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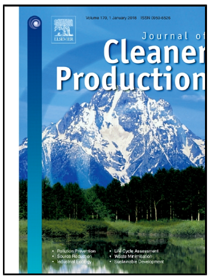

Optimal Processing Route for the Utilization and Conversion of Municipal Solid Waste into Energy and Valuable Products

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Highlights

- A superstructure based optimization model is developed.
- Optimal MSW processing networks are determined.
- The optimization problem is formulated as an MINLP model.
- MINLP model is linearized to its equivalent MILP form.
- Sensitivity analysis identified influential technical and economic parameters.

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Optimal Processing Route for the Utilization and Conversion of Municipal Solid Waste into Energy and Valuable Products

Muhammad Rizwan[a], Yousef Saif[a], Ali Almansoori[a,*], Ali Elkamel[a,b]

[a] Department of Chemical Engineering, Khalifa University of Science and Technology, The Petroleum Institute, P. O. Box 2533, Abu Dhabi, United Arab Emirates

[b] Department of Chemical Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada

*Corresponding author: aalmansoori@pi.ac.ae, +971-2-6075552

Abstract

A systematic design of municipal solid waste (MSW) management system can lead to identify a promising and/or sustainable way of handling MSW by processing it into energy and valuable products. In this study, a systematic framework is developed for the superstructure-based optimization of MSW processing routes. The proposed superstructure includes the potential technological alternatives (such as recycling, composting, anaerobic digestion with electricity generation, gasification followed by catalytic transformation, gasification with electricity generation, plasma arc gasification with electricity generation, pyrolysis with electricity generation, incineration with electricity generation, and landfill with electricity generation) for producing valuable products from MSW. Based on the developed superstructure, a mixed integer nonlinear programming (MINLP) model is developed to identify the optimal MSW processing pathways considering two different MSW handling scenarios. For ease of the

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solution, the MINLP model is linearized to its equivalent MILP form, and solved in GAMS. The solution to the optimization problem provides the optimal/promising route for the synthesis of useful products from MSW under chosen economic objective function. The developed framework is applied on a case study of Abu Dhabi Emirate to find the optimal processing pathway for handling and processing of MSW into energy and value-added products. The optimization results show that an integrated pathway comprising of recycling the recyclable components of MSW along with the production of bioethanol from the rest of the waste via gasification followed by catalytic transformation can provide potential economic benefits. A sensitivity analysis is also executed to investigate the effect of key economic and technical parameters on the optimization results.

***Key words*:**

Municipal solid waste; Superstructure-based optimization; Sustainable management; Waste-to-energy; Mixed integer nonlinear programming

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1. Introduction

Municipal solid waste (MSW) generally includes all types of solid waste generated from residential, institution, and commercial establishments (Karak et al., 2012). It is commonly collected by the local government bodies. In a study on worldwide scenario of MSW, it is suggested that MSW generation may exceed 2 billion tons per year globally that is a potential threat to the ecosystem (Karak et al., 2012). Ineffective handling and disposal of MSW may cause degradation of valuable land, and pose health and environmental problems (Tan et al., 2014). However, the effective management of MSW is a big challenge for the local government authorities and municipality planners due to industrialization, limited land resources and increasing population (Khan et al., 2016). Therefore, a systematic and efficient MSW management strategy is needed to balance the need for the sustainable handing of MSW as well as the protection of environment (Tan et al., 2014). Furthermore, with proper waste management practice and under waste to energy (WTE) concept, MSW can be processed into various useful products such as biogas, bioethanol, electricity, etc. These products can be used as a source to provide some part of the primary energy currently supplied by the fossil fuels (Fodor and Klemeš, 2012).

MSW management generally refers to the collection of waste, segregation of mixed waste into its constituents, recycling of recyclable components, treatment, resource recovery and disposal of the waste. A number of MSW management hierarchies exist with different orders but in most cases the suggested order is: (1) reduce the waste, (2) reuse, (3) recycle materials, (4) treatment and heat recovery, and (5) landfill (Finnveden et al., 2005). After the recycling of recyclable components, there are many technologies available for taking care of remaining

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waste such as composting, anaerobic digestion, gasification, pyrolysis, plasma arc gasification, incineration, etc. An effective waste management strategy could integrate waste recycling with various WTE technologies. In current practices, the use of system analysis tools is a useful choice to synthesize a promising waste management strategy (Seadon, 2010).

