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A multi-objective optimization model for strategic waste management master plans

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ABSTRACT

The optimization of solid waste management strategies is challenging due to the various alternatives and objectives, particularly in terms of the material and energy recovery systems. This paper presents a systematic optimization framework that identifies the most beneficial set of waste to energy (WTE) management strategies through non-linear mathematical modelling. The proposed model determines the optimum allocation of the different waste streams to selected waste management facilities, including material recovery facilities (MRFs), incinerators, anaerobic digestion (AD) plants, and sanitary landfills with gas recovery. The waste generated was divided into three streams, namely readily biodegradables, recyclables, and non-recyclables. The model objectives included maximum material and energy recovery, financial profitability, as well as minimum carbon footprint. The optimum hybrid strategy was based on the relative importance of each objective, which was acquired through a Fuzzy Analytic Hierarchy Process (AHP). The optimization framework was tested to generate an optimum 20-year hybrid waste management strategy for an example country, the United Arab Emirates (UAE). The optimum strategy included the complete allocation of readily biodegradable waste to AD plants up to the 14th year, followed by gradual disposal in landfills for additional waste. All MRF rejects and non-recyclables were disposed in landfills throughout the assessment period. The multi-objective optimum strategy would recover enough energy to cover approximately 4.2% of the total energy demand in the UAE while reducing around 97.6% of the carbon footprint from landfilling. In terms of the net present value, the optimum hybrid strategy would increase profitability by about 288% compared to the existing practices in the UAE.

1. Introduction

Climate change has climbed the global political agenda as its serious environmental consequences have been occurring at a rapidly increasing pace. Over the last century, the global surface temperature has increased by approximately 0.75 °C, with increasing CO_2 concentrations in the atmosphere, from a pre-industrial level of 278–379 ppm (UNFCCC, 2007). The Intergovernmental Panel on Climate Change (IPCC) asserts that the main reason behind the increasing greenhouse gas (GHG) emissions is anthropogenic activities, one of which is waste management (IPCC, 2013). In recent years, waste to energy (WTE) technologies have emerged as an alternative to municipal solid waste (MSW) management. WTE contributes to the mitigation of climate change in two ways: 1) reducing the GHG emissions from landfills, and 2) offsetting conventional energy production from fossil fuels (Perrot and Subiantoro, 2018). In 2018, around 18% of the waste generated worldwide was treated in WTE plants, an increase of ~14% from 2012 (Kaza et al., 2018). WTE systems provide major environmental and economic benefits by converting waste into accessible energy through thermochemical or biochemical processes (World Energy Council, 2016). Thermochemical processes, such as incineration and gasification, utilize high temperatures to convert waste into energy products. On the other hand, biochemical systems, such as anaerobic digestion (AD) and fermentation, convert organic wastes to liquid or gaseous fuels using biological agents (Ouda et al., 2016).

WTE systems typically process selected waste streams as part of an integrated solid waste management (ISWM) strategy. Such WTE-based ISWM strategies would include a combination of the following: material recovery facility (MRF), sanitary landfill, and

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Nomenclature

AD	Anaerobic Digestion
AHP	Analytical Hierarchy Process
CAPEX	Capital Costs
CF_i	Fraction of Carbon in the Dry Matter of Waste Material *i*
CH_4	Methane
CI_t	Cash Inflow in Year *t*
CO_2	Carbon Dioxide
CO_t	Cash Outflow in Year *t*
dm_i	Dry Matter Fraction of Waste Material *i*
DOC	Degradable Organic Carbon
DOC_F	Fraction DOC Dissimilated
EC_{CH4}	Energy Content of Methane
E_{CH4}	Total CH_4 Emissions in a Year
E_{CO2}	Carbon Dioxide Emissions
EF	Emission Factor
E_{rev}	Annual Energy Revenues
ERP	Energy Recovery Potential
ET	Electricity Tariff
F	CH4 Fraction in Landfill Gas
FCF_i	Fraction of Fossil Carbon in the Total Carbon of Waste Material *i*
GHG	Greenhouse Gas
HHV	High Heating Value
H_i	Mass Fraction of Hydrogen
i	Discount Rate
IPCC	Intergovernmental Panel on Climate Change
ISWM	Integrated Solid Waste Management
LHV	Low Heating Value
M	Mass of Organic Waste Treated
MCF	Methane Correction Factor
M_{CH4}	Total Methane Mass Generated
MENA	Middle East and North Africa
M_i	Mass Fraction of Material *i*
MRF	Material Recovery Facility
M_{sale}	Annual Revenue Generated from Sales of Marketable Materials
MSW	Municipal Solid Waste
MSW_F	MSW Fraction Disposed to the Landfill
MSW_T	Total MSW Generated
M_x	Molar Mass of Compound *x*
NPV	Net Present Value
OF_i	Oxidation Factor
OPEX	Operational Costs
OX	Oxidation Factor
R	Total Amount of CH_4 Recovered in a Year
SP	Unit Sale Price per Ton of Marketable Materials
t	Economic Life of Project
TF	Tipping Fee per Ton of Processed Waste
TF_{rev}	Annual Revenue Generated from Tipping Fees
UAE	United Arab Emirates
WCCM	Weighted Comprehensive Criterion Method
WF_i	Fraction of Waste Material *i*
W_{gate}	Weight of Waste Received at the Facility
W_{inc}	Total Waste Incinerated
$W_{product}$	Weight of Marketable Materials
WTE	Waste to Energy
$\Delta H_{v,H2O}$	Heat of Vaporization of Water
η	Efficiency of Energy Conversion
$\mathscr{M}$	Set of all Waste Streams
$\mathscr{S}$	Set of Waste Management Facilities

$\mathscr{T}$	Set of Assessment Periods
$D_{m,t}$	Available Waste Quantity of Material *m* in Year
Ut	Recyclable Material in Year *t*
γ	Non-Recovered Fraction of Recyclables
$P^s_{m,t}$	Profit Present Worth Value of Processing One Ton of Material m in Year *t* Using Facility *s*
$P^s_{Dig,t}$	Profit Present Worth Value of Processing One Ton of Digestate in Year *t* Using Facility *s*
$MP_{Dig,t}$	Profit Present Worth Value of Selling One Ton of Digestate in the Market in Year *t*
$P_{Ash,t}$	Profit Present Worth Value of Landfilling One Ton of Ash in Year *t*
$P_{Rec,t}$	Profit Present Worth Value of Processing One Ton of Material in MRF in Year *t*
E^s_m	Amount of Energy Produced from One Ton of Material *m* Using Facility *s*
E^s_{Dig}	Amount of Energy Produced from One Ton of Digestate Using Facility *s*
E_{Ash}	Amount of Energy Produced from One Ton of Ash
C^s_m	Amount of CO_2e Emitted from One Ton of Material *m* Using Facility *s*
C^s_{Dig}	Amount of CO_2e Emitted from One Ton of Digestate Using Facility *s*
C_{Ash}	Amount of CO_2e Emitted from One Ton of Ash
A^s_m	CAPEX Value for Processing One Ton of Material *m* Using Facility *s*
A^s_{Dig}	CAPEX Value for Processing One Ton of Digestate Using Facility *s*
A_{Ash}	CAPEX Value for Processing One Ton of Ash
A_{Rec}	CAPEX Value for Processing One Ton of Material in MRF
B	Very Large Number
k_1, k_2	Fraction of Processed Material Transformed to Digestate and Ash, Respectively
$X^s_{m,t}$	Quantity of Material m Processed Using Facility *s* During Period *t*
R^s_t	Digestate Sent to Facility *s* (Incinerator or Landfill) During Period *t*
O_t	Digestate Sold in the Market During Period *t*
$W_{m,t}$	Ash, Resulting from Processing Material *m* in an Incinerator, Landfilled During Period *t*
Y^1_t, Y^2_t, Y^3_t	Binary Variables Used to Indicate the Destination of Digestate Stream
$\mathscr{P}$	Profit
$\mathscr{E}$	Energy Recovery
$\mathscr{C}$	Carbon Footprint
MX^s_m	Maximum $X^s_{m,t}$
MR^s	Maximum R^s_t
MW_m	Maximum $W_{m,t}$
$\mathscr{P}^{opt}$	Optimum Profit
$\mathscr{E}^{opt}$	Optimum Energy Recovery
$\mathscr{C}^{opt}$	Optimum Carbon Footprint
V	Variance
$\alpha_1, \alpha_2\alpha_3$	Importance Weight of Each Objective
l, m, u	Fuzzy Triangular Numbers
C	Crisp Values
λ_{max}	Maximum Eigenvalue
CI	Consistency Index
n	Number of Objective Functions
RI	Random Consistency Index
CR	Consistency Ratio
S_i	Fuzzy Synthetic Extent Value
γ_i	Minimum Degree of Possibility

one or multiple types of WTE plants. Integrated strategies should be tailored to specific local waste characteristics, as well as other environmental and economic conditions (Mutz et al., 2017). For example, biochemical WTE plants would be favored if readily biodegradable organic fractions were dominant in the waste stream (Boukelia and Salah, 2012). Similarly, the energy yield of various waste materials significantly affects the economics of thermochemical conversion systems. Hence, establishing an ISWM strategy with a single type of WTE system might not always provide optimal environmental and financial benefits simultaneously.

