

A breakeven grid-emission threshold for waste-to-energy: reordering municipal solid waste pathways under Bahrain's fossil-dependent grid

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Abstract

Waste-to-energy (WtE) incineration is widely promoted as a climate-mitigation route for municipal solid waste (MSW), yet its net benefit depends on the carbon intensity of the electricity it displaces, a dependence rarely quantified as a decision threshold. This paper establishes that threshold and shows how it reorders MSW pathways under a fossil-dependent grid. Ten management pathways are assessed against four years of complete national waste-tonnage data (2019–2022) for the Kingdom of Bahrain, applying IPCC Tier-1 and iWARM accounting on a consistent grid-emission basis of 0.727 kg CO₂-eq/kWh. Full incineration remains a net emitter and breaks even only above roughly 0.96 kg CO₂-eq/kWh, a threshold that moves further out of reach as the grid decarbonises. Every material-recovery pathway instead delivers a net climate benefit, and recovery-led portfolios dominate single-technology options. A recommended integrated portfolio diverts the large majority of MSW from landfill, recovering 1,508 GWh/yr of energy-equivalent and saving 1,017 kt CO₂-eq/yr. Because the controlling variable is grid carbon intensity rather than local geography, the framework transfers to any economy weighing incineration against recovery during an energy transition.

1. Introduction

Municipal solid waste (MSW) management is increasingly recognised as a pivotal determinant of sustainable development rather than an ancillary municipal service. As many as twelve of the seventeen United Nations Sustainable Development Goals are directly influenced by MSW outcomes, spanning public health, climate action, sustainable urbanisation, and responsible consumption (Sharma et al. 2021; Bashir et al. 2022). Yet many low- and middle-income economies continue to depend on landfilling and uncontrolled disposal, the least preferred options on the waste hierarchy and significant sources of greenhouse gas (GHG) emissions (Tan et al. 2014). Reconciling this recognised potential with prevailing practice requires evidence on which pathways deliver the greatest climate and energy benefits under specific national conditions.

These stresses are particularly acute in Small Island Developing States (SIDS), where limited landfill capacity, elevated per-capita infrastructure costs, narrow resource bases, import dependence, and the environmental burden of tourism converge (Agamuthu and Herat 2014; Fuldauer et al. 2019). Per-capita waste generation in SIDS frequently approaches that of industrialised economies, even as institutional capacity, regulation, data systems, and recycling markets remain underdeveloped. These pressures intensify where high population density coincides with a fossil-fuel-dependent grid, because limited land sharpens the landfill constraint while a carbon-intensive grid widens the climate advantage of every recovery pathway by increasing the emissions displaced (Mata-Lima et al. 2021).

The transition from a linear "take, make, dispose" paradigm to a circular economy reframes MSW from a residual liability into a portfolio of recoverable resource streams (Eelager et al. 2025). A systematic review underscored that no single technology is optimal across all criteria and that selection benefits from integrated and multi-criteria assessment (Vitorino de Souza Melaré et al. 2017). This is corroborated by Tan et al. (2014) whose mixed-integer linear programming formulation for Iskandar Malaysia showed that the least-cost configuration meeting renewable-energy and recycling targets was dominated by material recovery (56%) and composting (27%), with only marginal landfill-gas recovery (14%) and incineration (3%). Collectively, these studies substantiate the premise that integrated, recycling-led portfolios tend toward optimality. Feasibility extends beyond technical performance, however: Valentine (2026) qualitative assessment of Guam found strong interest in circular-economy principles yet persistent barriers including resource scarcity, low awareness, and limited economies of scale.

Material-specific analyses reinforce this case. For Taiwan, Chen (2016) found metal recycling delivered the largest per-tonne GHG mitigation ($\sim 3,205$ kg CO₂-eq tonne⁻¹), while paper and plastic recycling yielded the greatest absolute energy savings, but cautioned that these benefits are contingent on grid carbon intensity, material purity, and secondary-market maturity. The life-cycle assessment of Al-Salem et al. (2014) for Greater London concurred, finding textile and paper

recycling delivered the largest net improvements, while thermo-chemical treatment of plastic was advantageous only where petrochemical markets existed.

Energy recovery introduces a further dependency. Brinck et al. (2011) traced the evolution of waste-to-energy incineration at Aalborg's Reno-Nord plant, documenting a reversal in the per-capita GHG balance from a net emission of $\sim 30 \text{ kg CO}_2\text{-eq person}^{-1}$ in 1960 to a net saving of $\sim 770 \text{ kg CO}_2\text{-eq person}^{-1}$ by 2005. Fossil-derived combustion contributed about two-thirds of GHG turnover without energy recovery, but only 10–15% with modern recovery technology. This carries two implications for Bahrain. Incineration's climate performance depends on whether its electricity displaces fossil generation, so the benefit weakens as the grid decarbonises and is offset by the combustion penalty once recovery efficiency is realistic. Bahrain's grid remains dominated by natural-gas combined-cycle generation with an emission factor of $\sim 0.73 \text{ kg CO}_2\text{-eq per kWh}$ (Brander 2011), which is not carbon-intensive enough for WtE to break even, so the displacement advantage accrues to material-recovery pathways rather than to incineration.

Island-context studies sharpen these conclusions. In the densely populated Maltese Islands, substantive climate benefits required integrating climate objectives into waste policy, with further abatement dependent on intensified recycling, source-separated organic collection, and route optimisation (Camilleri-Fenech et al. 2018). Recent SIDS assessments corroborate this: recycling- and composting-oriented scenarios most reduced landfilled volume in Fiji (Matagi et al. 2024), while uncontained landfilling in the Maldives generates escalating, climate-amplified leachate risks (Wang et al. 2025).

Environmental-management capacity across the region has only recently begun to mature. Rapid urbanisation and hydrocarbon-driven industrialisation outpaced institutional and educational infrastructure, and in Bahrain limited public and environmental awareness reflects this lag (Sreenivas et al. 2022). Quantitative waste-sector evidence remains correspondingly sparse. Yaman et al. (2020) evaluated three scenarios for the Dammam Metropolitan Area and ranked material recovery with composting highest for GHG savings, ahead of incineration; landfilling was a net emitter. For Bahrain, Abbas et al. (2020) reported through expert interviews that incineration faced the fewest barriers while composting and anaerobic digestion faced economic and managerial constraints, though that assessment was qualitative and did not quantify GHG outcomes. Alsabbagh and Alnaser (2023) projected that prevailing measures could deliver only a $\sim 23\%$ reduction by 2040 under a baseline trajectory, short of a 30%-by-2035 target requiring additional waste-sector mitigation. Interest in organic-fraction valorisation extends across the Gulf. Bonk et al. (2015) assessed dark fermentation for Abu Dhabi but identified source separation, not yet practised there, as the binding precondition.

The Kingdom of Bahrain illustrates these pressures acutely: a densely populated island economy with among the region's highest per-capita waste-generation rates, consigning all collected MSW to a single landfill now nearing capacity (Coskuner et al. 2020). The same study estimated a peak post-closure landfill-gas potential of about 57 GWh in 2020, roughly 0.23% of national electricity output. This underscores the limited mitigation value of landfill-gas recovery as a standalone strategy.

These pressures call for a progression beyond landfill dependence rather than a single substitute. Three configurations span the option space for an arid, gas-dominated system: a recycling-led pathway pairing a material recovery facility (MRF) with windrow composting; an energy-recovery pathway combusting waste to displace fossil generation; and an integrated portfolio coupling MRF and composting with residual-only WtE. Which best suits such a system remains unresolved, as does how the answer depends on MRF recovery rate, composting penetration, and grid carbon intensity. No study has yet quantified these trade-offs for a gas-dependent island economy using complete national data.