Several studies have been conducted on the management and utilization techniques for solid waste with the focus on economic and energy assessment of specific treatment technologies, and/or waste management in specific regions (Khan et al., 2016). Systems engineering models have been the focus of many research studies where various optimization models (e.g., linear programming (LP), mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP), stochastic programming, hybrid models, etc.) are developed for the design and solution of MSW management system (Ghiani et al., 2014). Many studies also focused on the use of life cycle assessment tools for the environmental impact assessment (Othman et al., 2013).

In the context of optimization formulations, Santibañez-Aguilar et al. (2013) developed an optimization model for the MSW supply chain system with multi-nodes. A multi-objective MILP problem is formulated for the simultaneous maximization of economic benefits and percentage of waste consumption. Minoglou and Komilis (2013) proposed a simplified methodology for the optimization of integrated MSW management system. A non-linear mathematical model (with 32 decision variables) is developed with the objectives to (1) minimize the total cost of MSW management systems, and (2) minimize the equivalent CO_2 emissions. Tan et al. (2014) proposed a sustainable waste management strategy for Iskandar Malaysia. Based on the superstructure comprising of four technologies (composting, material

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recycling facility, incineration, and landfill gas recovery system), an MILP model is formulated to synthesize a cost effective MSW processing network. Ng et al. (2014) incorporated WTE concept into the MSW management system. In their work, fuzzy multi-objective optimization is employed for the supply network design and treatment of MSW with the objective function to minimize the cost and maximize the waste reduction as well as the generation of electricity. Niziolek et al. (2015) presented a superstructure-based approach for producing liquid transportation fuels, olefins and aromatics from MSW. An MINLP model is formulated that is solved by global optimization based branch-and-bound algorithms to identify the optimal process topology. Lee et al. (2016) developed a mathematical model to optimize Hong Kong MSW management system. The developed model adopts integer LP and mixed integer programming. Khan et al. (2016) performed a techno-economic assessment to help municipality planners in the province of Alberta, Canada in developing waste processing facilities. A comprehensive review and summary on the development and use of optimization models for MSW management system can be found in Ghiani et al. (2014).

Despite many studies with the focus on MSW network design, the potential of integrating biofuels production option from MSW with other waste treatment technologies is not exploited in a comprehensive and generic way, e.g., by modeling numerous potential alternatives at each stage of MSW processing and further conversion into value-added products. The sustainable MSW strategy will not only reduce the burden on environment but also process the solid waste into various energy products, thus can contribute towards primary energy supply. Therefore, in this work, this research gap is addressed by developing a systematic modeling framework for the sustainable handling and processing of MSW into biofuels and a number of other energy

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products.

In this study, first a comprehensive MSW superstructure model is proposed that includes the potential available technological alternative at each stage for the treatment and conversion of MSW into valuable products. Based on the superstructure, an MINLP model is developed under the objective function of maximizing the net profit of MSW management system. The MINLP problem is linearized to its equivalent MILP problem, and solved in GAMS by employing CPLEX solver. The developed framework is applied and tested on a small case study based on the MSW data of Abu Dhabi Emirate. It also allows (1) the integration of recycling of recyclable components in MSW with the treatment of the rest of the waste, and (2) treatment of mixed MSW without considering the recycling option. The objective of the case study is to identify the optimal processing route for the treatment and conversion of MSW into valuable products under different scenarios. A sensitivity analysis is performed to investigate the effect of key economic and technical parameters on the net profit and the optimal solution found. Furthermore, the developed framework is not site specific; it is generic in nature, therefore, it can be implemented to any site/locality given that the necessary MSW data is available.

2. Modeling framework

2.1. Problem statement

A superstructure is given (developed) that is composed of potential technological/processing alternatives available for handling and conversion of MSW into various energy and valuable products, the optimization problem is defined as: determine the optimal processing pathway

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for the sustainable utilization and conversion of MSW into value-added products. In this work, the objective function of the optimization formulation is chosen as to maximize the net profit, which can be defined as the difference between the revenue (obtained by selling the products) and cost (operational and capital cost).