Multiple studies were conducted to assess the feasibility of different WTE techniques from financial, environmental, and energy perspectives. A study was conducted in Nigeria to assess potential electricity generation from MSW (Ogunjuyigbe et al., 2017). For the southern part of Nigeria, where the organic fraction is high, AD and landfill gas utilization were found to be more feasible, while in the northern part, incineration and landfill gas utilization were superior. Another research study was conducted to assess the feasibility of WTE systems in selected middle-income countries in the Middle East and North Africa (MENA) region (Abdallah et al., 2019). Establishing an AD-based strategy with an MRF facility was found to be optimal according to a multi-criteria assessment based on the analytical hierarchy process (AHP). However, other tested WTE scenarios were found to be more beneficial than the AD strategy under one or more criteria. Additionally, a study was undertaken to evaluate the energy potential of several WTE options in Pakistan (Korai et al., 2016). It was found that biochemical and thermochemical treatment scenarios would generate 5.9−11.3 and 2.7−184.5 kW/ton of waste, respectively. From a financial perspective, a life cycle costing analysis was conducted to evaluate the feasibility of incineration and AD-based strategies in the United Arab Emirates (UAE) (Abdallah et al., 2018). It was found that, based on local conditions, an incineration-based management strategy was more financially feasible, with a net present value (NPV) of 181 million USD, compared to −127 million USD for an AD-based strategy. Additionally, Hadidi and Omer (2017) assessed the financial feasibility of WTE systems in Saudi Arabia. They found that AD was the most financially feasible, while gasification had a higher capacity for energy production. Alzate-Arias et al. (2018) evaluated AD and incineration systems based on financial feasibility and found that both systems were feasible, with a net present profit of 1.05 and 5.60 million USD, respectively. Moreover, S.T. Tan et al. (2014)a,b assessed the economic and environmental impacts of implementing incineration and AD systems. It was found that incineration had a higher energy potential, while AD proved to be more sustainable by generating less GHG emissions.

Overall, the findings of the above-mentioned feasibility studies show that establishing an ISWM strategy based on a single type of WTE system does not necessarily realize maximum benefits. Hence, optimizing the selection of WTE systems as part of a hybrid waste management master plan can potentially achieve maximum benefits and minimize negative impacts. Limited studies have been previously conducted for the optimization of WTE-based management strategies; e.g., Luoranen and Horttanainen (2007) developed a decision-support model for the feasibility of WTE investments in ISWM strategies (Luoranen and Horttanainen, 2007). Another study was conducted for optimizing the allocation of organic waste to three available incinerators in a South Korean area to maximize energy recovery and minimize the payback period (Taskhiri et al., 2014). Moreover, a study established an optimization model incorporated with GIS to provide the optimum number, capacity, and location of selected WTE facilities (incinerators and landfill gas utilization) for maximum energy recovery in Malaysia (Tan et al., 2014a,b).

Despite the previous applications of optimization in waste management, to date, no work has been published on the optimization of the entire waste stream allocation to multiple management facilities, including WTE systems, within ISWM strategies involving an extended planning scenario. The present research aims to establish a multi-objective optimization model for hybrid WTE-based management strategies using non-linear mathematical modelling. The proposed model prioritizes the objectives based on the local agenda of each country, as no single strategy fits all situations, particularly given the variable demographic, economic, and environmental factors. The framework of the model, along with the main objectives and inputs, are thoroughly explained. The relative importance of the selected objectives is determined using Fuzzy AHP methodology. Such integration between Fuzzy AHP and multi-objective optimization has been effectively implemented in other application fields, including: maintenance management (Alsyouf et al., 2020), supplier selection (Shaw et al., 2012), order allocation in sustainable supply chain (Kumar et al., 2016), and facility location (Wichapa and Khokhajaikiat, 2017). The established model is then tested on a selected country (UAE) by applying its specific waste characteristics and local economic features. The optimized hybrid strategy would demonstrate the allocation of waste fractions over different waste management facilities in order to achieve optimum environmental, energy, and economic benefits. This paper is intended to provide decision-makers with a comprehensive systematic framework through which an optimal ISWM strategy incorporating WTE systems can be obtained. Additionally, this work facilitates the transition to sustainable waste management systems by maximizing the benefits according to the local circumstances.

2. Methodology

This research establishes a multi-objective optimization model to systematically design the optimal WTE-based management strategy for a given study area. The methodology presents the general framework of the proposed model, including main components, parameters, and objectives. The base computations of energy production, carbon footprint, and financial profitability are presented for the selected WTE facilities, followed by the mathematical modelling implemented in the optimization process. The compiled local conditions and calculated model parameters for the UAE are outlined in order to test and validate the model in the discussion section.

2.1. General framework

Fig. 1 shows the general framework for the proposed optimization model. The raw inputs constitute waste composition and characteristics, features of waste management facilities, and local conditions. The waste streams are categorized in the model as 1) recyclables, 2) non-recyclables, 3) readily biodegradables, or 4) waste processing by-products. The waste characteristics primarily include chemical composition and energy content, while the local conditions cover the tipping fees, electricity tariff, and discount rate. The selected management facilities include: 1) material recovery facility, 2) AD plant, 3) incinerator, and 4) sanitary landfill with gas recovery. The optimization objectives comprise 1) energy potential, 2) financial profitability, and 3) carbon footprint. The weight (importance) of each objective is obtained through the Fuzzy AHP method based on expert opinion. The model is intended to determine the optimal allocation of each waste fraction for maximizing energy production and profitability while minimizing GHG emissions.

Fig. 2 shows the general layout for a hybrid WTE-based ISWM strategy, including waste and energy streams, recovery and

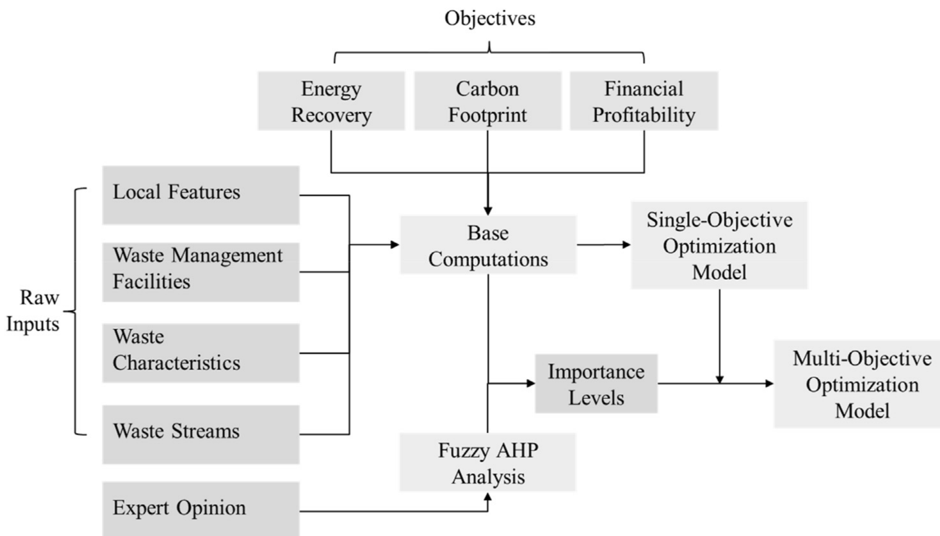

Fig. 1. General framework of the proposed optimization model.

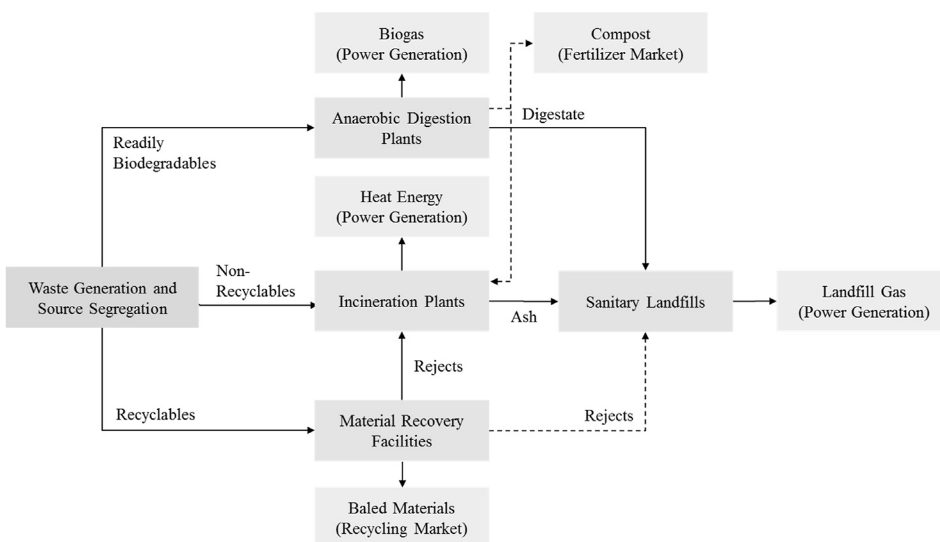

Fig. 2. General layout for hybrid WTE-based waste management strategy.

disposal facilities, processing by-products, and recovered materials. The dotted lines in the figure represent the alternative fates for by-products.

Table 1 presents the accepted feedstock, the typical by-product(s), and the fate of by-product(s) of the selected waste management facilities.

2.2. Base computations

The computations used to prepare the optimization model inputs include energy recovery, GHG emissions, and financial profitability for each waste management facility. The base computations are summarized in Table 2; further details can be found Abdallah et al. (2018, 2019).

Table 1
Main features of the selected waste management facilities.

