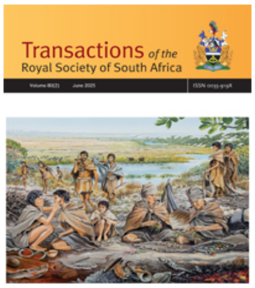

Transactions of the Royal Society of South Africa

ISSN: 0035-919X (Print) 2154-0098 (Online) Journal homepage: www.tandfonline.com/journals/ttrs20

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To cite this article: G. P. A. Pereira & A. S. Fitchett (2025) The potential for diverting food waste from landfill in South Africa, Transactions of the Royal Society of South Africa, 80:2, 97-109, DOI: 10.1080/0035919X.2025.2561705

To link to this article: https://doi.org/10.1080/0035919X.2025.2561705

Published online: 26 Sep 2025.

Transactions of the Royal Society of South Africa, 2025
Vol. 80, No. 2, 97–109, https://doi.org/10.1080/0035919X.2025.2561705

The potential for diverting food waste from landfill in South Africa

G. P. A. Pereira & A. S. Fitchett *

School of Civil and Environmental Engineering, University of the Witwatersrand, Johannesburg, South Africa
*Author for correspondence: E-mail: *anne.fitchett@wits.ac.za*

Food waste has the potential for transformation into value-added products as a sustainable strategy for diverting waste from landfills in South Africa. This study uses a social cost–benefit framework to evaluate various waste conversion technologies, including anaerobic digestion, aerobic composting, vermicomposting, and black soldier fly larvae, within South Africa's unique socio-economic and environmental landscape. Quantitative waste composition analyses are combined with technology evaluations, revealing significant costs for landfilling, the current status quo, and underscoring the economic and environmental urgency of strategic food waste diversion. Highlighting gate fees' critical role, the findings advocate adjusting these fees to reflect true environmental costs and incentivise alternatives. Notably, black soldier fly larvae and vermicomposting technologies emerge as dual-benefit strategies for waste reduction and resource recovery. Policy and infrastructure advancements are recommended to enable the broad adoption of these technologies, emphasising their importance in achieving sustainability and economic objectives.

Keywords: Food waste; anaerobic digestion; vermicomposting; black soldier fly larvae; landfill

1. INTRODUCTION

Waste management poses a significant global challenge, characterised by rising waste generation and complex systems of production and consumption. In South Africa, landfill capacity in major cities is rapidly diminishing, compounded by inadequate planning, weak separation-at-source systems, limited advanced treatment facilities outside metropolitan areas, and high transport costs that encourage illegal dumping (DEA, 2018; GreenCape, 2022; De Klerk, 2023).

Food waste carries both ethical and environmental dimensions. On the one hand, hunger and food insecurity remain widespread; on the other, organic waste contributes to greenhouse gas emissions from decomposing organics (particularly methane, with a global warming potential 28 times greater than CO_2), groundwater contamination, odours, and pest problems, particularly in communities living near poorly managed landfills (Du Preez and Lottering, 2011; Moolla *et al*., 2013; Mataloni *et al*., 2016). Vulnerable populations are disproportionately affected, while informal waste pickers face unsafe working conditions. The urgency of addressing these issues is further magnified by evidence linking landfill proximity to increased respiratory illness, certain cancers, and adverse birth outcomes (Du Preez and Lottering, 2011; Moolla *et al*., 2013; Mataloni *et al*., 2016).

South Africa's National Waste Management Strategy 2020 (NWMS) sets ambitious diversion targets (40% organic waste and 30% food waste by 2025) to mitigate these impacts (DEFF, 2020). Yet, despite the policy impetus, the economic loss from the disposal of recoverable resources is valued at R825 billion annually (approx. USD 57 billion, 2016 conversion rate) (Nahman *et al*., 2012; Oelofse and Nahman, 2013; DEA, 2016).

This study evaluates the potential of four organic waste conversion technologies – anaerobic digestion (AD), composting, vermicomposting (VC), and black soldier fly (BSF) processing – to reduce landfilling and generate value-added products in South Africa. By combining quantitative cost analysis, life-cycle assessment (LCA), and social cost–benefit analysis (SCBA), the study addresses a critical gap: understanding the comparative private and external costs of these alternatives under South African conditions.

2. FOOD WASTE IN THE LITERATURE

2.1 Food waste in the South African context

Globally, around one-third of food produced for human consumption is lost or wasted each year – an estimated 1.3 billion tonnes (Gustavsson *et al*., 2011). In South Africa, food loss and waste average 9.04 million tonnes annually, equivalent to about 31% of the country's agricultural output (Oelofse and Nahman, 2013). More recent estimates, accounting for imports and exports, place losses closer to 10.3 million tonnes per year (Oelofse *et al*., 2021). Nearly half of this occurs during processing and packaging (49%), while 18% arises at the consumption stage – more than three times higher than earlier national estimates for household waste. Losses at the consumption stage are especially concerning, as they involve high-value, nutrient-rich foods that are less likely to be recovered or repurposed.

As shown in Figure 1, organic waste – including garden waste, food waste, and residues from sugar, sawmilling, and paper industries – forms the largest single fraction of general waste landfilled in South Africa, comprising roughly 27% of all disposed waste. This highlights both the scale of the challenge and the opportunity for diversion. Food waste