To address this gap, this study assesses which MSW pathway delivers the greatest climate and energy benefit under Bahrain's conditions across four years of complete national tonnage data (2019–2022), evaluating ten scenarios that span landfilling, full incineration, graded MRF recovery, composting penetration, and an integrated portfolio. Per-tonne

emission and energy intensities are derived using IPCC Tier-1 and iWARM methods on a common grid-emission basis, so recycling and thermal pathways are compared under identical assumptions. A sensitivity analysis locates the grid emission factor at which incineration shifts from net saver to net emitter, and the results separate the climate-optimal configuration from the operationally deployable one, providing the quantitative basis for a waste-sector contribution absent from Bahrain's Nationally Determined Contribution (NDC).

2. Materials and Methods

2.1 Description of the study area

The Kingdom of Bahrain is an archipelagic small island developing state (SIDS) with a land area of approximately 780 km² and a 2017 population of about 1.5 million. This yields a density near 2,000 residents km⁻² that ranks among the highest worldwide. Its hyper-arid climate (mean annual precipitation ~ 76 mm) constrains the moisture-dependent decomposition kinetics governing composting and landfill gas generation. MSW from all four governorates is consolidated at the Askar Landfill, ~ 25 km south of Manama, operational since 1986 and now nearing capacity (Coskuner et al. 2020).

2.2 MSW boundary and tonnage data

Waste-tonnage data were obtained from the Askar Landfill gate-record dataset for 1 January 2019 to 31 December 2022, covering 772,847 individual delivery records across 48 complete calendar months. The IPCC defines MSW as waste from households together with similar commercial, institutional, and garden or park sources (IPCC 2006). Applying this definition, five waste categories were retained: domestic, commercial, household-bulky, garden/park, and expired-food. The remainder fell outside the IPCC MSW definition and were excluded: construction and demolition, industrial, animal, tyre, liquid, hazardous, and specialised medical and sanitary streams, all managed separately in Bahrain.

Figure 1 presents the annual IPCC-compatible MSW tonnage deposited at Askar. Generation averaged ~ 994,650 tonnes/yr and was stable across the period apart from an 8.2% dip in 2020, driven by lower commercial and garden waste and consistent with COVID-19 restrictions on commercial activity and landscaping; tonnages recovered to near-2019 levels by 2021. Domestic waste was the largest fraction throughout, followed by commercial.

2.3 MSW composition

MSW composition was taken from a national waste characterisation study (Dowding 2017) and held constant across all four years, since the gate records resolve tonnage by source but not by material. The stream is dominated by food waste, followed by plastics, paper and cardboard, and garden and park waste, with the remaining mass across textiles, glass, metals, and minor residual fractions (Fig. 2). Three derived aggregates govern the scenario accounting: a recyclable fraction (paper, plastics, glass, metals) of 48.2%, a fossil-carbon fraction entering the WtE calculation (plastics and textiles) of 34.2%, and a compostable organic stream (food plus garden and park) of 44.2% that defines the feedstock available to composting in all scenarios. The national open-data series (Information & eGovernment Authority 2025) corroborates this profile at the aggregate level but reports only seven material classes and does not resolve plastics by type, so the Dowding characterisation is retained as the primary basis for incineration accounting. That series also shows interannual variation in the major fractions, so holding composition constant is a deliberate simplification adopted for consistency with the single available type-resolved characterisation.

2.4 Scenario portfolio

Ten pathways were defined to characterise the climate and energy implications of alternative MSW management for Bahrain, comprising a landfilling baseline, a full-thermal WtE scenario, Group A (four scenarios varying MRF recovery rate

under full composting penetration), Group B (three scenarios varying composting penetration at a fixed MRF recovery rate), and one integrated portfolio. They are built from four treatment routes, each with a characteristic climate signature: material recovery (MRF), which yields a net GHG saving by displacing virgin-material production; composting of the food fraction, which carries a small CH₄ and N₂O emission; waste-to-energy (WtE) incineration, whose net outcome depends on the carbon intensity of the displaced grid electricity; and landfilling without gas capture, a net emitter (+ 0.265 tCO₂-eq per tonne under current practice). The resulting allocation of MSW across these streams for each scenario is shown in Fig. 3.

These scenarios bracket the realistic decision space rather than enumerating arbitrary configurations. Two pathways anchor its end-members: the baseline (BL) reflects current practice, in which over 98% of MSW is landfilled (Naser 2022), while W1 represents the fully thermal pathway favoured in local stakeholder consultations (Abbas et al. 2020). Groups A and B then vary the two dominant performance levers, MRF recovery rate and composting penetration, independently, while the integrated portfolio combines them into one operationally realistic configuration.

2.4.1 Baseline scenario

The baseline (BL) deposits 100% of collected MSW at the Askar Landfill without controlled gas collection, reflecting current disposal practice.

2.4.2 Full-thermal WtE scenario (W1)

W1 combusts 100% of MSW with electricity recovery. Together, BL and W1 bound the response space between current practice and the thermal end-member.

2.4.3 Group A: MRF recovery rate scenarios

Four scenarios (S1–S4) vary the MRF material-recovery rate (40%, 60%, 80%, and 100% respectively), with composting fixed at 100% of organic waste. These rates span the documented operational range: mature UK MRFs achieve roughly 90–92% recovery on incoming dry materials (Ali and Courtenay 2014), whereas less developed operations typically achieve 40–60%. Primary data from operating EU facilities confirm that recovery is strongly polymer- and plant-dependent, with sorting rates ranging from below 50% to above 90% for the same polymer across different plants (Antonopoulos et al. 2021). Treating recovery rate as a variable rather than a fixed assumption is deliberate: Jaunich et al. (2019) found that a 10% decline in recovery was sufficient to exclude the mixed-waste MRF from every cost-optimal solution, indicating that system optimality is too sensitive to this parameter to fix a priori.

2.4.4 Group B: Composting penetration scenarios

Three scenarios (C1–C3) vary composting penetration (50%, 75%, and 100% of the food fraction), with MRF recovery fixed at 80%. C3 is mathematically identical to S3 and is included in both groups to anchor the comparison.

2.4.5 Integrated portfolio (IP)

The IP combines all four routes: MRF at 80% recovery of the recyclable fraction, composting of 100% of the food fraction, WtE incineration of 50% of the combustible residual remaining after MRF (unrecovered paper, plastics, and textiles), and landfilling of the inert and stabilised remainder. The 50% residual-combustion fraction is a deliberately conservative choice: it confines WtE to a minor residual-management role rather than a primary treatment route, limiting exposure to the stranded-asset risk discussed in Section 3.8 while still recovering energy from material that would otherwise be landfilled. The resulting 2022 mass balance allocates 38.6% to MRF, 44.2% to composting, 6.2% to WtE, and 11.1% to landfill, an 88.9% landfill diversion, broadly consistent with the EU Landfill Directive's 10%-by-2035 target (European Union 2018).

2.5 Methodological framework

The overall methodological framework, comprising six sequential stages from data inputs through scenario definition to policy implications, is presented in Fig. 4.