Facility	Feedstock	By-products	Fate of By-products
Material recovery facility	Recyclables	Recycling rejects (unrecovered recyclables)	Landfilled or incinerated
Sanitary landfill	All MSW streams	Landfill gas	Uncollected, flared or utilized
Incinerator	All MSW streams except glass and metal fractions	Heat and ash	Heat used for electricity generation, and ash is landfilled
Anaerobic digester	Readily biodegradables	Biogas and digestate	Biogas flared for electricity generation, and digestate either landfilled, incinerated, or sold

Table 2
Detailed computations used for the proposed optimization model inputs.

	Facility	Computations	Remarks	Typical values	References
Energy Recovery	AD Plant	• $C_nH_aO_bN_c + [(4n - a - 2b + 3c)/4]H_2O \rightarrow [(4n - a + 2b + 3c)/8]CO_2 + [(4n - a - 2b - 3c)/8]CH_4 + cNH_3$ • $M_{CH4} = (16 \times [(4n - a - 2b - 3c)/8])/[(M_C \times n) + (M_H \times a) + (M_O \times b) + M_N]$ • $ERP = M_{CH4} \times EC_{CH4} \times \eta$	• $C_nH_aO_bN_c$ is the general formula of waste • *n, a, b,* and, *c*, are the chemical composition of waste • M_{CH4} is the total methane mass generated (kg) • M_x is the molar mass of compound *x* (g/mol) • *ERP* is the energy recovery potential (kWh) • EC_{CH4} is the energy content of methane (kWh/kg) • η is the efficiency of energy conversion in the process	• EC_{CH4} is 14.31 kWh/kg • η is 30%	(Ogunjuyigbe et al., 2017); (Ouda et al., 2014); (IRENA, 2015)
	Incinerator	• $LHV = \sum M_i \times [HHV_i - [(\Delta H_{V,H20}) \times (9 \times H)]]$ • $ERP = W_{dry} \times LHV \times \eta$	• *LHV* is the low heating value of waste stream (MJ/kg) • M_i is the mass fraction of material *i* in the waste stream (%) • HHV_i is the high heating value of waste material *i* (MJ/kg) • $\Delta H_{v,H2O}$ is the heat of vaporization of water (MJ/kg) • H_i is the mass fraction of hydrogen (%)	• η is 30%	(Ouda et al., 2014); (IRENA, 2015)
Financial Profitability	All facilities	• $NPV = \sum (CI_t - CO_t) \times (1 + i)^{-t}$ • $E_{rev} = ET \times ERP$ • $TF_{rev} = W_{gate} \times TF$ • $M_{sale} = W_{product} \times SP$	• *NPV* is the net present value (USD) • CI_t is the cash inflow in year *t* (USD), including energy sales and tipping fees • CO_t is the cash outflow in year *t* (USD), including capital costs (CAPEX), operational costs (OPEX), and landfilling costs • *t* is the economic life of the project (years) • *i* is the discount rate (%) • E_{rev} is the annual energy revenues (USD/year) • *ET* is the electricity tariff (USD/kWh) • *ERP* is the energy recovery potential (kWh) • TF_{rev} is the annual revenue generated from tipping fees (USD/year) • W_{gate} is the weight of waste received at the facility (ton/year) • *TF* is the tipping fee per ton of processed waste (USD/ton) • M_{sale} is the annual revenue generated from sales of marketable materials, e.g., recyclables and digestate (USD/year). • $W_{product}$ is the weight of marketable materials (ton/year) • *SP* is the unit sale price per ton of marketable materials (USD/ton)	• CAPEX is 3,500–7,000 USD/kW for AD and incineration facilities • Annual OPEX is 2.2 and 3.2% of the CAPEX for AD and incineration plants • CAPEX for MRFs is 125 USD/ton, while OPEX is 20 USD/ton • CAPEX for engineered landfills is 25,000–40,000 USD/ton/day, while OPEX is 10–120 USD/ton • Landfill fees is 10–30 USD in low-income countries, and 40–100 USD in high-income countries	(Zhao et al., 2016); (IRENA, 2015); (Tchobanoglous and Kreith, 2002); (Hoornweg and Bhada, 2012)
Greenhouse Gas Emissions	AD Plant	• $E_{CH4} = (M \times EF) - R$	• E_{CH4} is the total CH_4 emissions in a year (Mg CH_4/year) • M is the mass of organic waste treated (Gg/year) • EF is the emission factor (g CH_4/kg) • R is the total amount of CH_4recovered in a year (Gg CH_4/year).	• Emission factor is 0.8 g CH_4/kg. • Global warming potential factor of 28.	(R. Pipatti et al., 2006a; 2006b)
	Incinerator	• $E_{CO2} = W_{inc} \times \sum (WF_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times 44/12$	• E_{CO2} is the carbon dioxide emissions (Gg/year) • W_{inc} is the total waste incinerated (Gg/year) • WF_i is the fraction of waste material i • dm_i is the dry matter fraction of waste material i • CF_i is the fraction of carbon in the dry matter of waste material i • FCF_i is the fraction of fossil carbon in the total carbon of waste material i	–	Rogoff and Screve (2011)

(*continued on next page*)

Table 2 (*continued*)

Facility	Computations	Remarks	Typical values	References
		• OF_i is the oxidation factor (fraction) • 44/12 is the conversion factor from C to CO_2		
Landfill	• $E_{CH4} = [(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12) - R] \times (1 - OX)$	• E_{CH_4} is the total CH_4 emissions in a year (Gg CH_4/year) • MSW_T is the total MSW generated (Gg/year) • MSW_F is the MSW fraction disposed to the landfill • MCF is the methane correction factor • DOC is the degradable organic carbon • DOC_F is the fraction DOC dissimilated • F is the CH_4 fraction in landfill gas (fraction) • 16/12 is the conversion of C to CH_4 • R is the recovered CH_4 in a year (Gg CH_4/year) • OX is the oxidation factor (fraction)	• MCF is 0.6 • DOC_F • F is 0.5 • R is 90% • OX is 0	(Coburn et al., 2006); (Riitta Pipatti et al., 2006a, 2006b)

2.3. Mathematical modelling

A multi-objective mixed-integer non-linear programming model is used to obtain an optimum hybrid waste management strategy based on the selected criteria. In the following subsections, the model formulation and solution approach, including the model transformation to a linear model and the multi-objective solution, are discussed. The first step in establishing the optimization model is to define the input and performance parameters, as well as the decision variables, as follows:

Input Parameters.

- $\mathscr{M}$: Set of all waste streams $m \in \{1,2,3\}$, where *1* is readily biodegradables, *2* is post-recovery recyclables, and *3* is non-recyclables
- $\mathscr{S}$: Set of waste management facilities $s \in \{1,2,3\}$, where *1* is anaerobic digester, *2* is incinerator, and *3* is landfill
- $\mathscr{T}$: Set of assessment periods $t \in \{1,\ldots,T\}$

Performance Parameters.

- $D_{m,t}$: Available waste quantity of material m in year t.
- U_t : Recyclable material in year t
- γ: Non-recovered fraction of recyclables (U_t) in an MRF. Note: $D_{m=2,t} = \gamma U_t$.
- $P^s_{m,t}$: Profit present worth value of processing one ton of material m in year t using facility s
- $P^s_{Dig,t}$: Profit present worth value of processing one ton of digestate in year t using facility s
- $MP_{Dig,t}$: Profit present worth value of selling one ton of digestate in the market in year t.
- $P_{Ash,t}$: Profit present worth value of landfilling one ton of ash in year t
- $P_{Rec,t}$: Profit present worth value of processing one ton of material in MRF in year t
- E^s_m :Amount of energy produced from one ton of material m using facility s
- E^s_{Dig} :Amount of energy produced from one ton of digestate using facility s
- E_{Ash} :Amount of energy produced from one ton of ash
- C^s_m :Amount of CO_2e emitted from material m using facility s
- C^s_{Dig} :Amount of CO_2e emitted from one ton of digestate using facility s
- C_{Ash} :Amount of CO_2e emitted from one ton of ash
- A^s_m: CAPEX value for processing one ton of material m using facility$s$
- A^s_{Dig}: CAPEX value for processing one ton of digestate using facility$s$
- A_{Ash}: CAPEX value for landfilling one ton of ash
- A_{Rec}: CAPEX value for processing one ton of material (U_t) in MRF
- B: Very large number
- $k_1,\ k_2$: fraction of processed material transformed to digestate and ash, respectively

Decision Variables.

- $X^s_{m,t}$: Quantity of material m processed using facility s during period t
- R^s_t: Digestate sent to facility s (incinerator orA_{Ash} landfill) during period t
- O_t: Digestate sold in the market during period t
- $W_{m,t}$: Ash, resulting from processing material m in an incinerator, landfilled during period$t$

- Y_t^1, Y_t^2, and Y_t^3: Binary variables used to indicate the destination of the digestate stream. In other words, if readily biodegradable waste is processed in the digester during period t, then $Y_t^1 = 1$ and if the digestate is incinerated then $Y_t^2 = 1$. Likewise, if the digestate is disposed of in the landfill, then $Y_t^3 = 1$.