Published online 26 Sep 2025

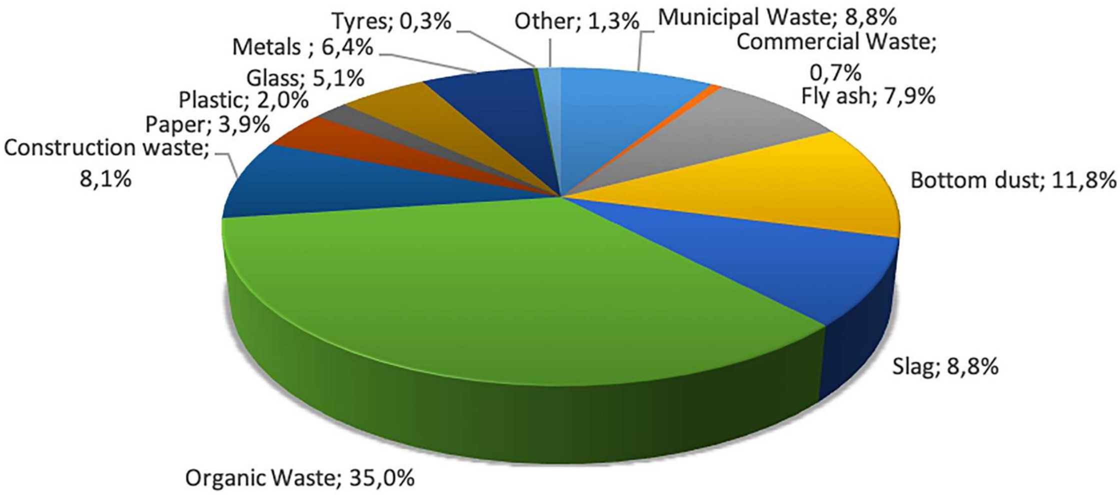

Figure 1. Breakdown of general waste generated – adapted from 2018 SoWR.

contributes about one-third of this category. The scale of organic deposition has disproportionate impacts: methane emissions, leachate generation, odour, and landfill instability. These challenges underline the urgency of diversion strategies. Regional and seasonal patterns add further complexity – urban centres tend to report higher levels of packaged and processed food waste, while rural areas experience greater losses during primary production and handling. Recognising these variations is essential for designing targeted interventions.

2.2 Cost assessment methods and implications of landfilling

Researchers use both qualitative and quantitative approaches to evaluate waste management technologies. Qualitative methods such as the Analytic Hierarchy Process (AHP) and multicriteria decision modelling (MCDM) rank options according to cost, demand, waste volumes, and environmental impact (Song *et al*., 2020). Quantitative approaches – such as Life Cycle Assessment (LCA), Social Cost–Benefit Analysis (SCBA), and optimisation models – monetise social and environmental impacts, providing a more comprehensive economic valuation (Friedrich and Trois, 2013). LCA captures environmental effects across the system, while SCBA integrates environmental, social, and economic costs into decision-making.

The environmental and health burdens of landfilling remain substantial. Despite relatively low financial costs, landfilling does not account for wider environmental and social externalities. A 2023 audit found that only 17.5% of South African landfills complied with 80% or more of regulatory standards (De Klerk, 2023). Earlier studies assessed environmental and social impacts separately (De Wit and Nahman, 2009; Nahman, 2011), while Nahman *et al*. (2012) later synthesised these findings to estimate the full economic cost of landfilling in South Africa.

2.3 Food waste diversion strategies

Food waste management is shifting toward innovative and sustainable alternatives. Anaerobic digestion (AD), windrow composting (WC), in-vessel composting (IVC), vermicomposting (VC), and black soldier fly (BSF) processing are increasingly applied due to relatively low capital and operating costs (Coelho *et al*., 2019). Comparative studies show that AD generally achieves the greatest environmental benefits, especially in reducing greenhouse gas emissions relative to composting and landfilling (Slorach *et al*., 2019; Fan *et al*., 2023). BSF processing, meanwhile, produces high-value protein for feed while reducing organic waste and associated emissions (Lalander *et al*., 2018).

Recent work stresses the need for integrated assessment tools. Yang *et al*. (2022) highlight the value of combining LCA with social life-cycle costing (LCC) to ensure that environmental, economic, and social outcomes are considered holistically. This integrated perspective is particularly important in contexts like South Africa, where technology adoption must balance cost, performance, and social benefits.

3. RESEARCH METHOD

The methodology comprises three linked components:

1. Quantitative estimation of landfilling costs
2. Review and integration of life-cycle assessment (LCA) data for alternative organic waste treatment technologies, and
3. Application of social cost–benefit analysis (SCBA) to compare landfilling versus alternative food waste treatment technologies in South Africa.

The Benefit Transfer Method (BTM) was applied to adapt cost estimates from peer-reviewed studies and industry reports for the South African context, enabling inclusion of both private (market-based) and external (environmental and social) costs.

3.1 Quantitative estimation of landfilling costs

Private and external costs were estimated using national waste data, municipal tariffs, and cost coefficients from prior studies (e.g., BDA Group, 2009; Nahman, 2011; Oelofse *et al*., 2021). Costs were normalised to R/tonne and scaled for different landfill capacities. Gate fee revenue was derived from published municipal tariffs, adjusted to 2023 Rands using CPI escalation. Section 4 provides detailed parameter sources and calculation steps.

3.2 Review of LCA data for alternative technologies

A targeted literature review was undertaken to compile economic, environmental, and social performance data for AD, IVC, VC, and BSF. Data extraction focused on CapEx, OpEx, yields, emissions, energy recovery, and co-products. Where South African data were unavailable, international figures were adjusted for local conditions by applying South Africa – specific factors, such as Eskom's electricity grid emission intensity (coal-dominated and significantly higher than EU/US averages), local waste composition, and prevailing market prices for energy and by-products. This ensured that avoided emissions, energy recovery benefits, and cost estimates reflected South African operating conditions. The consolidated dataset forms the input for SCBA (see Table 1) and see Section 5 for expanded results.

3.3 Social cost–benefit analysis (SCBA)

SCBA integrated private and external cost datasets for each treatment option. Externalities were monetised using hedonic pricing models and LCA-derived values. All costs and benefits were expressed in R/tonne and scaled using throughput data from representative sites (DEA, 2018; Oelofse *et al.*, 2021). Scenario comparisons used annualised estimates, and sensitivity testing was applied to key variables such as gate fees, product prices, and process yields.

4. DETERMINING THE COST OF LANDFILLING IN SOUTH AFRICA

This study evaluates the costs associated with landfilling in South Africa, focusing on 158 active general waste landfills. To determine the costs of landfilling in South Africa the following is required:

1. Private costs and benefits
2. Environmental externalities
3. Social externalities

Environmental externalities are determined using the benefit transfer method and the social disamenity cost from a literature review using the hedonic pricing model both in South Africa and internationally. This methodology scrutinises variables such as the nature of the waste, landfill operational practices, and regional climate, which together influence the volume and effects of LFG and leachate (Nahman, 2011; Friedrich and Trois, 2013, 2016).

