007/s12649-018-00546-0

Dell'Orto, A., Moodley, P., & Trois, C. (2023). Advances in combined biohydrogen and biomethane production processes from municipal-based lignocellulosic waste at small scale. In P. Moodley, R. C. Ray, & E. B. Gueguim Kana (Eds.), Advances in Lignocellulosic Biofuel Production Systems: Vol. Chapter 15 (pp. 329–346). Woodhead Publishing. https://doi.org/10.1016/B978-0-323-91192-4.00017-1

Dell'Orto, A., & Trois, C. (2022). Considerations on bio-hydrogen production from organic waste in South African municipalities: A review. South African Journal of Science, 118(Special issue: Waste as a Resource), 81–88. https://doi.org/10.17159/sajs.2022/12652

DFFE. (2022a). National GHG Inventory Report—South Africa 2020 (8; p. 486). South African Department of Forestry, Fisheries and the Environment (DFFE). https://www.dffe.gov.za/sites/default/files/reports/8nationalgreenhousegasreport2022.pdf

DFFE. (2022b). South Africa's Mitigation Potential Analysis Update Report (p. 107). South African Department of Forestry, Fisheries and the Environment (DFFE).

Durban Solid Waste. (2023). DSW unpublished data [dataset].

Fatima, A., Basak, B., Ganguly, A., Chatterjee, P. K., & Dey, A. (2020). Biohydrogen Production Through Dark Fermentation of Food Wastes by Anaerobic Digester Sludge Mixed Microbial Consortium. In A. S. Kalamdhad (Ed.), Recent Developments in Waste Management (pp. 57–70). Springer. https://doi.org/10.1007/978-981-15-0990-2_6

Friedrich, E., & Trois, C. (2013). GHG emission factors developed for the collection, transport and landfilling of municipal waste in South African municipalities. Waste Management, 33(4), 1013–1026. https://doi.org/10.1016/j.wasman.2012.12.011

Ghimire, A. (2015). Dark fermentative biohydrogen production from organic waste and application of by-products in a biorefinery concept [Université Paris-Est]. https://theses.hal.science/tel-01404689/document

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Kissoon, S., & Trois, C. (2017). Advancement of the Waste Resource Optimization and Scenario Evaluation (W.R.O.S.E) model to include social indicators for waste management decision making in developing countries. Proceedings Sardinia 2017, 8.

Kissoon, S., & Trois, C. (2019). Application of the WROSE model to municipal Integrated Waste Management Plans: Focus on socio-economic and institutional indicators. Proceedings SARDINIA2019, 8.

Micolucci, F., Gottardo, M., Bolzonella, D., Pavan, P., Majone, M., & Valentino, F. (2020). Pilot-scale multi-purposes approach for volatile fatty acid production, hydrogen and methane from an automatic controlled anaerobic process. Journal of Cleaner Production, 277, 124297. https://doi.org/10.1016/j.jclepro.2020.124297

Møller, J., Boldrin, A., & Christensen, T. H. (2009). Anaerobic digestion and digestate use: Accounting of greenhouse gases and global warming contribution. Waste Management & Research, 27(8), 813–824. https://doi.org/10.1177/0734242X09344876

Moodley, L., Papanicolaou, R., & Domun, V. (2019). Insufficient Airspace—Please Load Airspace. Proceedings of the Landfill 2019 Conference and Exhibition, 11.

Moussa, R. N., Moussa, N., & Dionisi, D. (2022). Hydrogen Production from Biomass and Organic Waste Using Dark Fermentation: An Analysis of Literature Data on the Effect of Operating Parameters on Process Performance. Processes, 10(1), Article 1. https://doi.org/10.3390/pr10010156

Mu, L., Zhang, L., Zhu, K., Ma, J., Ifran, M., & Li, A. (2020). Anaerobic co-digestion of sewage sludge, food waste and yard waste: Synergistic enhancement on process stability and biogas production. Science of The Total Environment, 704, 135429. https://doi.org/10.1016/j.scitotenv.2019.135429

Our World in Data. (2020). Sector by sector: Where do global greenhouse gas emissions come from? Our World in Data. https://ourworldindata.org/ghg-emissions-by-sector

Panigrahi, S., Sharma, H. B., & Dubey, B. K. (2020). Anaerobic co-digestion of food waste with pretreated yard waste: A comparative study of methane production, kinetic modeling and energy balance. Journal of Cleaner Production, 243, 118480. https://doi.org/10.1016/j.jclepro.2019.118480

Pognani, M., Barrena, R., Font, X., & Sánchez, A. (2012). A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. Waste Management, 32(5), 799–805. https://doi.org/10.1016/j.wasman.2011.12.018

Statistics South Africa. (2021). Mid-year population estimates (Statistical Release P0302, p. 45). Statistics South Africa. http://www.statssa.gov.za/?page_id=1854

Trois, C., Abera, Y., Dell'Orto, A., Kissoon, S., & Gómez-Sanabria, A. (2023). Application of the WROSE Model for Promoting Effective Decision-Making and Sustained Climate Change Stabilization in the South African Waste Sector. In H. El Bari & C. Trois (Eds.), Waste Management in Developing Countries (pp. 39–62). Springer International Publishing. https://doi.org/10.1007/978-3-031-28001-6_3

Trois, C., & Jagath, R. (2011). Sustained Carbon Emissions Reductions through Zero Waste Strategies for South African Municipalities. Integrated Waste Management - Volume II. https://doi.org/10.5772/17216

US EPA. (2006). Solid waste management and greenhouse gases—A life-cycle assessment of emission and sinks. 3rd Edition. U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyNET.exe/60000AVO.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2006+Thru+2010&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C06thru10%5CTxt%5C00000000%5C60000AVO.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL#

US EPA. (2016, January 12). Understanding Global Warming Potentials [Overviews and Factsheets]. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Warfsmann, J., Puszkiel, J. A., Passing, M., Krause, P. S., Wienken, E., Taube, K., Klassen, T., Pistidda, C., & Jepsen, J. (2023). Applying wash coating techniques for swelling-induced stress reduction and thermal improvement in metal hydrides. Journal of Alloys and Compounds, 950, 169814. https://doi.org/10.1016/j.jallcom.2023.169814