2.3.1. Model formulation

The objective functions required for optimization are developed based on the above-mentioned parameters. Equations (12)–(26) illustrate the different functions and constraints formulated for the optimization model. Objective functions (12) to (14) are used to maximize the total profit (max $\mathscr{P}$), maximize energy recovery (max $\mathscr{E}$), and minimize carbon footprint (min $\mathscr{C}$), respectively. Constraint (15) prevents the digester from processing waste streams other than readily biodegradable waste, while constraint (16) ensures that 40% of waste processed in the digester becomes digestate. Constraint (17) ensures that if the readily biodegradable waste is processed in the digester, the digestate is seR_t^2nt either to an incinerator, a landfill, or the market. Constraints (18) to (21) link the binary variables used for the destination of digestate, i.e., Y_t^1 with $X_{1,t}^1$, Y_t^2 with, Y_t^3 with R_t^3 and Y_t^4 with O_t. Constraint (22) ensures that if the readily biodegradable waste or digestate are processed in the incinerator, then 10% of their total amount is landfilled as ash. Constraint (23) states that 10% of the waste processed in the incinerator (ash) is landfilled. Constraints (24) and (25) ensure that if the digester or incinerator is used at any year, it must be utilized for the following years with at least the same capacity. Constraint (26) ensures an adequate mass balance for each waste stream over different management facilities during each period. Constraint (27) sets the variables $X_{m,t}^s$, R_t , and $W_{m,t}$ to continuous positive variables. Constraint (28) defines Y_t^1, Y_t^2,Y_t^3 and Y_t^4 as binary values (0 or 1).

$$\max \mathscr{P} = \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} \sum_{s \in \mathscr{S}} P_{m,t}^s \times X_{m,t}^s - \sum_{m \in \mathscr{M}} \sum_{s \in \mathscr{S}} A_m^s \times \max_{t \in \mathscr{T}} \left(X_{m,t}^s\right) + \sum_{s \in \{2,3\}} \sum_{t \in \mathscr{T}} P_{Dig,t}^s \times R_t^s + \sum_{t \in \mathscr{T}} MP_{Dig,t} \times O_t - \sum_{s \in \{2,3\}} A_{Dig}^s \times \max_{t \in \mathscr{T}} \left(R_t^s\right) + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} P_{Ash,t} \times W_{m,t} - \sum_{m \in \mathscr{M}} A_{Ash} \times \max_{t \in \mathscr{T}} \left(W_{m,t}\right) + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} P_{Rec,t} \times U_t - \sum_{m \in \mathscr{M}} A_{Rec} \times \max_{t \in \mathscr{T}} \left(U_t\right) \tag{12}$$

$$\max \mathscr{E} = \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} \sum_{s \in \mathscr{S}} E_m^s \times X_{m,t}^s + \sum_{s \in \{2,3\}} \sum_{t \in \mathscr{T}} E_{Dig,t}^s R_t^s + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} E_{Ash,t} \times W_{m,t} \tag{13}$$

$$\min \mathscr{C} = \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} \sum_{s \in \mathscr{S}} C_m^s \times X_{m,t}^s + \sum_{s \in \{2,3\}} \sum_{t \in \mathscr{T}} C_{Dig,t}^s \times R_t^s + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} C_{Ash,t} \times W_{m,t} \tag{14}$$

$$X_{m,t}^s = 0, \ \forall m \in \mathscr{M} \backslash \{1\}, s \in \mathscr{S}, t \in \mathscr{T} \tag{15}$$

$$k_1 X_{1,t}^1 = \sum_{s \in \{2,3\}} R_t^s + O_t, t \in \mathscr{T} \tag{16}$$

$$Y_t^1 = Y_t^2 + Y_t^3 + Y_t^3, \quad t \in \mathscr{T} \tag{17}$$

$$B \times Y_t^1 \geq X_{1,t}^1, \quad t \in \mathscr{T} \tag{18}$$

$$B \times Y_t^2 \geq R_t^2, t \in \mathscr{T} \tag{19}$$

$$B \times Y_t^3 R_t^3, t \in \mathscr{T} \tag{20}$$

$$B \times Y_t^4 \geq O_t, t \in \mathscr{T} \tag{21}$$

$$k_2 \left(X_{m,t}^2 + R_t^2\right) = W_{m,t}, \quad m = 1, t \in \mathscr{T} \tag{22}$$

$$k_2 X_{m,t}^2 = W_{m,t}, \ \forall m \in \mathscr{M} \Big/ \{1\}, t \in \mathscr{T} \tag{23}$$

$$\sum_{m \in \mathscr{M}} X_{m,t}^s \leq \sum_{m \in \mathscr{M}} X_{m,t+1}^s, \ \forall t \in \mathscr{T}, s = 1 \tag{24}$$

$$\sum_{m \in \mathscr{M}} X_{m,t}^s + R_t^s \leq \sum_{m \in \mathscr{M}} X_{m,t+1}^s + R_{t+1}^s, \ \forall t \in \mathscr{T}, s = 2 \tag{25}$$

$$\sum_{s \in \mathscr{S}} X_{m,t}^s = D_{m,t}, \quad \forall m \in \mathscr{M}, t \in \mathscr{T} \tag{26}$$

$$X_{m,t}^s, \ R_t^s, \ W_{m,t}, O_t \geq 0, \ \forall m \in \mathscr{M}, s \in \mathscr{S}, \ t \in \mathscr{T} \tag{27}$$

$$Y_t^1, Y_t^2, Y_t^3, Y_t^4 \in \{0, 1\}, \ \forall \ t \in \mathscr{T} \tag{28}$$

2.3.2. Solution approach

Equation (12) is non-linear due to the use of the $\max_{t \in \mathscr{T}}(.)$ function. To simplify the solution method, this non-linear objective function can be linearized by adding the following decision variables (MX_m^s, MR^s, and MW_m) and a new set of constraints. Note that $\max_{t \in \mathscr{T}}(U_t)$ is kept unchanged since it is a non-varying parameter. These variables store the maximum quantity of material m processed in facility s. This is specifically applied for the maximum profit function (Equation (12)), which can be modified as follows:

$$\max \mathscr{P} = \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} \sum_{s \in \mathscr{S}} P_{m,t}^s \times X_{m,t}^s - \sum_{m \in \mathscr{M}} \sum_{s \in \mathscr{S}} A_m^s \times XM_m^s + \sum_{s \in \{2,3\}} \sum_{t \in \mathscr{T}} P_{Dig,t}^s \times R_t^s + \sum_{t \in \mathscr{T}} MP_{Dig,t} \times O_t - \sum_{s \in \{2,3\}} A_{Dig}^s \times MR^s + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} P_{Ash,t} \times W_{m,t} - \sum_{m \in \mathscr{M}} A_{Ash} \times MW_M + \sum_{m \in \mathscr{M}} \sum_{t \in \mathscr{T}} P_{Rec,t} \times U_t - \sum_{m \in \mathscr{M}} A_{Rec} \times \max_{t \in \mathscr{T}} \left(U_t\right)$$

$$X_{m,t}^s \leq MX_m^s, \quad \forall m \in \mathscr{M}, \ s \in \mathscr{S}, \ t \in \mathscr{T} \tag{30}$$

$$R_t^s \leq MR^s, \ s \in \mathscr{S}, \ t \in \mathscr{T} \tag{31}$$

$$W_{m,t} \leq MW_m, \ \forall m \in \mathscr{M}, \ t \in \mathscr{T} \tag{32}$$

Since the CAPEX cost is to be minimized, the new constraints ensure that X_m^s, MR^s, and MW_m have a value equal to the maximum quantity among all periods, and thus they replace the maximum functions in Equation (12).

The multi-objective formulation presented in Section 2.3.1 is solved using a scalarization approach referred to as the weighted comprehensive criterion method (WCCM) (Hamdan et al., 2019; Hamdan and Cheaitou, 2017a; Marler and Arora, 2004). The WCCM normalizes all the objective functions into one function that minimizes the variation from the optimal solution of each objective function. To apply the WCCM approach, the model should be solved for each objective function, i.e., Equations (13), (14) and (29), subject to constraints (15) to (28) and (30) to (32) to get the optimal value of each objective function ($\mathscr{P}^{opt}$, $\mathscr{E}^{opt}$ and $\mathscr{C}^{opt}$). Subsequently, the model is solved using a new objective function that integrates the variation of all the objective functions as follows:

$$\min V = \alpha_1 \frac{\mathscr{P} - \mathscr{P}^{opt}}{\mathscr{P}^{opt}} + \alpha_2 \frac{\mathscr{E} - \mathscr{E}^{opt}}{\mathscr{E}^{opt}} + \alpha_3 \frac{\mathscr{C}^{opt} - \mathscr{C}}{\mathscr{C}^{opt}} \tag{33}$$

where $\alpha_1, \alpha_2,$ and α_3 are the importance weight of each objective, based on the expert opinion, such that $\alpha_1 + \alpha_2 + \alpha_3 = 1$ (further explained in Section 2.3.3).

2.3.3. Multi-criteria decision making

In the proposed optimization framework, the Fuzzy AHP method is used to determine the importance weights, i.e., α_1, α_2, and α_3, of the objective functions. Fuzzy AHP is selected as it provides a pairwise comparison between the criteria and results with weights, such that $\alpha_1 + \alpha_2 + \alpha_3 = 1$. In addition, using the Fuzzy AHP accommodates uncertainty and vagueness during the evaluation process, where decision-makers can use linguistic variables rather than numerical representation (Hamdan and Cheaitou, 2017b). This linguistic evaluation is then transformed into fuzzy triangular membership functions (l, m, u) based on a standardized scale. Table 3 shows the linguistic variables in the Fuzzy AHP analysis as well as the scale used to convert these variables to fuzzy triangular numbers. In order to assemble the pairwise comparison matrix of the Fuzzy AHP in this study, an online survey was designed and shared with experts in the field of waste management. The average of the responses was calculated and used to develop the importance weights. The reliability of the responses was checked using Cronbach Alpha test and it was found to be reliable at a value of 0.77 (Tavakol and Dennick, 2011). Further details of the survey and responses are presented in the Supplementary Files.