2.6 Calculation methodology

Per-tonne emission and energy intensities were derived using the IPCC Tier-1 methodology and the iWARM model (EPA 2016) and applied to annual MSW tonnages: WtE gross emissions intensity $i_0 = 0.7010 \text{ tCO}_2\text{-eq/t MSW}$; WtE electricity recovery intensity = 727.2 kWh/t MSW ; MRF gross savings intensity at 100% recovery = $1.3171 \text{ tCO}_2\text{-eq/t MSW}$; MRF energy equivalent at 100% recovery = $1,812.2 \text{ kWh/t MSW}$. The WtE gross emissions intensity was obtained from the IPCC Tier-1 incineration relationship given in Eq. (1), summed over the fossil-carbon-bearing fractions (plastics, textiles) using IPCC default dry-matter, carbon-content, fossil-fraction, and oxidation values weighted by the MSW composition shown in Fig. 3 (Dowding 2017); the WtE electricity recovery intensity was derived from the as-received lower heating value of the bulk MSW stream (10.47 MJ/kg) at an assumed net electrical conversion efficiency of 25%, consistent with documented incineration efficiencies for Gulf MSW (Ouda et al. 2016). The MRF energy equivalent ($1,812.2 \text{ kWh/t MSW}$ at full recovery) is the iWARM-derived avoided primary-production energy for the recyclable fraction (paper, plastics, glass, metals; 48.2% of MSW); the corresponding gross-savings intensity was obtained by converting this avoided electricity to $\text{CO}_2\text{-eq}$ at the Bahraini grid factor (Eq. (2)). The composting emission factor was $80 \text{ kg CO}_2\text{-eq/t organic waste}$ (Yaman et al. 2020), reflecting the IPCC default CH_4 (4 kg/t) and N_2O (0.3 kg/t) emission factors weighted by AR5 GWP-100 values (28 and 265 respectively) (IPCC 2014). A consistent Bahraini grid emission factor of $0.7268 \text{ kg CO}_2\text{-eq/kWh}$ (Brander 2011) was applied for displaced electricity in both WtE and MRF calculations, ensuring that the two recovery pathways are compared on an identical grid basis. The per-tonne WtE and MRF intensities are retained from the type-resolved characterisation on which they were derived (recyclable fraction 48.2%, fossil-carbon fraction 34.2%), whereas the mass allocated to composting is taken on the Dowding source basis to include the garden and park organic fraction; the composting term is governed solely by organic mass and the composting emission factor, so this allocation does not affect the WtE or MRF intensities, and the distinction is stated here for transparency.

$$i_0 = \sum_j (WF_j \cdot dm_j \cdot CF_j \cdot FCF_j \cdot OF_j) \cdot (44/12) \quad (1)$$

$$i_{\text{MRF}} = e_{\text{MRF}} \cdot EF_{\text{grid}} = 1,812.2 \text{ kWh/t} \times 0.7268 \text{ kg CO}_2\text{-eq/kWh} = 1.3171 \text{ tCO}_2\text{-eq/t MSW} \quad (2)$$

In Eq. (1), i_0 is the WtE gross emissions intensity ($\text{tCO}_2\text{-eq/t MSW}$); the summation runs over the fossil-carbon-bearing fractions j (plastics, textiles); WF_j is the mass fraction of fraction j in the MSW stream; dm_j is its dry-matter content; CF_j is its carbon content; FCF_j is its fossil-carbon fraction; OF_j is its oxidation factor; and $44/12$ is the stoichiometric ratio converting carbon to CO_2 . In Eq. (2), i_{MRF} is the MRF gross-savings intensity ($\text{tCO}_2\text{-eq/t MSW}$), e_{MRF} is the MRF avoided primary-production energy at full recovery ($1,812.2 \text{ kWh/t MSW}$), and EF_{grid} is the Bahraini grid emission factor ($0.7268 \text{ kg CO}_2\text{-eq/kWh}$). Herein, e_{MRF} denotes the avoided cumulative primary-production energy of the recovered materials, as derived in iWARM. Valuing this avoided energy at the Bahraini grid emission factor provides a single, transparent basis on which material-recovery and energy-recovery pathways can be compared, rather than an assertion that recovered-material energy displaces domestic grid electricity directly. Because a share of virgin production occurs outside Bahrain and involves energy carriers other than grid electricity, this conversion is a simplification whose net directional effect is uncertain; its influence on the scenario ranking is examined in the sensitivity analysis (Section 3.6).

The Group A and B scenarios were calculated as:

$$Net = \left(\frac{m \cdot f_{\text{food}} \cdot \theta \cdot EF_{\text{comp}}}{1000} \right) - (m \cdot R \cdot i_{\text{MRF}})$$

where m is annual MSW tonnage (t), f_{food} is the compostable organic fraction (food + garden, 0.442), θ is composting penetration (0.50, 0.75, or 1.00), EF_{comp} is the composting emission factor (80 kg CO₂-eq/t organic), R is MRF recovery rate (0.40, 0.60, 0.80, or 1.00), and i_{MRF} is the MRF gross-savings intensity (1.3171 tCO₂-eq/t MSW). In Group A and B scenarios, the mass that is neither recovered at the MRF nor composted is directed to landfill; its disposal emissions are treated identically across all scenarios within each group and are therefore omitted from the comparative balance, which reports the net effect of the treatment choices that distinguish the scenarios. This is a conservative simplification: because the residual is dominated by non-degradable materials once the organic fraction is composted, its inclusion would lower the absolute savings of the lower-recovery scenarios modestly without altering the scenario ranking.

Energy recovery was calculated using Eq. (4). For the IP scenario, the four streams were calculated separately and summed, with mass balance enforced.

$$E = m \cdot R \cdot e_{\text{MRF}} \quad (4)$$

where E is the annual energy recovery (kWh/yr), m is annual MSW tonnage (t), R is the MRF recovery rate, and e_{MRF} is the MRF energy equivalent at full recovery (1,812.2 kWh/t MSW).

Pre-treatment, transportation, plant operation, and final disposal of incinerator bottom ash were considered outside the system boundary, consistent with comparable studies (Brinck et al. 2011; Yaman et al. 2020). Biogenic CO₂ emissions from the combustion of paper, food and wood waste were excluded under IPCC convention (IPCC 2006).

3. Results and Discussion

3.1 Inter-annual variation in MSW generation

The four-year dataset reveals a relatively stable annual MSW tonnage, ranging from 941,439 tonnes in 2020 to 1,025,171 tonnes in 2019, with year-on-year variation of less than 9% (Fig. 2). The 2020 drop is consistent with the documented impact of COVID-19-related restrictions on commercial activity, recreational landscaping, and household consumption (Yousefi et al. 2021; Jassim et al. 2023). The compositional shares of the five MSW source categories remained broadly stable over the four years, with DOM (domestic) consistently the largest single source at approximately 56–60%. This stability validates the assumption, adopted in this study, that composition can be treated as approximately constant across the four-year period.

3.2 Net GHG emissions across scenarios

Figure 5 presents the net GHG emissions of all ten pathways for each year of the 2019–2022 study period. Across all four years, the landfilling baseline (BL) and the full-incineration scenario (W1) are the only pathways that produce net positive emissions, at approximately + 250 to + 272 and + 162 to + 177 kt CO₂-eq/yr respectively. Every material-recovery scenario examined delivers a net climate dividend.

Increasing the MRF recovery rate from 40% (S1) to 100% (S4) raises the net climate dividend in approximately linear fashion, from – 496 kt CO₂-eq/yr at 40% recovery to – 1,293 kt CO₂-eq/yr at 100% recovery in 2022. Every MRF + composting scenario, including the least ambitious 40%-recovery case, outperforms the full-incineration scenario (W1, + 174 kt CO₂-eq/yr in 2022, a net emitter) by a decisive margin. This dominance arises because, under Bahrain's gas-dominated grid (emission factor 0.7268 kg CO₂/kWh), the avoided primary-production energy embodied in recovered materials displaces grid electricity at the same high carbon intensity as WtE-generated electricity, while the MRF stream carries none of the fossil-CO₂ combustion penalty intrinsic to incineration. As discussed in Section 3.6, the WtE result is

also fragile in a way the recovery pathways are not: at the assumed 25% net conversion efficiency the grid-displacement credit no longer offsets the fossil-CO₂ combustion penalty, so W1 is a net emitter at Bahrain's current grid factor and weakens further as the grid decarbonises toward Bahrain's 2035 renewable target. The composting-penetration scenarios show the opposite, much weaker sensitivity: raising composting penetration from 50% (C1) to 100% (C3) marginally reduces the net climate dividend, from – 1,045 to – 1,027 kt CO₂-eq/yr in 2022, because composting itself produces small but non-negligible CH₄ and N₂O emissions. The integrated portfolio (IP) delivers a net saving of approximately – 1,017 kt CO₂-eq/yr, placing it among the strongest-performing scenarios while diverting 88.9% of MSW from landfill.