2.2. Development of superstructure

A superstructure model for the utilization and conversion of MSW into useful products is formulated. The developed superstructure (shown in Fig. 1) is based on the information available in the literature on various MSW treatment technologies. It consists of different processing stages such as segregation of MSW into different components, recycling of recyclable components in MSW, treatment and conversion of MSW into different products. Numerous processing alternatives are incorporated and modeled for the treatment of MSW. As presented in Fig. 1, two indices are used to represent a technological alternative; the first one, *k*, shows the technological alternative, and the subsequent second one, *j*, shows the processing stage. The list of technological alternatives included in the MSW superstructure model is presented in Table 1. Note that depending upon the information available about MSW treatment technologies, more alternatives can be incorporated in the superstructure model.

MSW segregation: Mixed MSW generally contains many components such as food waste, paper, plastic, wood waste, glass, metal, textile, etc. (Qdais et al., 1997). The proposed MSW superstructure starts with the segregation of MSW into its constituents. The recyclable components are then recycled in next processing stage. In the developed superstructure model, the waste segregation step can also be bypassed to facilitate the handling of mixed MSW, which is modeled by introducing empty box, alternative ‘2,2’ (see Fig. 1).

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Recycling of recyclable components: The recyclable components in MSW (paper, plastic, glass, metal, textile) are recycled first via material recycling facility (MRF), and the remaining waste is sent to next processing stage for the further treatment and conversion into useful products. The recycling step can also be bypassed by the use of empty box, alternative '2,3', to facilitate the treatment of mixed MSW without recycling.

Treatment and conversion of MSW into energy and valuable products: For the processing and conversion of MSW into different energy and value-added products, a number of potential alternatives are incorporated in the MSW superstructure model. The included alternatives are: composting, anaerobic digestion followed by electricity generation from biogas, gasification followed by either electricity generation or catalytic transformation to produce bioethanol, plasma arc gasification followed by electricity generation, pyrolysis followed by electricity generation, incineration with electricity generation, and landfill based electricity generation.

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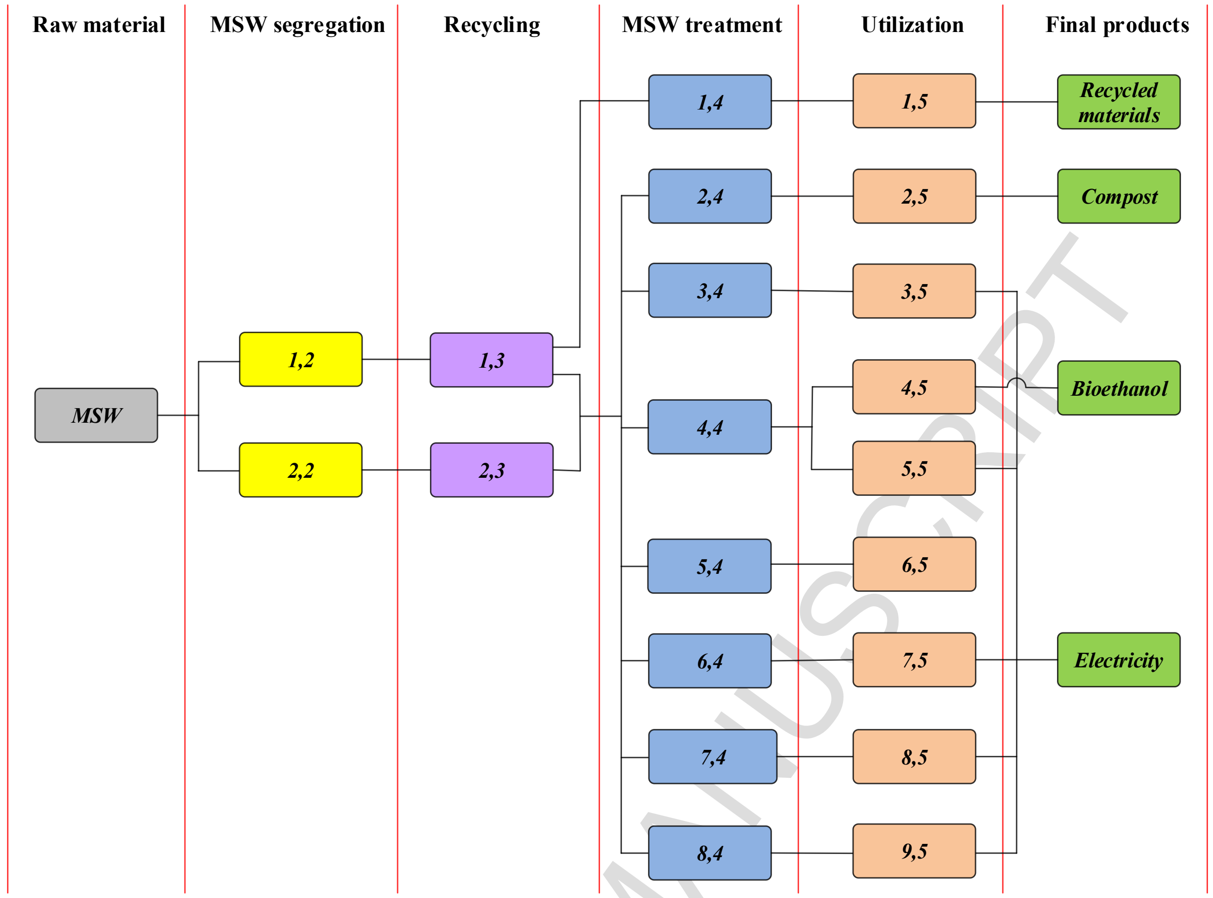