Prior to the Fuzzy AHP analysis, a consistency check must be carried out. First, the fuzzy triangular numbers are transformed to crisp values (C) using the following equation:

$$C = \frac{l + m + u}{3} \tag{34}$$

Next, the maximum eigenvalue (λ_{max}) of the crisp evaluation matrix is calculated and is used to calculate the consistency index (CI) as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{35}$$

where n represents the number of objective functions. Finally, the consistency ratio (CR) is calculated as the ratio of the CI to the random consistency index (RI). The RI is available in Saaty (1990) and is based on the number of items under evaluation. It should be noted that the CR should be less than 0.1:

$$CR = \frac{CI}{RI} \le 0.1 \tag{36}$$

Following the consistency check, the relative importance levels for the objective functions are computed. The first step is to calculate the fuzzy synthetic extent value for each objective function ($i = 1, \ldots, n$) as follows:

$$\boldsymbol{S_i} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij} \right) \otimes \left(\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} u_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} l_{ij}} \right), \tag{37}$$

Next, the possibility of the superiority of each objective function fuzzy synthetic extent value i compared to the other objectives ($V(S_2 \ge S_1)$) can be calculated as follows:

$$V_{ij}(S_i \ge S_j) = \sup_{y \ge x} \left[\min\left(\mu_{S_i}(y), \mu_{S_j}(x) \right) \right] = \begin{cases} 0, & if\ l_j \ge u_i \\ 1, & if\ m_i \ge m_j \\ \dfrac{l_j - u_i}{(m_i - u_i) - (m_j - l_j)}, & otherwise \end{cases}. \tag{38}$$

Finally, the importance level for each objective function is calculated as follows:

$$\alpha_i = \frac{\gamma_i}{\sum_{i=1}^{n} \gamma_i}, \tag{39}$$

Table 3
Selected linguistic variables and fuzzy triangular numbers.

Linguistic variables	Fuzzy triangular numbers (*l, m, u*)	Linguistic variables reciprocal (*1/u,1/m, 1/l*)
Equally preferable	(1.0, 1.0, 3.0)	(1/3.0,1.0,1.0)
Slightly preferable	(1.0, 3.0, 5.0)	(1/5.0,1/3.0,1.0)
Fairly preferable	(3.0, 5.0, 7.0)	(1/7.0,1/5.0,1/3.0)
Extremely preferable	(5.0, 7.0, 9.0)	(1/9.0,1/7.0,1/5.0)
Absolutely preferable	(7.0, 9.0, 9.0)	(1/9.0,1/9.0,1/7.0)
Exactly equal	(1.0, 1.0, 1.0)	–

where γ_i is the minimum degree of possibility calculated as $\gamma_i = \min_j V(S_i \geq S_j)$.

3. Case study

As a case study, the proposed optimization model is applied to the UAE to determine the optimal national hybrid WTE-based ISWM strategy. In 2018, the UAE had a population of 9.6 million, increasing at 1.25% per annum. The average annual energy consumption was 11,263 kWh per capita, placing the country as one of the highest energy consumers worldwide (World Bank, 2018). Approximately 98.5% of the electricity production was provided from natural gas. The UAE is aiming to achieve 27% of the produced energy from renewable sources by 2021, increasing to 44% by 2050 (MOCCUAE, 2017). Moreover, the UAE aims to reduce GHG emissions from power generation by 70% before 2050 (Ministry of Environment and Water of UAE, 2014). Such transition towards sustainable development could improve the country's environmental performance, expressed by one of the highest per capita carbon footprints in the world, at 21.6 tons CO_2e (World Bank, 2018). As a major contributor to the carbon footprint of the country, the waste sector is subject to new regulations that aim to maximize diversion from landfills. WTE presents a unique opportunity for the country to address its waste management challenges while meeting part of its energy requirements. The current waste management strategy in the UAE mostly constitutes sanitary landfills, with minor recycling activities taking place at source or in MRFs.

3.1. Local conditions

To calculate the raw inputs, certain local parameters need to be identified for the study area. Table 4 shows the waste generation characteristics, operating parameters, and local market conditions in the UAE; used to prepare the optimization model inputs (Abu Dhabi Distribution Co., 2017; Environment Agency-Abu Dhabi, 2016; Mutz et al., 2017; Tchobanoglous and Kreith, 2002; US EPA, 2005). As shown in Table 4, the high fraction of organics (39%) is advantageous if the waste is treated using anaerobic digestion. On the other hand, high fractions of recyclables (51%) can potentially increase energy yield through incineration. Given the diverse potential of the waste under various WTE systems, there is a need for an optimization model to select an optimum strategy tailored for the local operating and market conditions.

3.2. Raw inputs

The raw inputs include the specific attributes (energy recovery, carbon footprint, and profitability) of each waste stream processed in relevant waste management facilities, calculated as per Section 2.2 using the local conditions of the study area. Table 5 shows the specific energy production, GHG emissions, NPV, and CAPEX of each waste stream and processing by-product for different management facilities in the UAE. As shown in Table 5, the following observations can be made:

- Treatment of readily biodegradable waste in anaerobic digesters generates less energy per ton compared to incinerators, while treatment by incinerators produces zero GHG emissions in contrast to AD.
- Treatment of readily biodegradable waste in either AD or incineration plants emits less GHG emissions compared to landfilling with gas recovery.
- The CAPEX per ton of processed readily biodegradable waste is higher in incinerators compared to anaerobic digesters due to the higher costs incurred for constructing incineration facilities.
- Energy recovery from recyclables (MRF rejects) and non-recyclables is only valid through treatment in incineration and landfilling with gas recovery facilities.
- Treatment of MRF rejects in incineration facilities generates higher energy compared to landfilling. However, it emits greater GHG emissions.
- Utilizing incineration facilities to treat non-recyclables generates higher energy and emits less GHG emissions compared to landfilling.
- The processing of digestate in incineration facilities generates higher energy and emits no GHG emissions compared to landfilling.
- Treatment of readily biodegradable waste in incineration facilities has a higher NPV compared to AD and landfills, mainly due to the higher revenues from electricity sales.
- Treatment of recyclables in incineration facilities has higher NPV compared to landfilling for the same reason.
- The NPV of treating non-recyclables in landfills with gas recovery is higher compared to incineration, mainly due to the higher OPEX values required for operating incineration facilities.
- Treatment of digestate and ash in landfills generates negative NPVs due to the lack of sufficient revenues required to cover the expenses.
- The digestate can be marketed rather than treated, though it is typically sold at a market price close to its recovery cost. Thus the market sale of digestate is neglected (Corré and Conijn, 2016).

4. Discussion

In this section, the application of the developed optimization

Table 4
Local waste characteristics, operating parameters, and market conditions in the UAE.

Waste generation	Per capita generation rate (kg/capita/day)	1.66
Waste composition	Recyclables	51
	Non-recyclables	10
	Readily biodegradables	39
Operating parameters	MRF recovery rates for papers, plastics, glass, and metals, respectively (%)	60, 70, 80, and 90
	Landfill gas collection efficiency (%)	75
	Ash produced from incinerators (%)	10
	Digestate produced form anaerobic digesters (%)	40
Local market conditions	WTE tipping fees (USD/metric ton)	14
	Landfill gate fee (USD/metric ton)	28
	Electricity tariff (USD/kWh)	0.08
	Discount rate (%)	10

Table 5
Local attributes of various waste streams and byproducts allocated to relevant management facilities.

Stream	Readily Biodegradables			Recyclables			Non-Recyclables		Digestate		Ash
Facility	Incineration	AD	Landfill	Incineration	MRF	Landfill	Incineration	Landfill	Incineration	Landfill	Landfill
Carbon Footprint (gCO_2/metric ton)	0.0	2,240	404,026	526,295	–	106,194	12,755	43,446	0.0	404,026	–
Energy Recovery (kWh/metric ton)	1,790	1,770	198	1,083	–	52	223	26	4,277	198	–
NPV (USD/metric ton)[a]	96 to 16	95 to 16	26 to 4	56 to 9	−12 to −2	17 to 3	12 to 2	15 to 3	222 to 36	−16 to −3	−28 to −5
CAPEX (USD/metric ton)[b]	817	606	161	494	168	161	101	161	1,953	161	161

[a] NPV range represents the NPV in the first and final year of the assessment period. The values decrease along the assessment period due to the incorporation of discount rates in the OPEX and revenues.

[b] CAPEX values are separated from NPVs as they are computed once initially and not included in the annual computation of NPVs. However, calculating the final NPV constitutes subtracting the CAPEX value from the total NPV.