3.3 Energy recovery across scenarios

Figure 6 presents the annual energy recovery by scenario over 2019–2022. Two structural patterns emerge. First, the MRF + composting scenarios scale energy recovery linearly with MRF recovery rate, rising from approximately 730 GWh/yr at 40% recovery to 1,828 GWh/yr at 100% recovery in 2022, where the MRF + composting energy is reported as the iWARM-derived avoided primary-production energy equivalent. Second, the integrated portfolio recovers 1,508 GWh/yr in 2022, below S4 (100% MRF recovery) but above S3 (80% MRF recovery alone), reflecting the additional contribution of the residual WtE component. Composting-penetration scenarios are not plotted because they affect only composting emissions rather than the energy-recovery balance. The Baseline is omitted because landfilling without material recovery, waste-to-energy conversion, or landfill-gas capture yields zero energy recovery across all years.

3.4 Mass balance of the integrated portfolio

For the integrated portfolio in the 2022 inventory year (total MSW = 1,008,917 tonnes), MRF processes the 48.2% recyclable fraction at 80% effective recovery, capturing 389,038 tonnes (38.6% of MSW) for reprocessing. Composting handles 445,538 tonnes (44.2% of MSW) of food and garden waste at 100% penetration. WtE incineration processes 62,755 tonnes (6.2% of MSW), comprising 50% of the combustible residual remaining after MRF (paper, plastics, and textile fractions not recovered by the MRF). The remaining 111,586 tonnes (11.1% of MSW) is landfilled. The integrated portfolio therefore diverts 88.9% of MSW away from landfill, comparable to the diversion rates targeted in mature European waste-management jurisdictions.

3.5 Scenario comparison and pathway selection

Figure 7 maps all ten pathways in the net-GHG–landfill-diversion trade-off space for the 2022 inventory year, with bubble area scaling with annual energy recovery, and Table 1 reports the full performance indicators. The maximum-recovery MRF and composting scenario (S4) achieves the largest net saving at – 1,293 kt CO₂-eq/yr, and every material-recovery scenario outperforms full incineration: even the 40%-recovery S1, at – 496 kt CO₂-eq/yr, sits well below W1 (+ 174 kt CO₂-eq/yr), which is a net emitter ranking above only the landfilling baseline. The integrated portfolio is among the strongest performers at – 1,017 kt CO₂-eq/yr, comparable to the fixed-80%-recovery MRF scenarios while diverting 88.9% of MSW from landfill. Composting penetration has only a modest effect on the net climate result: reducing it from 100% to 50% (C3 to C1) marginally improves the balance, from – 1,027 to – 1,045 kt CO₂-eq/yr, because the organic fraction carries a small net CH₄ and N₂O emission when composted. This does not argue against high composting penetration, which the portfolio retains for its landfill-diversion and avoided-methane benefits; it indicates only that the marginal climate value of composting is small relative to material recovery.

Table 1

Annualised performance indicators for all scenarios, 2022 inventory year (MSW = 1,008,917 t). Landfill diversion is the mass fraction not consigned to landfill (material recovery + composting + WtE residual).

Scenario	Net GHG (kt CO ₂ -eq/yr)	Energy recovery (GWh/yr)	GWP (tCO ₂ -eq/t MSW)	Landfill diversion (%)
BL: Landfilling (baseline)	+ 267	0	+ 0.265	0
W1: WtE incineration	+ 174	734	+ 0.172	100
S1: MRF 40% + Comp 100%	-496	731	-0.492	63
S2: MRF 60% + Comp 100%	-762	1,097	-0.755	73
S3: MRF 80% + Comp 100%	-1,027	1,463	-1.018	83
S4: MRF 100% + Comp 100%	-1,293	1,828	-1.282	92
C1: MRF 80% + Comp 50%	-1,045	1,463	-1.036	61
C2: MRF 80% + Comp 75%	-1,036	1,463	-1.027	72
C3: MRF 80% + Comp 100% (= S3)	-1,027	1,463	-1.018	83
IP: Integrated portfolio	-1,017	1,508	-1.008	89

Although S4 leads on the net-GHG axis, it is not recommended as a national strategy, and neither is the full-incineration scenario (W1). W1 represents 100% incineration of MSW, a configuration with high capital cost, significant air-quality implications, no source separation benefit, and high stranded-asset risk under a decarbonising grid; it is moreover outperformed on net GHG by every material-recovery scenario examined. S4 assumes complete recovery of the recyclable fraction at the MRF, a level not demonstrated at scale anywhere in the world; it is included as a mathematical upper bound on the response surface rather than an operationally realistic configuration. The integrated portfolio (IP), by contrast, achieves a near-maximal climate dividend at operationally realistic recovery rates. It recovers energy from both material recovery and residual combustion, diverts most waste from landfill, and remains tractable under current institutional capacity. It is therefore recommended as the preferred national strategy.

3.6 Sensitivity to key parameters

The qualitative ranking of scenarios is robust to plausible variation in the grid and composting emission factors. The full-incineration result (W1) is most sensitive to the grid factor: at the IPCC default of 0.202 kg CO₂-eq/kWh, W1 emits approximately + 559 kt CO₂-eq/yr, and at 0.85 kg CO₂-eq/kWh it remains a net emitter at approximately + 84 kt CO₂-eq/yr. The breakeven factor at which WtE shifts from emitter to saver is approximately 0.96 kg CO₂-eq/kWh. This lies above Bahrain's current grid factor (0.7268 kg CO₂-eq/kWh), so at 25% conversion efficiency WtE does not break even on the present grid, and it moves further from breakeven as the grid decarbonises toward Bahrain's 2035 renewable-energy target (Supreme Council for Environment 2024). The MRF and composting scenarios scale with the grid factor in the same direction as WtE but from a far stronger position and without a combustion penalty, so they remain the top-ranked pathways across the entire range examined; the recycling-led advantage is therefore structural rather than contingent on a particular grid assumption. Raising the composting emission factor from 80 to 172 kg CO₂-eq/t of wet garden waste, the aerated dome value reported by Friedrich and Trois (2013), reduces the S3 net saving from - 1,027 to - 986 kt CO₂-eq/yr in 2022, a change of about 4% that does not alter the qualitative ranking.

3.7 Validation against comparable case studies

The results of this work can be benchmarked against the wider literature, though direct numerical comparison holds only for studies using comparable iWARM- or LCA-based grid-displacement accounting. At operational (80%) recovery the present MRF estimate is $-1.018 \text{ tCO}_2\text{-eq/t}$, rising to -1.282 at full recovery. The operational value brackets the -1.091 reported independently for Dammam (Yaman et al. 2020), supporting the magnitude of recovery-led mitigation in a similar Gulf grid context. The incineration results diverge in sign but agree in magnitude: the present full-incineration result (W1, $+0.172 \text{ tCO}_2\text{-eq/t}$) and the Dammam value (-0.147) both sit close to zero, indicating a near-neutral WtE balance under realistic conversion efficiency and grid-displacement credits. The sign of this balance is set by grid carbon intensity: because WtE electricity can be as carbon-intensive as the fossil generation it displaces, a cleaner grid erodes its avoided-emissions credit (Pfadt-Trilling et al. 2021).