By drawing on existing evaluation estimates done by the BDA Group (2009), in an Australian context, the calculation of unit costs for leachate and local air pollutants (LAP) factors in geographical and socio-economic conditions in a South African context.

Climate impacts of greenhouse gases are uniform, irrespective of the emissions' origin. However, when considering LAP, leachate emissions, and disamenities, these factors require more nuanced consideration, which relates to the population density near the landfill. Additionally, willingness to pay is influenced by income levels and the preferences for environmental quality. These factors can significantly vary between countries, especially when comparing developed and developing nations (European Commission, 2000).

To adjust for differences in income and environmental preferences, the following formula is used (European Commission, 2000; Nahman, 2011):

$$\overline{E_{SA}} = E_{AUS} \times \left(\frac{I_{SA}}{I_{AUS}}\right)^{Q}$$

Where: E_{SA} = The adjusted estimate (applicable to South Africa), E_{AUS} = The original estimate (from Australia), I = Per capita income at purchasing power parity (PPP) rates, Q = Income elasticity of demand for environmental quality.

To account for socioeconomic differences, the Australian estimates for local air emissions and leachate are multiplied by the ratio of ISA/IAUS (approximately 0.34), reflecting the socioeconomic disparities between the two countries. A spreadsheet was developed with the listed landfills and their assumptions to determine the status quo external cost of landfilling in South Africa. There is no external benefit attributed to landfilling, and any benefit from electricity production is factored into the costing.

4.1 Disamenity costs in South Africa

Disamenity costs refer to the negative social impacts experienced by communities near landfill sites, including odours, pests, and reduced property values. These costs remain constant irrespective of waste volumes due to the landfill's presence (Du Preez and Lottering, 2011).

The Hedonic Pricing Method (HPM) is widely used to estimate these costs by evaluating how proximity to a landfill affects property values. In South Africa, studies by Du Preez and Lottering (2011) and Nahman (2011) have used HPM to quantify disamenity costs. For example, Du Preez and Lottering (2011) estimated a disamenity cost of approximately R5.83 per tonne of municipal solid waste (MSW) in New Brighton, while Nahman (2011) found a cost of R57.46 per tonne in Cape Town.

International comparisons reveal that disamenity costs vary by region and landfill management. The BDA Group (2009) reported costs ranging from 0.5 to 10 AUD per tonne in Australia, depending on management practices and population density. The European Commission (2000) and Eunomia (2002) provided estimates for Europe, with costs ranging from 1.27 to 8 Euros per tonne.

This study proposes disamenity costs in South Africa based on international benchmarks and local data:

- Urban Best Practice: R10.52 per tonne
- Rural Best Practice: R5.26 per tonne
- Urban Non-Compliant: R105.23 per tonne
- Rural Non-Compliant: R52.62 per tonne

These values reflect the economic impact of landfill disamenities and align with both national and international findings.

5. TECHNOLOGY COMPARISON

This section compares the CapEx, OpEx, revenue potential, and environmental impacts of four organic waste conversion technologies applicable to the South African context: AD, WC, IVC, BSF, and VC. All financial values are presented in 2023 ZAR, expressed per tonne of food waste processed (/t FW), using mid-point estimates from literature and market surveys.

5.1 Landfilling (status quo)

Landfilling remains the dominant waste management option in South Africa. Table 2 summarises private costs, including infrastructure, operation, maintenance, and

Table 1. Impacts identified for this study.

Type of cost	Impact Group	Description of impact	Impact Identification	
			Cost	Revenue
Internal	Infrastructure	Treatment and final disposal	OpEx and CapEx	
Internal	Recovery of food waste	Gate Fees		Market Price
Internal		Compost Protein (feed) Electricity		Market Price
External	Use of materials	Landfill diversion		Avoid material sent to landfill
External	Environmental	Replace chemical fertiliser		Reduces nitrogen fert. use + CO_2 sequestration
External		Emissions to air	GHG production (BTM)	Reduction in landfill GHG Replace coal power
External		Emissions to air	LAP production (BTM)	Reduction in landfill LAP Replace coal power
External		Emissions to ground	Leachate (BTM)	Reduction in landfill leachate
External	Quality of life	Disamenities	HPS	

capital investment. The estimated private cost for landfill gas (LFG) collection without energy recovery is R564.00/t MSW, increasing to R597.30/t MSW when energy production is included. Applying these values to the 158 landfills in this study yields an average combined CapEx and OpEx of R483.27/t MSW.

The average municipal gate fee, weighted by each municipality's waste volume, is R376.28/t waste. Only two landfills in the dataset currently generate electricity from LFG. At an electricity price of R2.10/kWh (NERSA, 2022), the total annual revenue from LFG-to-energy is estimated at R80.91 million per year, equivalent to R2.23/t of MSW. External costs are significant, averaging R135.07/t of waste when weighted for each landfill's GHG emissions, LAP, leachate production, and disamenity costs (see Table 3).

Table 2. Summary of results for status quo landfill private cost of 158 landfills in South Africa, weighted by provincial waste production.

Province	Number of landfill sites reviewed in this study	Waste generated as a percentage of total waste (%)	Landfill Capex and Opex Costs (R/ tonne waste)
Gauteng	19	14.7	534.84
KwaZulu-Natal	10	10.5	462.54
Limpopo	14	1.1	454.62
Mpumalanga	20	10.5	449.40
Northern Cape	17	17.9	471.62
Northwest	21	6.3	418.98
Eastern Cape	8	26.3	490.64
Freestate	26	4.2	438.29
Western Cape	23	8.4	507.08
Weighted total	158	100	484.67

5.2 Windrow composting

An aerobic process in which organic waste is placed in long rows and turned periodically to maintain oxygen levels, producing compost over several months. WC has an estimated OpEx and CapEx of R308/t FW. Revenue is generated from compost sales, though product quality and nutrient composition can vary. Assuming an average compost density of 548 kg/m³ (US Composting Council, 2021) and a market price of R530/m³, the equivalent value is R967.15/t of compost. Given that one tonne of food waste yields only 250 kg of compost (Kim *et al*., 2011), the resulting revenue is R241.78/t FW.