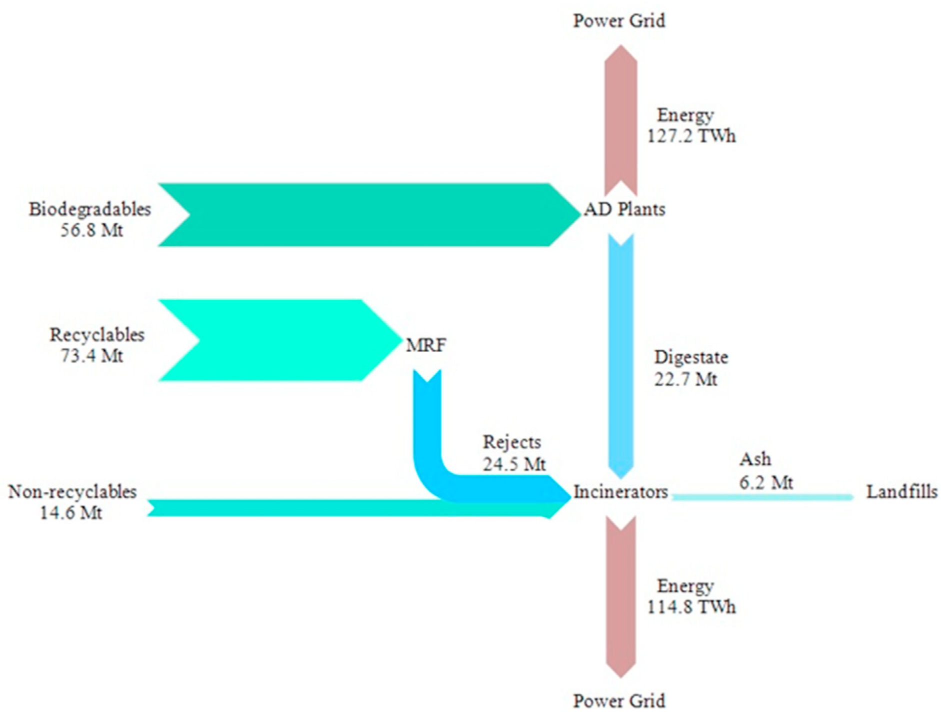

Fig. 3. Optimum allocation of waste streams over waste management facilities for maximum energy recovery.

model to identify the optimum hybrid WTE-based ISWM strategy in the UAE over a 20-year assessment period, is covered. The linear mathematical optimization model was developed and solved using CPLEX 12.8.0 programming platform. The single-objective optimized strategies are individually discussed, followed by the multi-objective optimum strategy incorporating the relative importance of various objectives. It should be noted that, since material recovery is paramount in sustainable waste management, recyclable materials were completely processed in MRFs in all optimized strategies.

4.1. Single-objective optimization

The optimization model can be utilized to determine the most suitable hybrid WTE-based ISWM strategy corresponding to each objective. The model optimizes the allocation of different waste streams over a 20-year assessment period in the UAE.

4.1.1. Objective 1: energy recovery

Fig. 3 shows the optimum allocation of waste streams to various waste management facilities for the maximization of energy recovery. The optimization model result indicates that readily biodegradable waste should be completely processed in AD facilities throughout the 20 years, while the digestate is incinerated along with non-recyclable waste and MRF rejects. Despite generating less energy per ton of readily biodegradable waste in AD compared to incineration, the processing of digestate in incinerators produces significant amounts of energy. The ash byproduct from incinerators is disposed of in landfills. The total energy recovered from this optimized waste allocation over the assessment period is around 242 TWh, which represents the maximum energy production from implementing a national hybrid WTE-based ISWM strategy in the UAE. With an average energy demand of 11,263 kWh/capita and an annual population growth rate of 1.25% (World Bank, 2018), the estimated total energy demand in the UAE over 20 years would be around 2,356 TWh. Therefore, the energy recovered from the optimized strategy could potentially cover 10.3% of the total energy demand in the UAE for over 20 years. Maximizing the energy recovery would emit around 14,025 Gg CO_2e at a total NPV of −1.7 billion USD.

4.1.2. Objective 2: carbon footprint

Fig. 4 shows the optimized allocation of waste streams to waste management facilities to minimize GHG emissions. The optimal

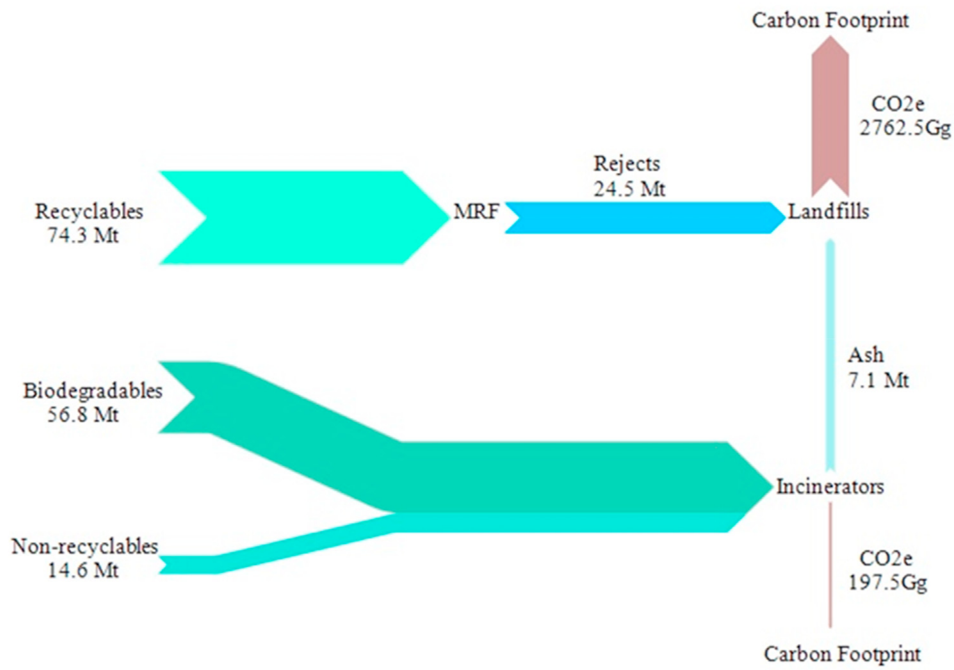

Fig. 4. Optimum allocation of waste streams over waste management facilities for minimum carbon footprint.

sustainable strategy suggests processing readily biodegradable waste and non-recyclables in incineration plants, while directly disposing MRF rejects in landfills throughout the 20-year assessment period. According to the IPCC guidelines, carbon emissions generated from the processing of biogenic materials, such as food waste, are not included in the overall GHG emissions. On the other hand, treatment of readily biodegradable waste in AD facilities generates methane (CH_4) which is introduced into the existing carbon cycle, contributing to the overall GHG emissions. Hence, to satisfy the second objective, the readily biodegradable waste was treated by incineration to reduce the GHG emissions. The total GHG emissions from the optimized waste strategy were 2,960 Gg CO_2e over the 20 years. Since the total GHG emissions from landfilling were 169,029 Gg CO_2e over the same period, the optimized strategy would reduce the carbon footprint by 166,069 Gg CO_2e in the UAE, i.e., 98.2% reduction. Furthermore, this optimized strategy would recover 112.7 TWh of energy at a total NPV of - 2.1 billion USD.

4.1.3. *Objective 3: profitability*

The optimum strategies for maximum energy recovery and minimum carbon footprint were constant throughout the assessment period. In contrast, the optimized hybrid strategy for maximizing profitability is more complex and temporally changing. Fig. 5 shows the optimum allocation of waste streams to waste management facilities in order to maximize profitability. In order to achieve the third objective, the result of the model indicates that all readily biodegradable waste is to be processed in AD plants in the first four years, followed by gradual disposal in landfills, reaching 31.6% in the last year. The additional readily biodegradable waste produced after the fourth year was disposed of in landfills rather than AD plants and incinerators. This decision was likely because energy sales from incinerating the additional readily biodegradable waste were insufficient to cover the incurred costs. Additionally, this allocation was more financially feasible due to the increasing costs of AD treatment as a result of depreciating energy revenues and tipping fees. The entire digestate produced over the 20 years was marketed at a price equal to its processing cost. The optimum allocation of recyclables and non-recyclables was complete disposal in landfills with gas recovery over the 20 years. This can be attributed to the insufficient revenues from tipping fees and energy sales to cover the required costs of combusting recyclables and non-recyclables in any given year. In contrast, the disposal of recyclables and non-recyclables in landfills with gas recovery would be more financially feasible due to the lower CAPEX and OPEX compared to incinerators. The total NPV from implementing such a hybrid WTE-based strategy would be 470 million USD, indicating a 381% increase in profitability compared to the NPV of the existing waste management strategy in the UAE (−167 million USD). Implementing this optimized hybrid strategy would result in the emission of 7,600 Gg CO_2e while recovering around 92.8 TWh of energy.

4.2. *Multi-objective optimization*

In addition to single-objective functions, the model can be used to identify a hybrid WTE-based ISWM strategy that corresponds to simultaneous optimization of all objectives based on their relative importance. The prioritization of strategic goals would vary depending on local conditions, such as the energy mix, availability of fossil fuels, environmental performance, climate change mitigation targets, and availability of investment funds. In the proposed model, the relative importance of multiple objectives is determined through the fuzzy AHP analysis. Table 6 shows the Fuzzy AHP results conducted for the UAE based on expert surveys. The financial profitability was the most prominent objective, with importance of 46.7%, followed by the carbon footprint and energy recovery, with importance of 34.4 and 18.9%, respectively.