Khafagy et al. (2024) modelling six Egyptian governorates with IPCC/CDM methane accounting and grid-displacement crediting at a lower grid factor of $0.51 \text{ kg CO}_2\text{-eq/kWh}$, found incineration to roughly double the avoided emissions of landfill-gas recovery and to deliver $0.32\text{--}0.57 \text{ kWh/t MSW}$. Their incineration balance is favourable where the present study's is near-neutral because of the baseline. Crediting incineration against open dumping with its large uncontrolled methane release dominates the comparison, whereas the present study credits against engineered landfill.

A consistent picture emerges from studies in other jurisdictions: Chen (2016) for Taiwan found metal recycling to deliver the largest per-tonne mitigation, with paper and plastics driving energy recovery ($\sim 10^{10} \text{ kWh/yr}$ avoided); Al-Salem et al. (2014) for Greater London judged the incumbent MRF and energy-recovery configuration preferable to landfilling on every impact category; Camilleri-Fenech et al. (2018) for Malta, the Mediterranean island closest to Bahrain in scale and density, reported substantial footprint reduction from expanded mechanical biological treatment; Brinck et al. (2011) for Aalborg recorded a net saving of $\sim 770 \text{ kg CO}_2\text{-eq/person/yr}$, though contingent on district heating and coal displacement that do not apply in Bahrain; and Tan et al. (2014) for Iskandar Malaysia identified a cost-optimal configuration dominated by MRF (56%) and composting (27%), echoing the integrated portfolio recommended here.

Several robust patterns emerge across these studies. Integrated portfolios consistently outperform single-technology pathways, and the climate case for incineration depends critically on the carbon intensity of the electricity it displaces. Organic-waste management, whether composting or anaerobic digestion, is a high-leverage mitigation route wherever food waste constitutes a large share of MSW, as in Bahrain (35.2%) and Saudi Arabia ($\sim 39\%$). Source separation and segregation infrastructure are foundational, unlocking value across every downstream pathway at once. The contribution of material recovery, however, is strongly conditioned by the achievable recovery rate: where separation efficiency is low, the climate and cost case for an MRF weakens sharply. The European evidence makes this concrete: Antonopoulos et al. (2021) drawing on primary data from operating sorting and recycling plants, estimated an overall end-of-life recycling rate for post-consumer plastic packaging in EU27 of only 14% in 2017, rising to a modelled ceiling of about 49% by 2030 under best-available practices, with film contamination, commingled collection, and weak markets for lower-value polymers identified as the principal constraints. These findings indicate that the recovery rates underpinning the upper scenarios are contingent on collection-system and product-design improvements upstream of the plant rather than on plant technology alone. Jaunich et al. (2019) showed for Wake County, USA, that a 10% recovery shortfall was enough to eliminate the mixed-waste MRF from every cost-optimal solution, with the lowest mitigation costs arising where recovery was paired with downstream thermal treatment rather than deployed alone, precisely why the present study treats MRF recovery rate as a primary axis of variation.

3.8 Policy implications and alignment with national strategy

Bahrain's NDC 3.0 frames its mitigation effort as three contributions with co-benefits, namely renewable energy (20% of installed capacity by 2035), afforestation, and mangrove planting covering only the energy, forestry, and cross-cutting sectors (Supreme Council for Environment 2024). However, it overlooks the waste sector despite its substantial untapped potential as over 98% of municipal solid waste is currently landfilled and under 2% recovered (Naser 2022).

Adoption of the integrated portfolio is estimated to deliver net GHG savings on the order of 1,017 kt CO₂-eq/yr at present tonnages, with 1,508 GWh/yr of recoverable energy, supporting the inclusion of a quantified waste-sector contribution in the next NDC.

The integrated portfolio accommodates the expert preference for incineration while retaining recycling's greater emissions savings (Abbas et al. 2020). Incineration is confined to a 6% residual fraction (Fig. 3). A WtE plant's climate benefit comes mainly from the grid electricity it displaces, so that benefit shrinks as the grid decarbonises. At the 25% net electrical efficiency adopted here, the displaced-grid credit rather than combustion governs the climate balance. A large incinerator built to run for 25–30 years could therefore lose much of its climate rationale partway through its life as Bahrain's grid approaches its 2035 renewable target. Keeping WtE confined to the residual fraction avoids that risk. Certain investments are required regardless of pathway: source separation, secondary-materials markets, organic-waste collection, and capacity building. These align with the barriers identified for WtE deployment across developing economies, where the binding constraints are typically not the conversion technology but the absence of skilled personnel, financing mechanisms, and an enabling regulatory structure (Khawaja et al. 2024).

4. Conclusions

At the prevailing grid carbon intensity, recycling-led material recovery is both the climate-optimal and the operationally deployable basis for MSW management in a land-constrained and gas-dependent island economy. Across ten pathways evaluated on four years of Bahraini waste-tonnage data, every material-recovery pathway delivered a net climate dividend while landfilling remained a net emitter at + 267 kt CO₂-eq/yr. Combined MRF and composting reached – 1,293 kt CO₂-eq/yr at full recovery. Recovery outperformed incineration across all recovery rates because recovered-material energy displaces grid electricity at the same carbon intensity as WtE but without the fossil-CO₂ combustion penalty. This advantage is structural and widens as the grid decarbonises. WtE is already a net emitter on Bahrain's current grid, and its breakeven grid factor of ≈ 0.96 kg CO₂-eq/kWh lies above present grid intensity. This expose dedicated WtE capacity to stranded-asset risk.

The integrated portfolio (MRF 80%, composting 100%, 50% residual WtE, 11.1% landfill) reconciles these competing pressures. It captures most of the achievable saving (– 1,017 kt CO₂-eq/yr), recovers 1,508 GWh/yr of energy, and reaches 88.9% landfill diversion at operationally realistic recovery rates which is critical for Bahrain as a land-constrained SIDS while accommodating the expert preference for incineration within a recycling-led strategy. It is recommended as the central pillar of Bahrain's MSW strategy, in line with Economic Vision 2030, the updated NDC, and the UN SDGs.

The climate ranking of waste pathways is governed not by combustion technology but by grid carbon intensity and separation efficiency. This mechanism, rather than any feature specific to Bahrain, is what carries the findings to other economies undergoing energy transition, where investment in source separation and secondary-materials markets pays off independent of the downstream treatment choice. The method couples disaggregated national tonnage with consistent grid-explicit emission factors and is readily portable to other data-constrained jurisdictions. Future work follows directly: a full life-cycle assessment covering collection, transport, and residue management; Tier-2/3 accounting from plant-specific and updated national characterisation; and dynamic optimisation resolving the cost-optimal portfolio under economic, social, and behavioural constraints.

Declarations

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Clinical trial number

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Declaration of competing interest

The author declares no conflicts of interest.

Author Contribution

MSJ is the sole author of this manuscript and was solely responsible for its conceptualisation, methodology, formal analysis, investigation, and the writing, review, and editing of the manuscript.

Ethical Approval

Not applicable. This study did not involve human participants, data collected from human participants, or animals; it draws on aggregate municipal solid waste gate-tonnage records provided by a government ministry.

Consent to participate

Not applicable (this study did not involve human participants).

Consent to publish

Not applicable.

Data availability

The author confirms that the data supporting the findings of this study are available upon reasonable request and subject to permission from the Ministry of Municipalities Affairs and Agriculture, Kingdom of Bahrain.