Aerobic composting produces net GHG emissions but also offers potential GHG savings (Friedrich and Trois, 2013). GHG emissions from composting facilities are primarily due to energy use, machinery, and minor methane and nitrous oxide releases. Literature suggests total emissions of 130.89 kg CO_2-eq/t FW. Using the BDA Group (2009) valuation method (40 A$$/t CO_2, 2008 prices) with a 7% discount rate over a 30-year lifespan, this equates to R65.00/t FW (2023 ZAR).

Compost can partially displace chemical fertilisers, and the associated GHG emissions, with this study assuming a 40% nutrient substitution efficiency (Boldrin *et al*., 2009). While composting does produce disamenity impacts, these are assumed equivalent to those from compliant landfill operations located at the same sites (Liu *et al*., 2020; see Table 4).

By equating the literature on emissions from composting to BDA Group (2009) emission damage from each pollutant (discounting over 30 year period at 7%) an estimated damage cost for emission from composting is made, but with a low level of confidence.

5.3 In-vessel composting

In-vessel composting (IVC) is a sealed and insulated composting system that regulates temperature, aeration, and moisture to accelerate decomposition, reduce odours, and produce pathogen-free compost. IVC is more capital-intensive, with combined OpEx and CapEx of R1106.50/t FW. High-quality compost can command R1368.61/t compost, resulting in R342.15/t FW revenue. The process reduces

Table 3. Summary of the economic results of impacts considered for the current status quo waste landfilling in South Africa per ZAR/year and ZAR/tonne (2022 ZAR).

			Impact Identification			Impact Valuation	
Type of cost	Impact Group	Description of impact	Cost (R/ tonne /year)	Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Cost (Million R/year)	Revenue (Million R/ year)
Internal	Infrastructure	Treatment and final disposal	484.67	–	36,284,479.84	17,585.84	–
Internal	Recovery of waste	Gate Fees	–	376.28	36,284,479.84	–	13,653.12
Internal		Energy (status quo)	–	2.23	36,284,479.84	–	80.48
External	Environmental	GHG emissions	83.68	–	36,284,479.84	3036.42	–
External		LAP emissions	1.19	–	36,284,479.84	43.13	–
External		Leachate	0.04	–	36,284,479.84	1.59	–
External	Quality of life	Disamenities	50.15 (7.86)	–	36,284,479.84	1819.81	–
Total of Internal Impacts						17,585.84	13,733.61
Total External Impacts						4900.94	0.00
Total Impacts						22,486.78	13,733.61
Assuming 100% Compliance							
Total of Internal Impacts						17,585.84	13,733.61
Total External Impacts						3366.49	0.00
Total Impacts						20,952.33	13,733.61

nitrogen losses by approximately 34% compared to windrow composting (Liu *et al*., 2020) and achieves better pathogen removal.

GHG emissions are estimated at 179 kg CO_2-eq/tFW, valued at R88.90/t FW using the BDA Group's discounted methodology. Local air pollutants are considered negligible compared to landfilling, with Mu *et al*. (2017) noting reductions in smog and respiratory effects. Food waste diversion to IVC reduces remaining landfill organic waste by roughly 31%. It is assumed that LAP is directly proportional to the proportion of organic matter in the waste body (Nahman, 2011; see Table 5).

5.4 Anaerobic digestion with biogas capture

A biological process where microorganisms degrade organic waste in the absence of oxygen, producing biogas (methane and CO_2) for energy and digestate for soil amendment. AD has an estimated OpEx and CapEx of R1153.75/t FW. Each tonne of FW yields approximately 0.57 t of digestate (Shao *et al*., 2023), valued at R551.28/t FW based on compost market prices.

Direct GHG emissions are estimated at 71.53 kg CO_2-eq/t FW, costing R35.52/t FW, while energy generation from biogas has a global warming potential (GWP) benefit of 338.25 kg CO_2-eq/t FW, valued at R167.86/t FW. Literature for replacing fertilisers varies due to feedstock, digestate, carbon sequestration, and N2O release assumptions (Schott *et al*., 2016). Fertiliser substitution benefits are calculated at 93.90 kg CO_2-eq/t FW (Schott *et al*., 2016), discounted to R46.63/t.

Local air pollutant costs are assumed equivalent to those from landfill gas-to-electricity operations, adjusted for a higher collection efficiency (98% vs 60%) due to the enclosed nature of AD, giving R0.55/t FW (see Table 6; Morrisa *et al*., 2013).

5.5 Vermicompost

VC is a biological process where organic waste is broken down by earthworms and microbes into nutrient-rich soil amendment, with worm biomass as a high-protein by-product for animal feed. In this study, the OpEx and CapEx for vermicomposting was estimated at R437/t FW. The primary product, vermicompost, commands a retail price of R4.32 to R5.31 per kg, translating to an approximate market value of R1728/t FW.

In addition to vermicompost, the process yields worm biomass as a valuable by-product, which can serve as a sustainable protein substitute in animal feed formulations. Based on Yadav *et al*. (2015), worm biomass production is approximately 4.21 kg/t FW. At a market price of R25 per kg, this represents an additional potential revenue of R105.25/t FW.

GHG emissions are low, estimated at 27.48 kg CO_2-eq/t FW (Komakech *et al*., 2015), valued at R13.65/t FW. Komakech *et al*. (2015) suggest substituting fish in animal feed with worm protein, saving 0.257 kg CO_2-eq/t FW. The study assumes negligible LAP due to low energy use and lack of transport emissions (see Table 7).

5.6 Black soldier fly processing

A process using larvae of the black soldier fly (*Hermetia illucens*) to rapidly convert organic waste into protein-rich larvae for animal feed and frass for use as fertiliser. BSF processing

Table 4. Summary of the economic assessment of impacts considered for open windrow composting per ZAR/year and ZAR/tonne (2022 ZAR), varying compliance.