163
164 Fig. 1. Superstructure for MSW management

165 Table 1. List of technological alternatives

Box No.	Technological alternative	Reference
1,1	MSW	Statistics Centre, Abu Dhabi (2016)
1,2	Segregation facility	Khan et al. (2016)
2,2	Empty	
1,3	MRF	Daskalopoulos et al. (1998); Tan et al. (2014)
2,3	Empty	
1,4	Empty	
2,4	Composting	Hareen (2009); Ng et al. (2014)

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3,4	Anaerobic digestion	Verma (2002)
4,4	Gasification	Khan et al. (2016); Klein and Themelis (2003)
5,4	Plasma arc gasification	Young (2010)
6,4	Pyrolysis	Cekirge et al. (2015); Young (2010)
7,4	Incineration	Murphy and McKeogh (2004)
8,4	Landfill	Leme et al. (2014)
1,5	Empty	
2,5	Empty	
3,5	Electricity generation from biogas	Akbulut (2012)
4,5	Catalytic transformation	Jacobs Consultancy (2013); Khan et al. (2016)
5,5	Electricity generation from syngas	Khan et al. (2016); Klein and Themelis (2003)
6,5	Electricity generation	Young (2010)
7,5	Electricity generation from pyrolysis products	Ng et al. (2014)
8,5	Electricity generation from incineration products	Ng et al. (2014)
9,5	Landfill based electricity generation	Leme et al. (2014)
1,6	Recycled materials	
2,6	Compost	
3,6	Bioethanol	
4,6	Electricity	

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2.3. Formulation of optimization model

In this work, a superstructure-based optimization model developed in earlier studies (Rizwan et al., 2013, 2015 (dealing with the synthesis of optimal biorefinery)) is adapted and extended for the purpose of optimal MSW utilization and management. In the original model by Rizwan et al. (2013, 2015), the capital cost modeling was not addressed. In the current formulation, the capital cost is also modeled in a generic way for each technological alternative included in MSW superstructure. The framework comprises of mass balance constraints and objective function.

2.3.1. Mass balance constraints

For each processing stage included in the superstructure, the mass balances must be satisfied. The general representations of processing stage (indexed as *j*) and technological alternative within stage *j* (indexed as (*k*,*j*)) are given by the flow diagrams in Fig. 2(a) and (b), respectively. Table 2 details the nomenclature used in this work.