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Figures

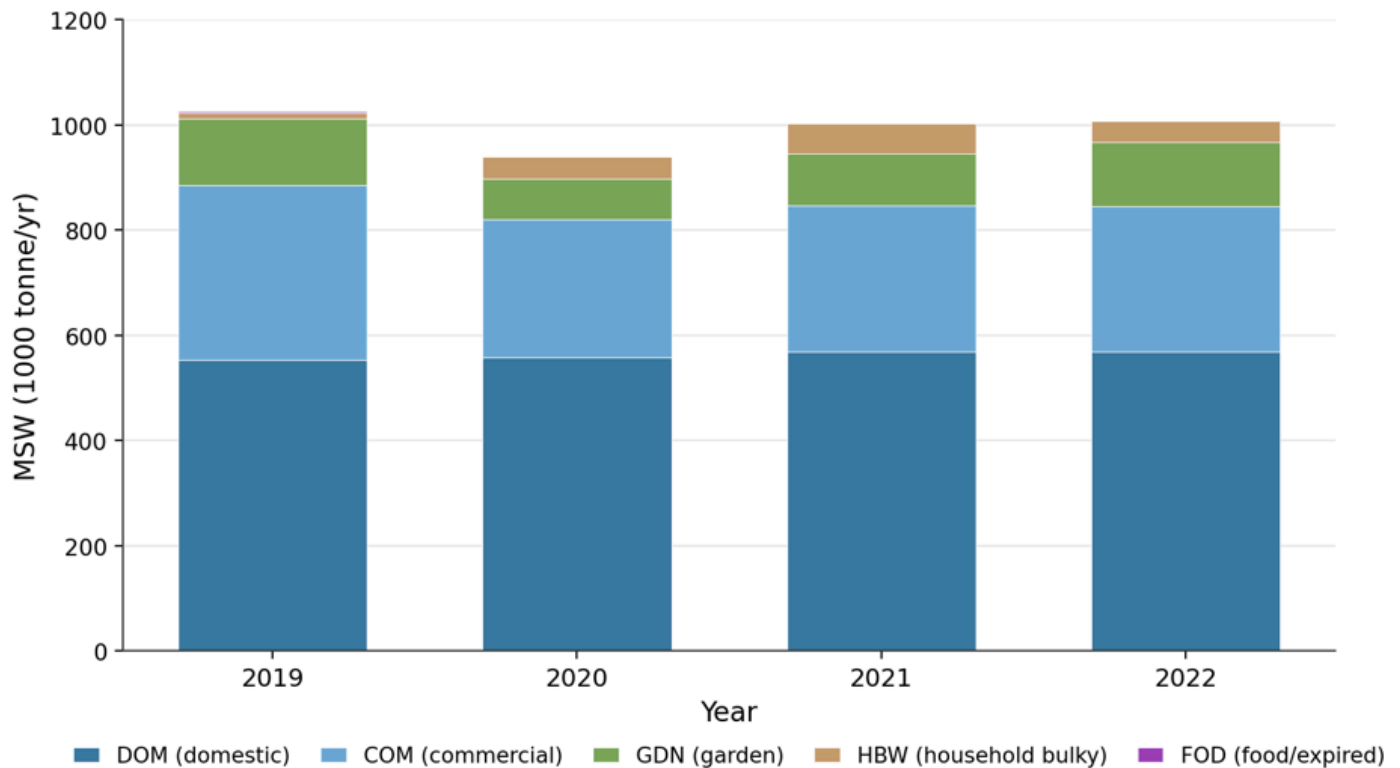


Figure 1

Annual IPCC-compatible MSW (DOM + COM + HBW + GDN + FOD) deposited at the Askar Landfill

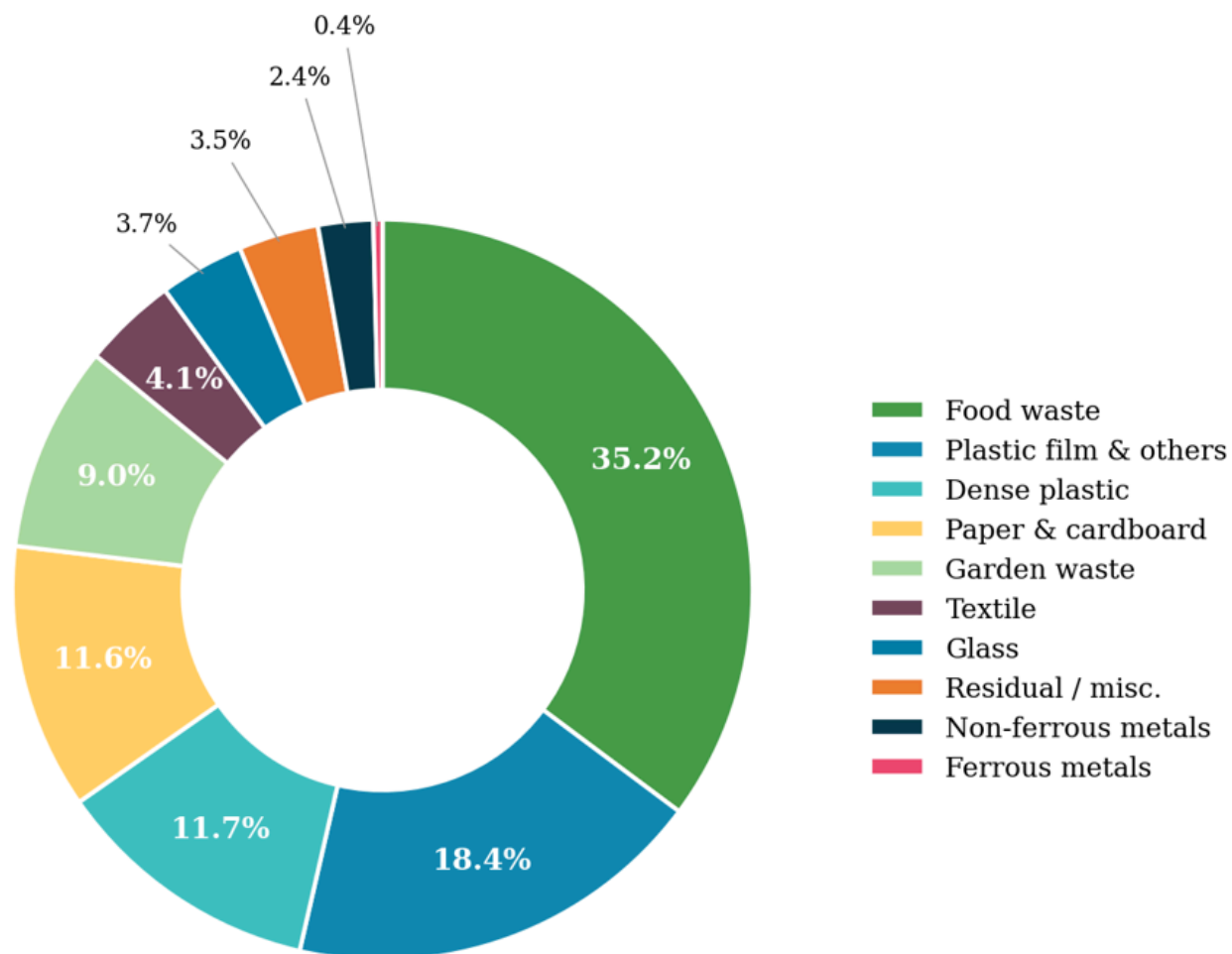


Figure 2

Mass-fraction composition of the mixed household and commercial MSW received at the Askar Landfill (Dowding 2017).