			Impact Identification			Impact Valuation	
Type of cost	Impact Group	Description of impact	Cost (R/ tonne /year)	Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Cost (Million R/year)	Revenue (Million R/ year)
Internal	Infrastructure	W-Compost O&M	308.00	–	3,030,271.60	933.32	–
Internal		Landfill O&M	484.67	–	33,254,208.23	16,117.17	–
Internal	Recovery of waste	Gate Fees – landfill	–	376.28	33,254,208.23	–	12,512.89
Internal		Gate fees – W-compost	–	376.28	3,030,271.60	–	1140.23
Internal		Food waste to compost	–	241.78	3,030,271.60	–	732.66
External	Environmental	Chemical fertiliser replacement	–	23.55	3,030,271.60	–	71.36
External		GHG – landfill	57.75	–	33,254,208.23	1920.57	–
External		GHG – compost	65.00	–	3,030,271.60	196.97	–
External		LAP – landfill	0.82	–	33,254,208.23	27.28	–
External		LAP – Compost	1.42	–	3,030,271.60	4.30	–
External		Leachate – landfill	0.03	–	33,254,208.23	1.00	–
External		Leachate – compost	–	–	3,030,271.60	–	–
External	Quality of life	Disamenity – compost	34.61 (5.43)	–	3,030,271.60	104.89	–
External		Disamenity – landfill	34.61 (5.43)	–	33,254,208.23	1151.05	–
Total of Internal Impacts						17,050.07	14,385.78
Total External Impacts						3406.07	71.36
Total Impacts						20,456.56	14,457.15
Assuming 100% Compliance							
Total of Internal Impacts						17,050.07	14,385.78
Total External Impacts						2347.07	71.36
Total Impacts						19,97.56	14,457.15

costs approximately R661.80/t FW. Product yields vary, but studies report between 28 and 32 kg of dried larvae per tonne of FW (Ites *et al*., 2020), with Guo *et al*. (2021) finding 30.94 kg dried larvae and 300 kg of compost output per tonne. Revenue potential ranges from R2028.00/t FW to R10,170.00/t FW, depending on market conditions (GreenCape, 2022).

Mertenat *et al*. (2019) suggest BSF emits 47 times less than WC, suggesting GHG emissions are low at 60 kg CO_2-eq/t FW, valued at R29.80/t FW, with fertiliser substitution benefits of 49.71 kg CO_2-eq/t, valued at R24.69/t FW. Local air pollutants are assumed negligible due to minimal energy and transport requirements (see Table 8).

6. RESULTS

6.1 Landfill costs and compliance

Financial viability requires total private income covering landfill costs. Only Western Cape, Kwa-Zulu Natal, and Free State cover expenses with gate fees. Western Cape has the highest gate fees, expected to rise above inflation (CoCT, 2021). Other provinces have gate fees below landfill costs, indicating financial non-viability. Northern Cape charges no gate fees, and Free State's high fees lack compliance, may indicate mismanagement or governance issues. Compliance saves R1534.45 million in disamenity costs annually, reducing total external costs by 18% and disamenity costs by 84% across South Africa. These figures highlight the discrepancy between private market costs and externalised social/environmental costs, which underpin the comparative analysis that follows.

6.2 Comparative analysis of conversion technologies

Private benefits include CapEx, OpEx, gate fees, and opportunity costs from diverted food waste. As seen in Figure 2 below, VC and BSF offer the highest private benefits, followed by AD and WC. IVC has a $B_P < 0$ and is not operationally and economically viable.

Opportunity costs dominate private benefits for VC (71%) and BSF (65%). Costing scenarios applied to waste volumes, including landfilling costs for remaining waste, show BSF and VC are economically viable (BP > 0), with AD and WC negative.

Table 5. Summary of the economic assessment of impacts considered for in-vessel composting per ZAR/year and ZAR/tonne (2022 ZAR), varying compliance.

			Impact Identification			Impact Valuation	
Type of cost	Impact Group	Description of impact	Cost (R/ tonne /year)	Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Cost (Million R/year)	Revenue (Million R/ year)
Internal	Infrastructure	IVC O&M	1106.50	–	3,030,271.60	3,353.00	–
Internal		Landfill O&M	484.67	–	33,254,208.23	16,117.17	–
Internal	Recovery of waste	Gate Fees – landfill	–	376.28	33,254,208.23	–	12,512.89
Internal		Gate fees – IVC	–	376.28	3,030,271.60	–	1,140.23
Internal		Food waste to compost	–	342.15	3,030,271.60	–	1,036.81
External	Environmental	Chemical fertiliser replacement	–	28.49	3,030,271.60	–	150.48
External		GHG – landfill	57.75	–	33,254,208.23	1,920.57	–
External		GHG – IVC	88.90	–	3,030,271.60	251.09	–
External		LAP – landfill	0.82	–	33,254,208.23	27.28	–
External		LAP – IVC	–	–	3,030,271.60	2.49	–
External		Leachate – landfill	0.03	–	33,254,208.23	1.00	–
External		Leachate – IVC	–	–	3,030,271.60	–	–
External	Quality of life	Disamenity – IVC	5.43	–	3,030,271.60	104.89	–
External		Disamenity – landfill	34.61 (5.43)	–	33,254,208.23	1,151.05	–
Total of Internal Impacts						19,470.17	14,689.93
Total External Impacts						3385.75	86.33
Total Impacts						22,855.91	14,776.26
Assuming 100% Compliance							
Total of Internal Impacts						19,470.17	14,689.93
Total External Impacts						2415.19	86.33
Total Impacts						21,885.35	14,776.26

External costs applied to waste volumes vary with landfill compliance, affecting disamenity costs and is summarised in Figure 3. Environmental benefits favour AD, followed by VC, BSF, and WC. The higher GHG avoidance of AD in South Africa is accentuated due to the coal-heavy grid mix applied in the LCA adjustments.

The total benefit varies depending on the compliance of the landfill sites as that impacts the disamenity cost. On a per tonne of FW basis, BSF and then VC have the highest benefit, followed by AD and then WC (Figure 4). All technologies have a total benefit, except for IVC which has a negative benefit. Applied to the total waste volume, the ranking remains the same, BSF has the highest B_T, followed by VC, AD, and WC. Landfilling is consistently outperformed by all scenarios.