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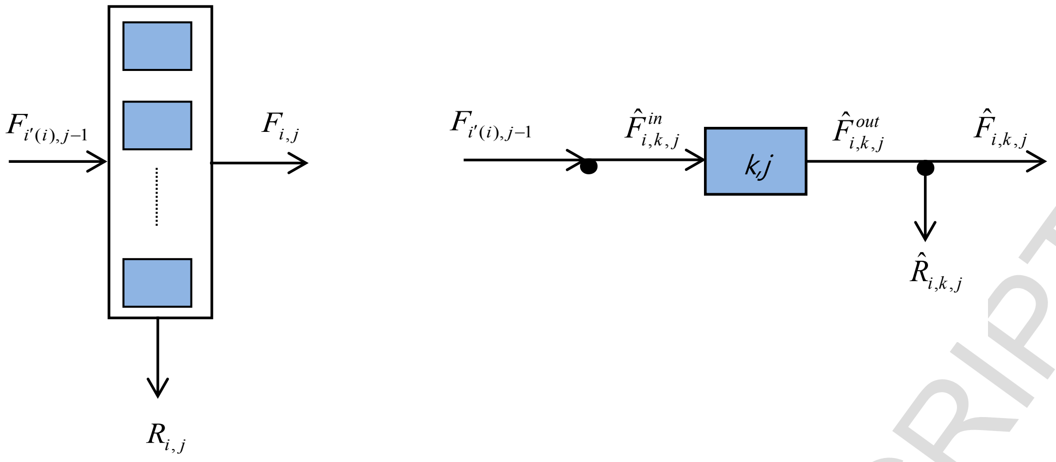

(a) (b)

Fig. 2. Representation of (a) processing stage *j*, (b) alternative *k* in stage *j* (modified from Rizwan et al. (2013))

As shown in Fig. 2(a), there is one incoming stream to stage *j* for each component *i* (*i* represents the component index that keeps record of all the involved components including those in raw material stream, or in product stream) termed as process stream $F_{i'(i),j-1}$ coming from stage *j-1* to stage *j* for necessary action/processing. There are two outgoing streams; (1) process stream $F_{i,j}$ leaving stage *j* and going onto stage *j+1* for further processing, and (2) residue stream $R_{i,j}$ leaving stage *j* for disposal (it contains the unreacted or leftover components). More information on the use and arrangement of indices can be found in Rizwan et al. (2013).

Binary variable $y_{k,j}$ is used to model the selection of technological alternative *k* from processing stage *j* (if corresponding alternative is chosen, $y_{k,j}$ equals to 1; otherwise $y_{k,j}$ equals to 0). This work is mainly focused on the screening and evaluation of technologies for the MSW treatment. Therefore, binary variables are the main decision variables as they will

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identify the optimal processing route for MSW treatment. The selection of technological alternative from a set of available alternatives at each stage is modeled by Eq (1) as follows:

$$\sum_{k \in K} y_{k,j} \le 1 \qquad \forall j \in J$$

(1)

Given this constraint, $F_{i,j}$, the flow of process stream leaving the stage j is given by:

$$F_{i,j} = \sum_{k \in K} (y_{k,j} \cdot \hat{F}_{i,k,j}) \qquad \forall i \in I, \forall j \in J \tag{2}$$

where $\hat{F}_{i,k,j}$ is the flow of component *i* in process stream leaving alternative *k* of stage *j*.

Similarly, $R_{i,j}$, the flow of component *i* in the residue stream leaving the stage *j* without continuing onto the next stage, is given by:

$$R_{i,j} = \sum_{k \in K} (y_{k,j} \cdot \hat{R}_{i,k,j}) \qquad \forall i \in I, \forall j \in J \tag{3}$$

where $\hat{R}_{i,k,j}$ is the flow of residue stream leaving alternative *k* of stage *j*. It contains the unreacted or leftover components.

As represented in Fig. 2(b), $\hat{F}^{in}_{i,k,j}$, the inlet flow of component *i* fed to technological alternative *k* of stage *j* is given by:

$$\hat{F}^{in}_{i,k,j} = \varepsilon_{i,k,j} \cdot F_{i(i'),j-1} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{4}$$

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where $F_{i(i'),j-1}$ is the flow of process stream of component *i* (indexed as *i'* at stage *j-1*) coming from stage *j-1*, $\varepsilon_{i,k,j}$ is known model parameter used to define the allocation of certain component *i* to alternative *k* of stage *j*.