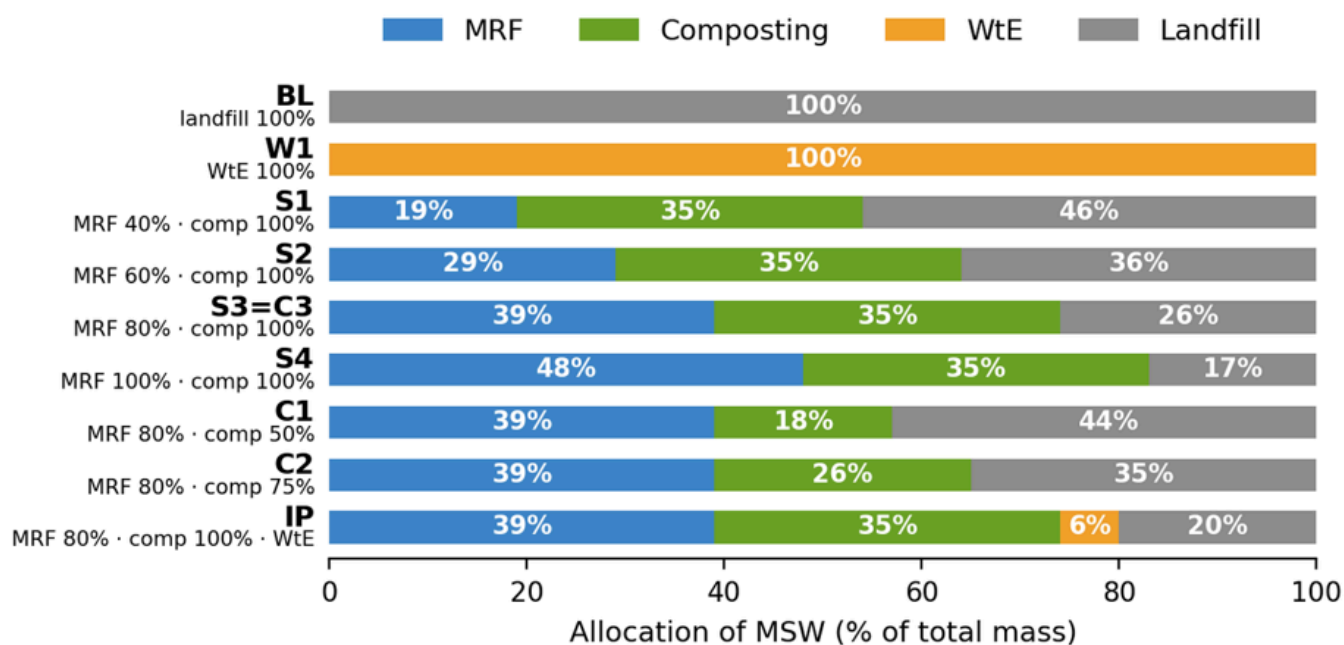


Figure 3

Allocation of MSW across the four treatment streams for each scenario.