Fig. 6 shows the optimum allocation of waste streams to waste management facilities over the 20-year assessment period. The optimum hybrid strategy for the UAE would include processing readily biodegradable waste in AD plants completely up to the 14th year, followed by gradual disposal in landfills. In the first 14 years, readily biodegradable waste is entirely treated by AD in order to enhance the environmental performance and profitability of the

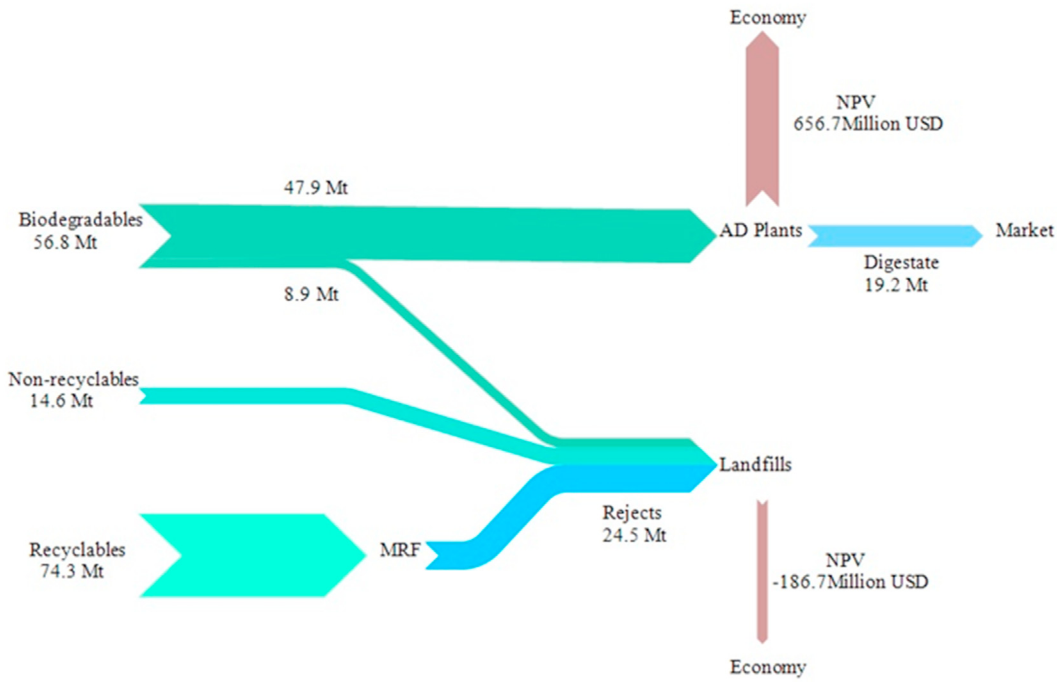

Fig. 5. Optimum allocation of waste streams over waste management facilities for maximum profitability.

Table 6
Fuzzy AHP analysis for relative importance of model objectives in the UAE.

Criteria	Relative importance[a]									Criteria
Financial profitability	AP	XP	FP	**SP**	EQ	SP	FP	XP	AP	Carbon footprint
Financial profitability	AP	XP	**FP**	SP	EQ	SP	FP	XP	AP	Energy recovery
Carbon footprint	AP	XP	FP	**SP**	EQ	SP	FP	XP	AP	Energy recovery

[a] EQ: Equally Preferable, SP: Slightly Preferable, FP: Fairly Preferable, XP: Extremely Preferable, AP: Absolutely Preferable.

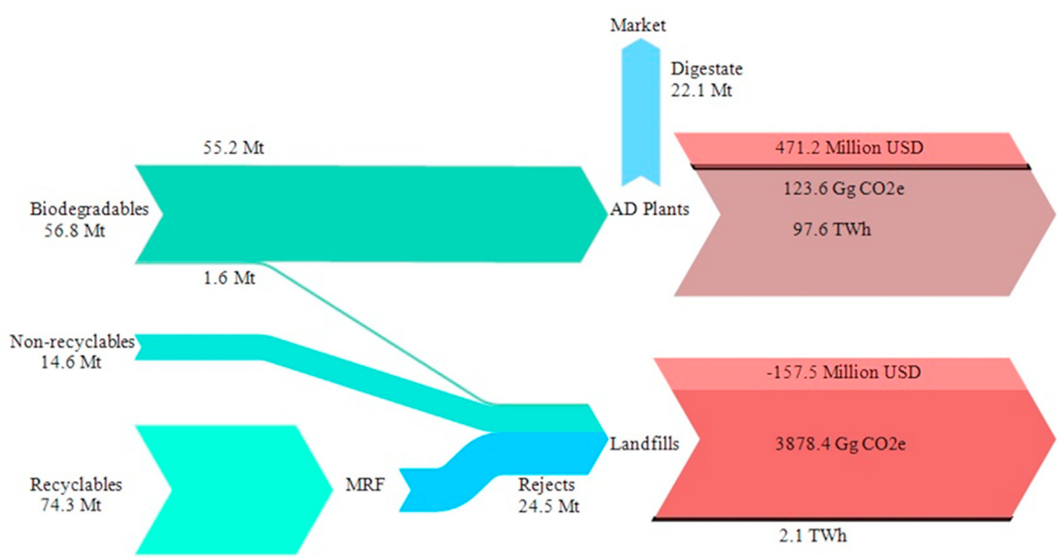

Fig. 6. Optimum allocation of waste streams over waste management facilities for multi-objective optimization.

overall strategy. Following the 14th year, additional readily biodegradable waste is gradually sent to landfills, rather than AD, due to the insufficient revenues from AD plants. Additional readily biodegradable waste is disposed of in landfills rather than incinerators in order to maximize profitability, which has the highest relative importance compared to other objectives. In addition, the resulting digestate from AD plants was entirely marketed. Similar to the optimized strategy for maximum profitability, MRF rejects and non-recyclables are entirely disposed of in landfills with gas recovery over the 20-year assessment period based on the Fuzzy AHP analysis.

Fig. 7 shows the annual cumulative energy production, carbon emissions, and profitability throughout the optimized hybrid strategy. The energy recovered in the opening year would be 4.04 TWh, increasing to 99.7 TWh in the final year. The cumulative energy production would cover 4.2% of the total energy demand in the UAE for over 20 years. The total GHG emissions in the opening year were 132.8 Gg CO_2e, with the total emissions of 4,002 Gg CO_2e in the last year. There was a 97.6% reduction in the cumulative carbon emissions compared to complete landfilling throughout the assessment period. The total NPV of the strategy in the initial year would be around −2.1 billion USD, mainly due to the incurred CAPEX costs. The cumulative NPV increases to 313.7 million USD in the final year, improving the profitability of the national waste management strategy by 288% compared to conventional landfill disposal of waste streams.

Fig. 8 summarizes the results of the single- and multi-objective optimized strategies for energy recovery, carbon footprint, and profitability. The figure is plotted as a fraction of the maximum value obtained from the single-objective analyses. As a result of incorporating relative importance, the optimum value of each objective in the multi-objective optimization is less than the maximum value of each single-objective optimization. It is also clear that the value of each objective in the multi-objective strategy is greater than all other non-maximized values in the single-objective strategies. Multi-objective strategies can thus provide the optimum scenario for each country based on specific local conditions.

4.3. Sensitivity analysis

A sensitivity analysis was performed to determine the impact of selected parameters on the outcomes of the multi-objective optimization. Those parameters included: 1) individual carbon footprints of waste fractions, 2) individual energy contents of waste fractions, 3) CAPEX of management facilities, 4) OPEX of management facilities, 5) electricity tariff, 6) landfilling fees, and 7) tipping fees. Variations in those parameters may occur due to multiple reasons, such as: changes in market conditions, energy production efficiencies, legislations, equipment purchases, as well as other economic and environmental factors. The energy recovery, carbon footprint, and profitability of the hybrid ISWM strategy were re-

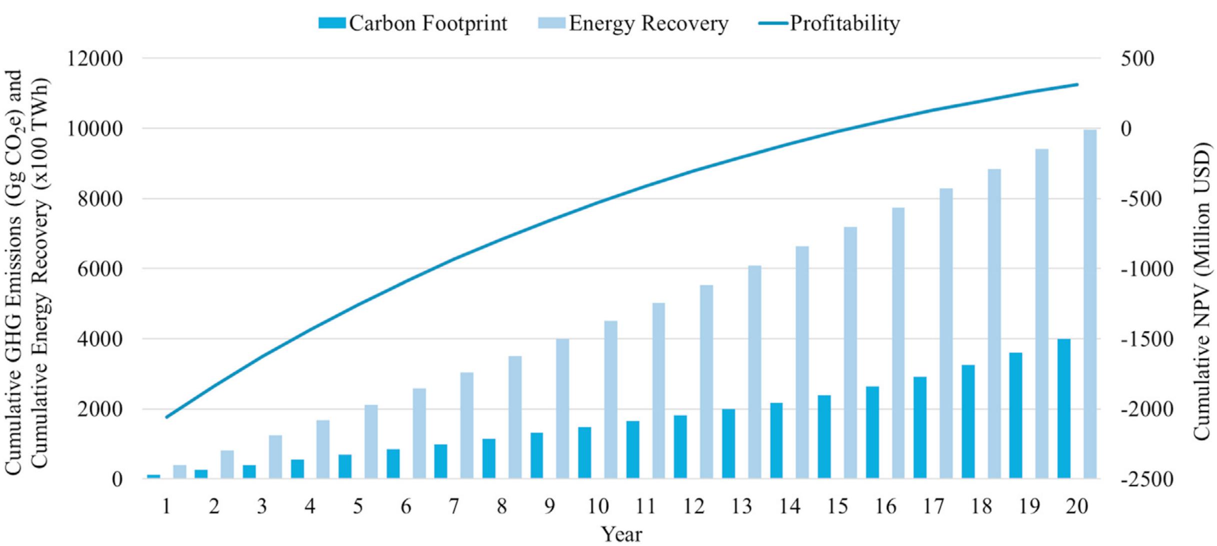

Fig. 7. Annual cumulative energy recovery, carbon footprint, and profitability of multi-objective optimized strategy.