The conversion of MSW into different products is modeled with the help of yield coefficient, $\alpha_{i,i',k,j}$, which is assumed to occur inside the alternative box. However, it can also be modeled with the help of stoichiometric data but due to lack of such data, the MSW conversion is modeled by introducing yield parameter as given by:

$$\hat{F}^{out}_{i,k,j} = \hat{F}^{in}_{i,k,j} + \sum_{i' \in I'} (\alpha_{i.i',k,j} \cdot \hat{F}^{in}_{i,k,j}) - (\theta_{i,k,j} \cdot \hat{F}^{in}_{i,k,j}) \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{5}$$

where $\alpha_{i,i',k,j}$ represents the products yield defined as the function of incoming flows, $\theta_{i,k,j}$ represents the conversion/consumption of component *i* in alternative *k* of stage *j*, $\hat{F}^{out}_{i,k,j}$ is the flow of process stream at the outlet of alternative *k* of stage *j*.

The separation is carried out at the outlet to separate the process stream from the residue stream which is given by:

$$\hat{F}_{i,k,j} = \hat{F}^{out}_{i,k,j} - \hat{R}_{i,k,j} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{6}$$

where $\hat{F}_{i,k,j}$ is the flow of component *i* in process stream leaving alternative *k* of stage *j*. $\hat{R}_{i,k,j}$ is the flow of residue stream leaving alternative *k* of stage *j* which is given by:

$$\hat{R}_{i,k,j} = \mu_{i,k,j} \cdot \hat{F}^{out}_{i,k,j} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{7}$$

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where $\mu_{i,k,j}$ is the split factor used for the separation of residue stream.

The alternative 1 of stage 1 represents the raw material assignment which is modeled as:

$$\hat{F}_{i,1,1} = \phi_i \qquad \forall i \in I \tag{8}$$

where ϕ_i is the raw material/feed composition.

2.3.2. Objective function

The optimization model is formulated with an objective function to maximize the annual net profit defined by Eq (9):

$$Profit = Product\ Sales - O\&M\ Cost - Capital\ Cost \tag{9}$$

$Product\ Sales$ is given by:

$$Product\ Sales = \sum_{i \in I} (Price_i \cdot F_{i,6}) \tag{10}$$

where $Price_i$ is the selling price of products. In Eq (10), the component index *i* covers over the products set only, which includes recycled materials, electricity, compost and bioethanol.

$O\&M\ Cost$ represents the operating & maintenance cost which is modeled as:

$$O\&M\ Cost = \sum_{j \in J} \sum_{k \in K} \sum_{i \in I} (OM_{k,j} \cdot y_{k,j} \cdot \hat{F}^{in}_{i,k,j}) \tag{11}$$

where $OM_{k,j}$ represents the operating and maintenance cost of each alternative *k* of stage *j*.

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Capital Cost includes the capital needed for necessary manufacturing and plant facilities. It is modeled as:

$$Capital\ Cost = \sum_{j \in J} \sum_{k \in K} (CCost_{k,j} \cdot y_{k,j}) \qquad (12)$$

where $CCost_{k,j}$ is the annualized capital cost of each technology *k* of stage *j* which is given by a generic function in Eq (13):

$$CCost_{k,j} = CCost_{k,j}^{base} \cdot \left(\frac{Capacity_{k,j}}{Capacity_{k,j}^{base}} \right)^{n_{k,j}} \cdot \left(\frac{M\&SI}{M\&SI^{base}} \right) \cdot ACCR \qquad \forall k \in K, \forall j \in J \qquad (13)$$

where $CCost_{k,j}^{base}$ is the capital cost of technology *k* of stage *j* in the base case, $Capacity_{k,j}$ represents the desired capacity of technology *k* of stage *j*, $Capacity_{k,j}^{base}$ represents the capacity in the base case at which capital cost is known, $M\&SI$ represents Marshall and Swift cost index for the current/reference year, $M\&SI^{base}$ represents Marshall & Swift cost index of the base year, the value of *n* is taken as 0.6 based on *six-tenths factor* rule (Peters et al., 2003). $CCost_{k,j}^{base}$, $Capacity_{k,j}$ and $Capacity_{k,j}^{base}$ are known model parameters. Marshall and Swift index data (Marshall & Swift/Boeckh, 2017) is used to update the capital cost (Peters et al., 2003).