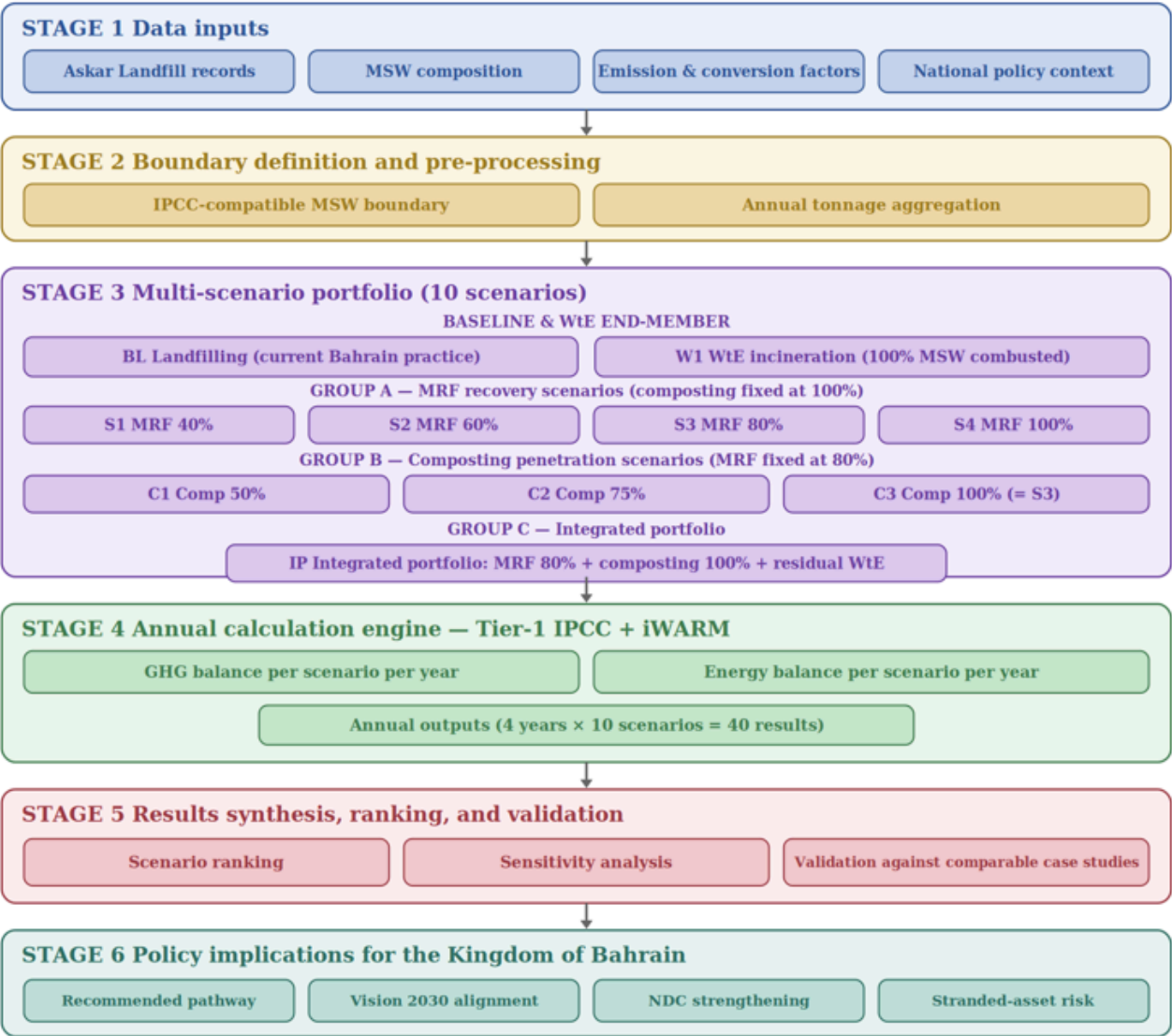


Figure 4

Methodological framework adopted in this study

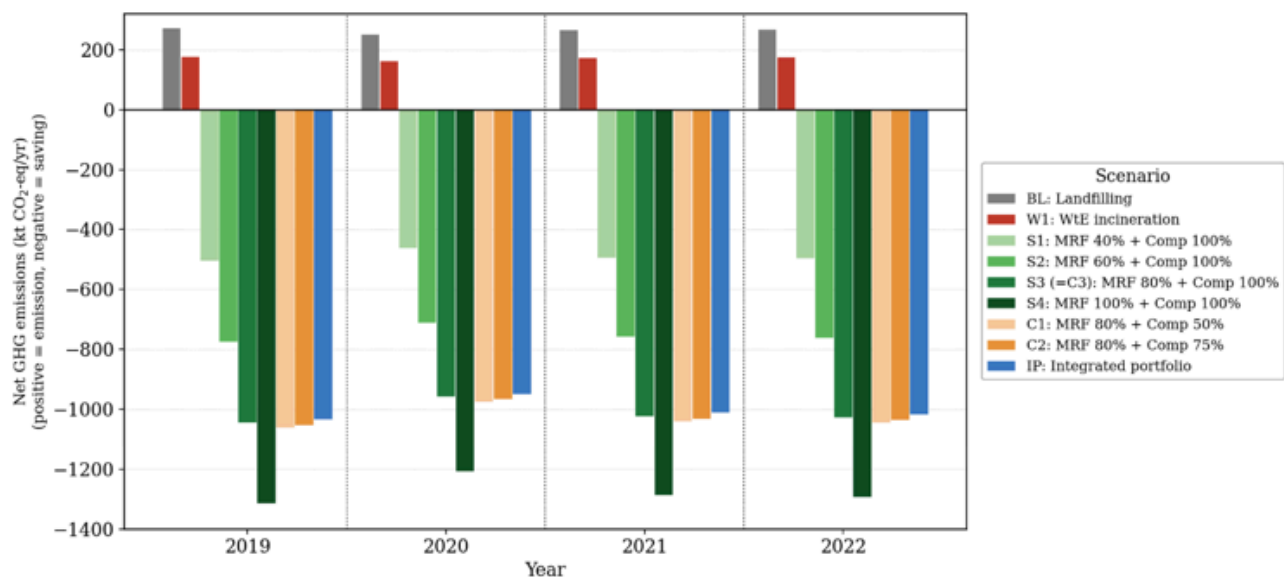


Figure 5

Net GHG emissions of MSW management scenarios for Bahrain, 2019–2022.

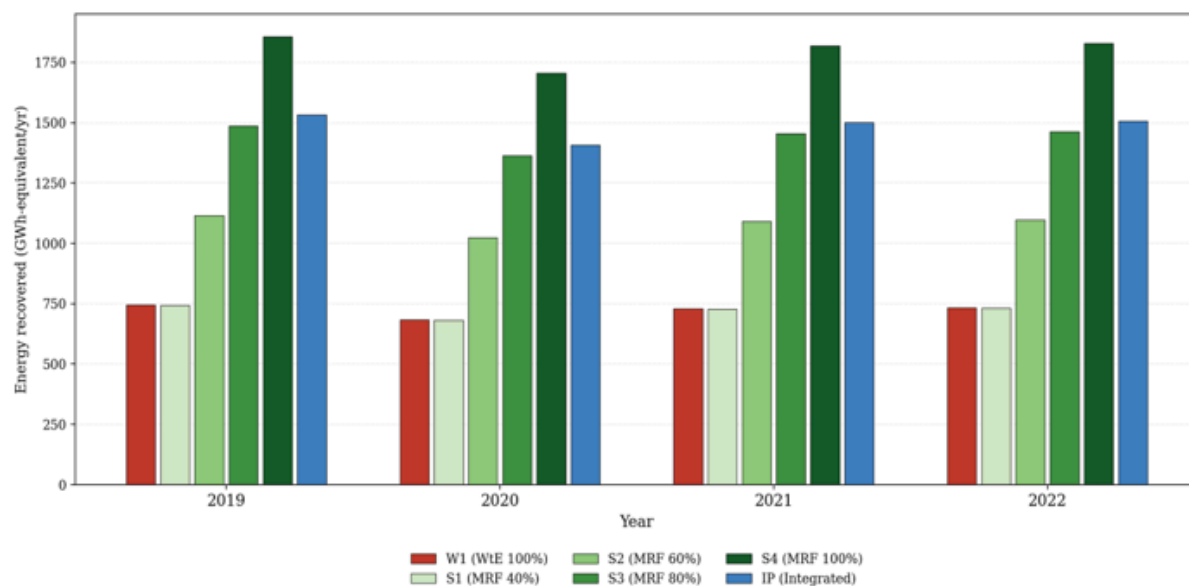


Figure 6

Annual energy recovery by scenario, 2019–2022. The MRF + composting energy is reported as the iWARM-derived avoided primary-production energy equivalent.

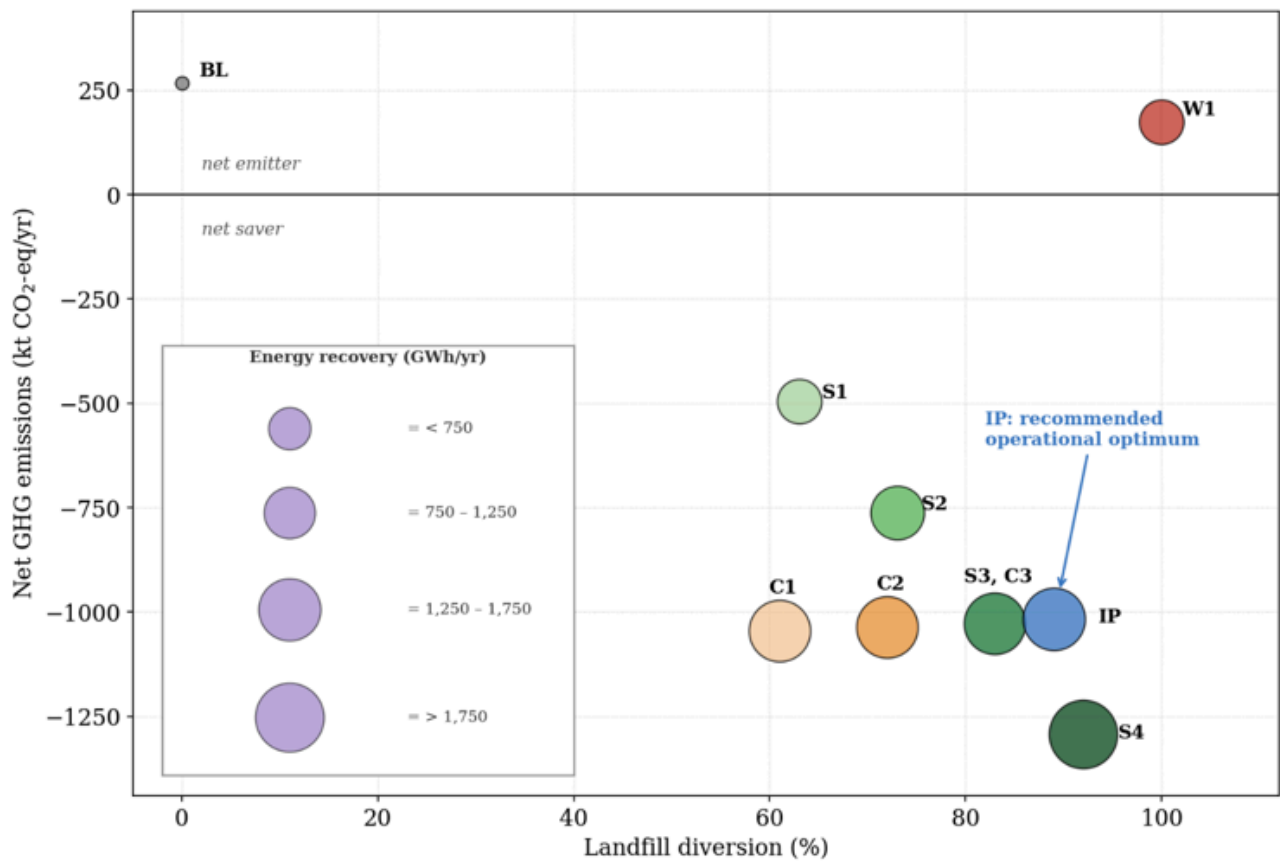


Figure 7

Trade-off between net GHG emissions and landfill diversion across all ten pathways for 2022 inventory year; bubble area scales with annual energy recovery.