7. DISCUSSION

The current landfilling practices in South Africa are economically, environmentally, and socially deficient. The majority of landfill sites are inadequately controlled, posing a serious threat to the environment (Remigios, 2010; Idowu *et al.*, 2019). This study estimates that landfills cost the economy, ecology, and surrounding community the equivalent of R8.7 billion per year.

7.1 Benefits of alternative waste management technologies

AD is consistently identified as the most environmentally preferable option, outperforming both composting and landfilling in terms of greenhouse gas (GHG) reduction and renewable energy generation (Bernstad and la Cour Jansen, 2012; Yang *et al.*, 2022). Numerous studies show that composting alternatives also yield lower environmental impacts than landfilling, though AD delivers stronger environmental and economic performance than WC in particular (Bong *et al.*, 2017; Slorach *et al.*, 2019; Lu *et al.*, 2020; Fan *et al.*, 2023). These findings align with the results of this study.

While prior studies predominantly focus on environmental impacts, recent analyses highlight the importance of incorporating social factors, such as societal life-cycle costing (LCC) and social cost–benefit analysis (LC-SCBA) (Yang *et al.*, 2022). The Eunomia (2002) report for the European Commission and Kim *et al.* (2011) demonstrate that externalities associated with waste management practices significantly influence the overall evaluation of waste management technologies.

BSF processing has emerged as a promising alternative, offering high-value protein products and reduced emissions, thus maximising ecological, social, and financial benefits (Lalander *et al.*, 2018). This study's results confirm BSF as

Table 6. Summary of the economic assessment of impacts considered for anaerobic digestion per ZAR/year and ZAR/tonne (2022 ZAR), varying compliance.

Type of cost	Impact Group	Description of impact	Impact Identification: Cost (R/ tonne /year)	Impact Identification: Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Impact Valuation: Cost (Million R/year)	Impact Valuation: Revenue (Million R/ year)
Internal	Infrastructure	AD O&M	1153.75	–	3,030,271.60	3496.18	–
Internal		Landfill O&M	484.67	–	33,254,208.23	16,117.17	–
Internal	Recovery of waste	Gate Fees – landfill	–	376.28	33,254,208.23	–	12,512.89
Internal		Gate fees – AD	–	376.28	3,030,271.60	–	1140.23
Internal		Food waste to electricity	–	697.32	3,030,271.60	–	2113.07
		Food waste to compost	–	551.28	3,030,271.60	–	1670.53
External	Environmental	Chemical fertiliser replacement	–	46.63	3,030,271.60	–	141.30
External		Fossil fuel elec. displacement	–	167.86	3,030,271.60	–	508.66
External		GHG – landfill	57.75	–	33,254,208.23	1920.57	–
External		GHG – AD	35.52	–	3,030,271.60	107.64	–
External		LAP – landfill	0.82	–	33,254,208.23	27.28	–
External		LAP – AD	0.55	–	3,030,271.60	1.67	–
External		Leachate – landfill	0.03	–	33,254,208.23	1.00	–
External		Leachate – AD	–	–	3,030,271.60	–	–
External	Quality of life	Disamenity – AD	5.43	–	3,030,271.60	16.45	–
External		Disamenity – landfill	34.61 (5.43)	–	33,254,208.23	1151.05	–
Total of Internal Impacts						19,613.35	17,436.72
Total External Impacts						3225.66	649.96
Total Impacts						22,839.01	18,086.68
Assuming 100% Compliance							
Total of Internal Impacts						19,613.35	17,436.72
Total External Impacts						2255.10	649.96
Total Impacts						21,868.45	18,086.68

the highest-ranked option in terms of total benefits, positioning it as a leading candidate for sustainable waste diversion and resource recovery.

The literature suggests that combined technologies, such as AD with BSF or WC, could enhance cost–benefit efficiency, as highlighted by Fan *et al.* (2023). Future research should focus on integrated waste management strategies tailored to regional and volumetric considerations to optimise the production of value-added by-products (Lalander *et al.*, 2018; Fan *et al.*, 2023).

7.2 Economic role of gate fees

Gate fees are critical economic instruments in South Africa's waste management, determining the financial viability of landfills while providing incentives for waste diversion. For instance, the City of Cape Town charges R640/t of municipal solid waste (MSW), which covers waste management costs and encourages alternatives to landfilling (DEA, 2018; City of Cape Town, 2021). By contrast, provinces such as the Northern Cape, which impose no gate fees, experience poor compliance, underscoring the link between fee structures and waste management practices (GreenCape, 2022; De Klerk, 2023).

Compliance with landfill regulations remains low, with only 17.5% of sites meeting required standards. This leads to significant environmental hazards and disamenity costs, estimated in this study at R1.8 billion annually (Nahman, 2011; De Klerk, 2023). Importantly, while higher gate fees can incentivise improved practices, without stronger governance they may also encourage illegal dumping, worsening environmental risks (DEA, 2018).

7.3 Policy and practice recommendations

Improving waste management in South Africa requires a balanced approach that integrates pricing, compliance, and investment in alternatives. Gate fees should be set to reflect the true costs of waste management, including externalities, while simultaneously funding compliance measures and supporting waste diversion (Nahman *et al.*, 2012).

Targeted investments in infrastructure and alternative technologies, such as VC and BSF, can deliver strong sustainability

Table 7. Summary of the economic assessment of impacts considered for vermicomposting per ZAR/year and ZAR/tonne (2022 ZAR), varying compliance.