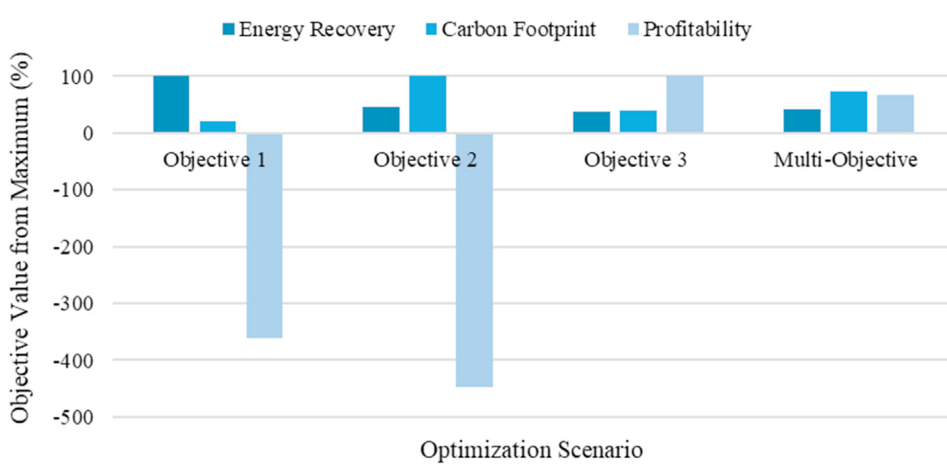

Fig. 8. Percentage of each optimized objective from maximum corresponding value.

computed when the selected parameters varied by ±10%. As the multi-objective optimization is influenced by the weighted objectives combined, variation in any of those parameters would potentially affect the overall outcomes. As shown in Fig. 9, the most influential parameters on the model outcomes were the electricity tariff and CAPEX, as well as the OPEX at a slighter level. The other parameters only affected their corresponding objective, e.g., the impact of the individual energy contents and carbon footprints of waste fractions on the overall energy recovery and carbon footprint, respectively. Likewise, the landfilling and tipping fees only affected the profitability outcome. It was found that the energy recovery was most sensitive to the +10% change in electricity tariff (19.1% greater energy output), and the −10% change in energy content of waste fractions (−9.8% reduction). Similarly, the carbon footprint was highly affected by the +10% increase in electricity tariff (197.9% greater emissions), as well as the +10% increase in the CAPEX of all facilities (−42.8% reduction). Likewise, the profitability was noticeably sensitive to the +10% increase in electricity tariff (65.2% greater NPV), and the +10% increase in CAPEX (−99.1% reduced NPV).

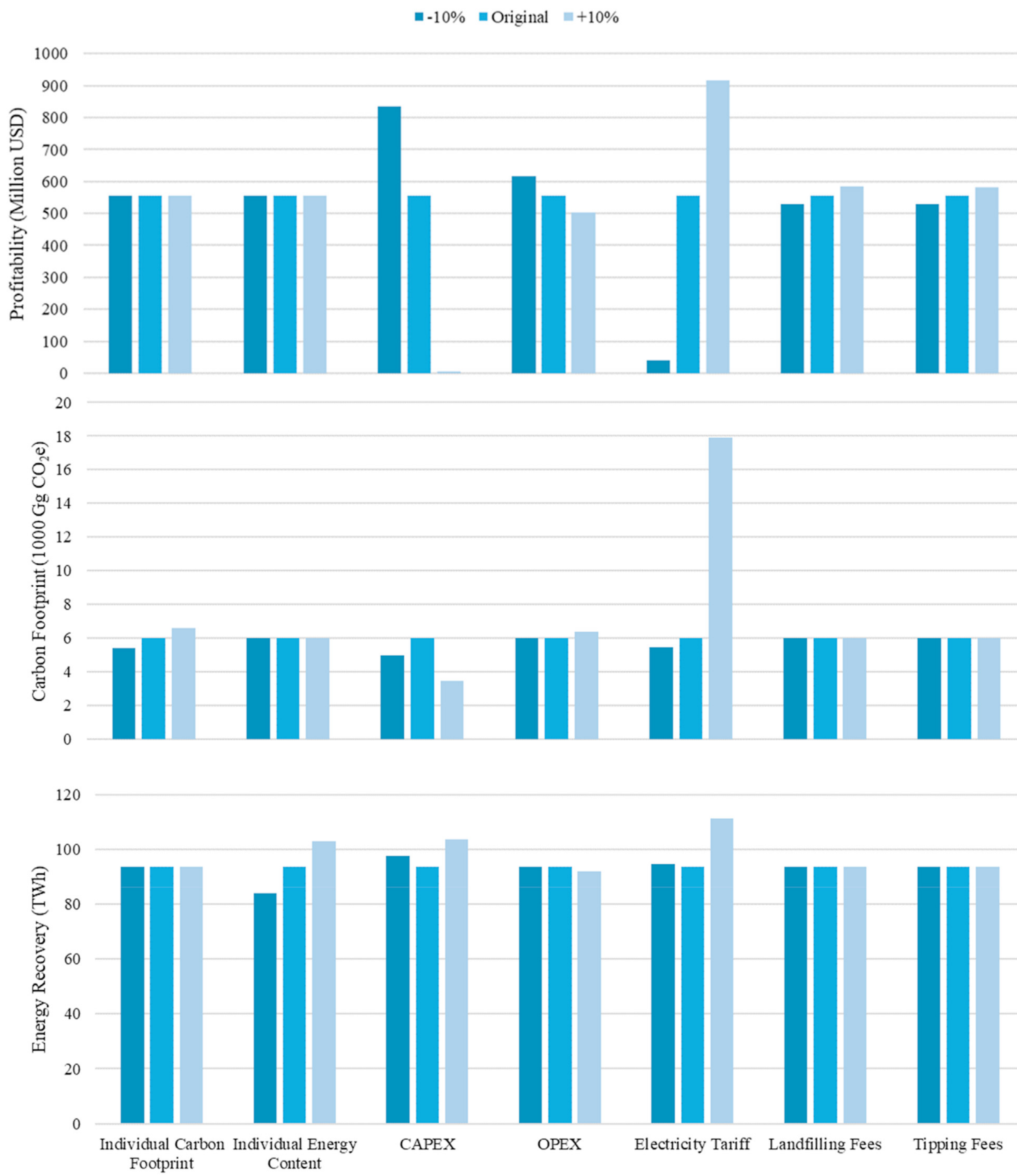

Fig. 9. Impacts of sensitivity analysis on energy recovery, carbon footprint, and profitability of the hybrid WTE-based ISWM strategy.

5. Conclusions

The shift to WTE-based management strategies is mainly driven by the global trend of increasing waste generation, GHG emissions, and energy demand. The present study provided an optimization model for hybrid WTE-based ISWM strategies. The purpose of the model was to optimize the allocation of waste streams to different waste management facilities for any region based on specific local conditions. The model was tested for the UAE, and the optimized strategy showed promising results in terms of the recovered energy, reduced carbon emissions, and increased profitability compared to the existing conventional management systems. However, the implementation of such a model may face multiple challenges, some of which are listed below, along with relevant recommendations:

- The proposed model included four types of waste management facilities, namely AD plants, incinerators, landfills with gas recovery, and MRFs. However, other facilities might be more suitable for waste management in some countries, based on local conditions. Therefore, incorporating further management facilities, such as composting and gasification, as potential destinations for waste streams would enhance the applicability of the optimization model.
- The objectives in the proposed model were maximizing energy recovery and profitability while minimizing carbon footprint. However, other objectives might be of greater interest to certain countries and should be incorporated into the model, such as minimizing land requirements.
- The importance weights of the objectives selected in the established model were computed using the Fuzzy AHP method based on expert assessment. However, existing approaches for deriving the weights from pairwise comparison matrices might be considered sophisticated and rarely applied. Also, the derivation of crisp weights could be subject to significant drawbacks, such as producing even priority vectors in the pairwise matrix, or providing weights equal to zero.
- In WTE-based ISWM strategies with AD plants, source separation and collection of organic waste will be required. The impact of such transformation, particularly on the financial evaluation, should be incorporated into the model.
- An enhancement of the proposed model would be including a broader spectrum of environmental and financial indicators, such as lifecycle assessment categories, payback period, and levelized cost of electricity.

Overall, this optimization model can be applied in all countries based on specific local conditions and strategic priorities. In order to facilitate replication of the established optimization framework, the detailed methodology and model implementation have been compiled in Abdallah et al. (2021). The paper is intended to provide a systematic methodology to decision-makers and researchers for the development of strategic waste management masterplans incorporating WTE facilities.

CRediT authorship contribution statement

Mohamed Abdallah: Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Sadeque Hamdan:** Methodology, Software, Validation, Data curation, Writing - original draft. **Ahmad Shabib:** Methodology, Formal analysis, Investigation, Writing - original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124714.

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