			Impact Identification			Impact Valuation	
Type of cost	Impact Group	Description of impact	Cost (R/ tonne /year)	Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Cost (Million R/year)	Revenue (Million R/ year)
Internal	Infrastructure	VC O&M	437.00	–	3,030,271.60	1324.23	–
Internal		Landfill O&M	484.67	–	33,254,208.23	16,117.17	–
Internal	Recovery of waste	Gate Fees – landfill	–	376.28	33,254,208.23	–	12,512.89
Internal		Gate fees – VC	–	376.28	3,030,271.60	–	1140.23
Internal		Food waste to Feed	–	105.25	3,030,271.60	–	318.94
		Food waste to compost	–	1728.00	3,030,271.60	–	5236.31
External	Environmental	Chemical fertiliser replacement	–	27.42	3,030,271.60	–	83.09
External		Feed substitution		0.72	3,030,271.60	–	2.18
External		GHG – landfill	57.75	–	33,254,208.23	1920.57	–
External		GHG – VC	13.65	–	3,030,271.60	41.36	–
External		LAP – landfill	0.82	–	33,254,208.23	27.28	–
External		LAP – VC	–	–	3,030,271.60	–	–
External		Leachate – landfill	0.03	–	33,254,208.23	1.00	–
External		Leachate – VC	–	–	3,030,271.60	–	–
External	Quality of life	Disamenity – VC	5.43	–	3,030,271.60	16.45	–
External		Disamenity – landfill	34.61 (5.43)	–	33,254,208.23	1151.05	–
Total of Internal Impacts						17,441.40	19,208.37
Total External Impacts						3157.72	85.27
Total Impacts						20,599.12	19,293.64
Assuming 100% Compliance							
Total of Internal Impacts						17,441.40	19,208.37
Total External Impacts						2187.16	85.27
Total Impacts						19,628.56	19,293.64

outcomes (Coelho *et al*., 2019). Municipalities could reinforce uptake by ensuring that gate fees for diversion technologies are set lower than those for landfilling, making alternatives financially preferable (DEFF, 2020).

The results of this study suggest that AD and in-vessel composting (IVC) most directly support the NWMS diversion targets, while BSF offers added circular economy benefits through protein recovery. A strategic combination of economic incentives, regulatory compliance, and sustainable practices is therefore essential to achieve long-term national waste management objectives.

8. CONCLUSION

This paper establishes a baseline for food waste management costs in South Africa and evaluates alternative technologies for their effectiveness in diverting waste from landfills while generating value-added products. The results highlight the urgent need for an integrated strategy that incorporates economic, ecological, social, and governance dimensions to transform food waste into a resource.

Current landfill practices impose an estimated R8.7 billion annual burden on the economy, environment, and communities, underscoring the role of regulatory compliance and effective governance. By contrast, technologies such as BSF and VC demonstrate strong potential for cost-effective diversion and resource recovery, with AD contributing to renewable energy generation. This study revises the cost estimates of landfilling in South Africa and provides policymakers with a cost–benefit framework to critically evaluate management options.

While the reliance on assumptions for external cost estimates limits precision, the findings offer reliable insights into the scale of externalities. Future research should generate more detailed economic data, but the evidence already supports a paradigm shift. With targeted policies and investments, food waste could shift from being a costly liability to serving as a cornerstone of South Africa's circular economy and sustainable development agenda.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

ORCID

A. S. Fitchett http://orcid.org/0000-0003-4676-296x

Table 8. Summary of the economic assessment of impacts considered for BSF per ZAR/year and ZAR/tonne (2022 ZAR), varying compliance.

			Impact Identification			Impact Valuation	
Type of cost	Impact Group	Description of impact	Cost (R/ tonne /year)	Revenue (R/ tonne /year)	Impact Quantification (tonnes/year)	Cost (Million R/year)	Revenue (Million R/ year)
Internal	Infrastructure	BSF O&M	661.80	–	3,030,271.60	2005.43	–
Internal		Landfill O&M	484.67	–	33,254,208.23	16,117.17	–
Internal	Recovery of waste	Gate Fees – landfill	–	376.28	33,254,208.23	–	12,512.89
Internal		Gate fees – BSF	–	376.28	3,030,271.60	–	1140.23
Internal		Food waste to high protein feed	–	1827.00	3,030,271.60	–	5536.31
		Food waste to compost	–	600.00	3,030,271.60	–	1818.16
External	Environmental	Chemical fertiliser replacement	–	24.69	3,030,271.60	–	74.82
External		Feed substitution	–	5.14	3,030,271.60	–	15.58
External		GHG – landfill	57.75	–	33,254,208.23	1920.57	–
External		GHG – BSF	29.80	–	3,030,271.60	90.30	–
External		LAP – landfill	0.82	–	33,254,208.23	27.28	–
External		LAP – BSF	–	–	3,030,271.60	–	–
External		Leachate – landfill	0.03	–	33,254,208.23	1.00	–
External		Leachate – BSF	–	–	3,030,271.60	–	–
External	Quality of life	Disamenity – BSF	5.43	–	3,030,271.60	16.45	–
External		Disamenity – landfill	34.61 (5.43)	–	33,254,208.23	1151.05	–
Total of Internal Impacts						18,122.60	21,007.59
Total External Impacts						3206.66	90.39
Total Impacts						21,329.26	21,097.99
Assuming 100% Compliance							
Total of Internal Impacts						18,122.60	21,007.59
Total External Impacts						2,236.10	90.39
Total Impacts						20,358.70	21,097.99

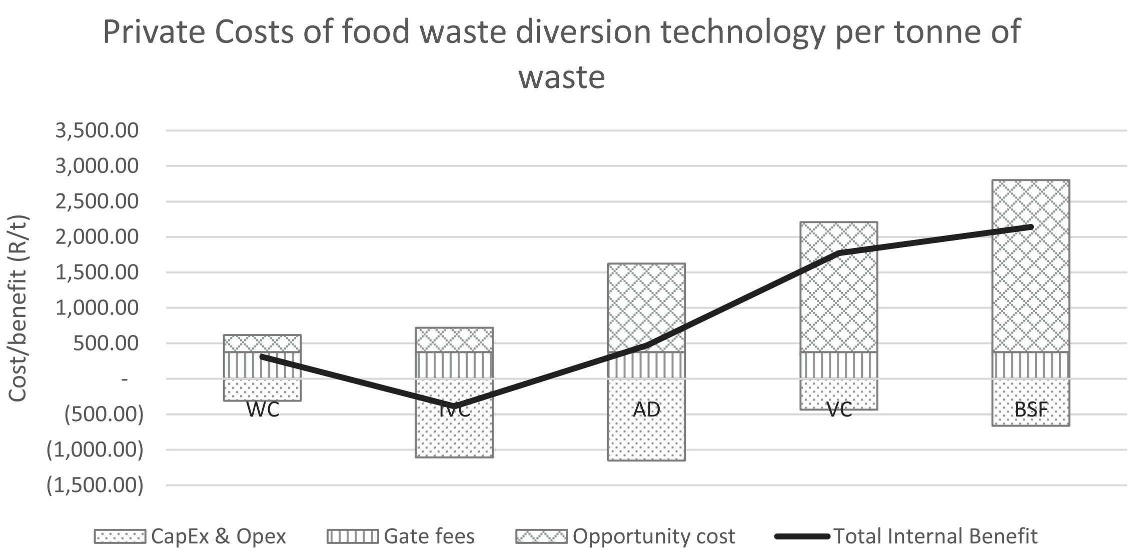

Figure 2. Summarising the private costs and benefits of food waste diversion technology and their potential financial viability (per tonne of food waste).

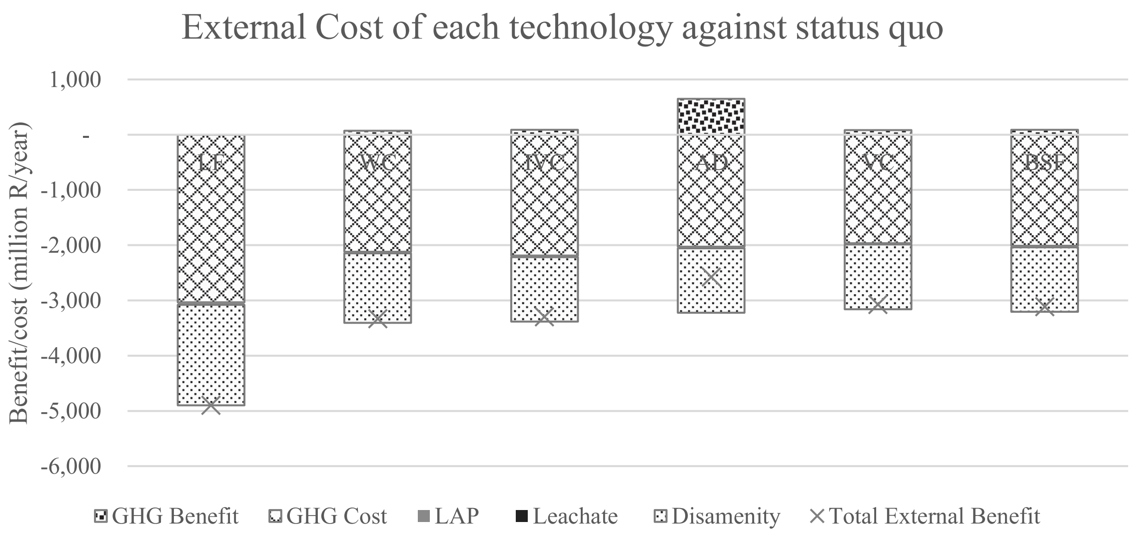

Figure 3. Summary of external benefit for each scenario assuming current state of compliance.

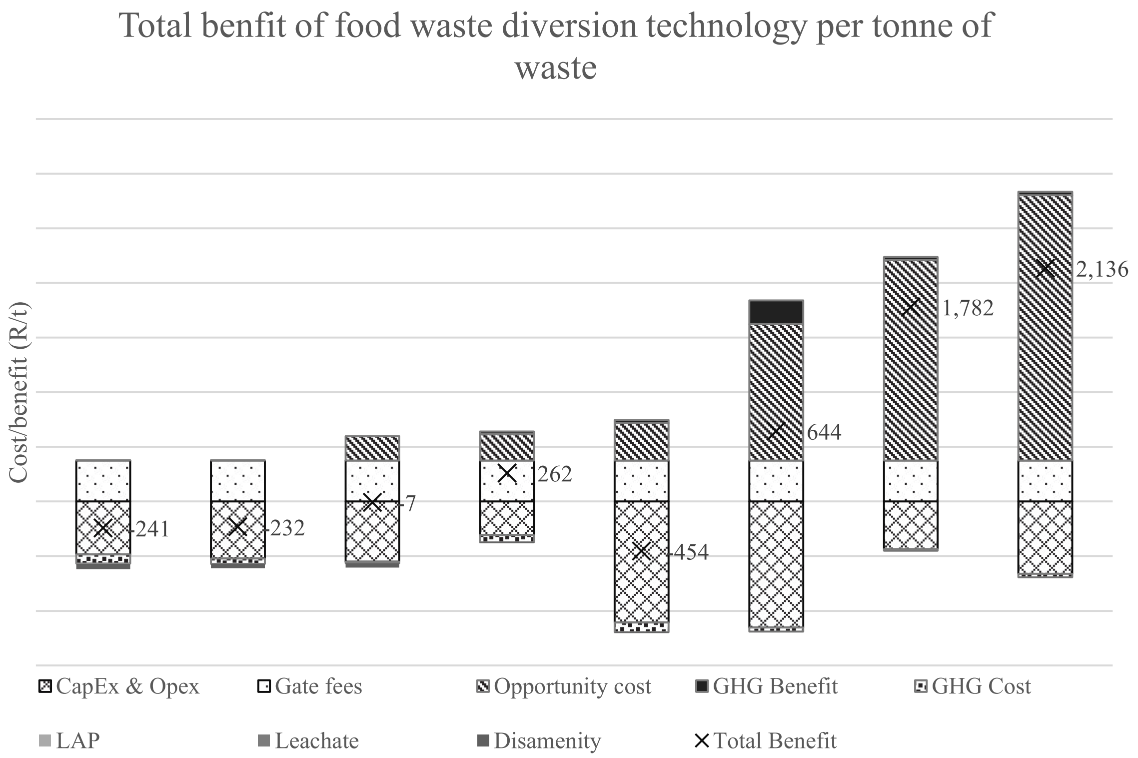

Figure 4. Summarising the total costs and benefits of food waste diversion technology (per tonne of food waste).

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