In Eq (13), $ACCR$ represents the annualized capital charge ratio (Towler and Sinnott, 2013) which is used to calculate the annualized capital cost, $CCost_{k,j}$. $ACCR$ is modeled by Eq (14):

$$ACCR = \frac{IR \cdot (1 + IR)^M}{(1 + IR)^M - 1} \qquad (14)$$

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where *IR* represents the interest rate which is assumed to be 7.5%, M represents the project life which is taken as 20 years.

Table 2. Nomenclature

Indices	
i	index that defines the components
i'	index used to define those components coming from the previous stage
k	index for technological alternative
j	index for processing stage
Sets	
I	set of components
K	set of technological alternatives
J	set of processing stages
Parameters	
$\alpha_{i,i',k,j}$	yield coefficient of product i with respect to the incoming flow of component i' in alternative k of stage j
$\theta_{i,k,j}$	conversion/consumption of component i in alternative k of processing stage j
$\varepsilon_{i,k,j}$	allocation of component i to alternative k of processing stage j
$\mu_{i,k,j}$	residue fraction of component i in alternative k of processing stage j
ϕ_i	composition of raw material/feed
$Price_i$	selling price of products
$OM_{k,j}$	operating and maintenance cost of alternative k of processing stage j
$CCost_{k,j}$	capital cost of alternative k of processing stage j
$CCost_{k,j}^{base}$	capital cost of alternative k of processing stage j in the base case
$Capacity_{k,j}$	desired capacity of alternative k of processing stage j
$Capacity_{k,j}^{base}$	capacity of alternative k of processing stage j in the base case at which capital cost is known

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$n_{k,j}$	sizing factor of alternative *k* of processing stage *j*
$M\&SI$	Marshall and Swift cost index for the current year
$M\&SI^{base}$	Marshall and Swift cost index of the base year
$\hat{F}^{U}_{i,k,j}$	upper limit of continuous variable $\hat{F}_{i,k,j}$
$\hat{F}^{L}_{i,k,j}$	lower limit of continuous variable $\hat{F}_{i,k,j}$
$\hat{R}^{U}_{i,k,j}$	upper limit of continuous variable $\hat{R}_{i,k,j}$
$\hat{R}^{L}_{i,k,j}$	lower limit of continuous variable $\hat{R}_{i,k,j}$
$\hat{F}^{in^U}_{i,k,j}$	upper limit of continuous variable $\hat{F}^{in}_{i,k,j}$
$\hat{F}^{in^L}_{i,k,j}$	lower limit of continuous variable $\hat{F}^{in}_{i,k,j}$
Binary variable	
$y_{k,j}$	binary variable; 1 if alternative *k* from stage *j* is selected and 0 if otherwise
Continuous variables	
$F_{i'(i),j-1}$	flow of component *i'* in the process stream coming from processing stage *j-1*
$F_{i,j}$	flow of component *i* in the process stream leaving processing stage *j*
$R_{i,j}$	flow of component *i* in the residue stream leaving processing stage *j*
$\hat{F}^{in}_{i,k,j}$	flow of component *i* in process stream at the inlet of alternative *k* of processing stage *j*
$\hat{F}^{out}_{i,k,j}$	flow of component *i* in process stream at the outlet of alternative *k* of processing stage *j*
$\hat{F}_{i,k,j}$	flow of component *i* in the process stream leaving alternative *k* of processing stage *j*
$\hat{R}_{i,k,j}$	flow of component *i* in the residue stream leaving alternative *k* of processing stage *j*
$\hat{P}_{i,k,j}$	additional continuous variable used for the linearization of Eq (2)
$\hat{Q}_{i,k,j}$	additional continuous variable used for the linearization of Eq (3)

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$\hat{S}_{i,k,j}$	additional continuous variable used for the linearization of Eq (11)

2.4. Linearization and solution

Bilinear terms appear in Eq (2), Eq (3) and Eq (11), where binary variables are multiplied with the continuous variables. These bilinear terms are linearized in this study by using the technique introduced by Glover (1975) for mixed integer products. In this technique, the mixed integer products appearing in the model are replaced by new continuous variables, which are required to satisfy some additional constraints.

Linearization of Eq (2): The mixed integer product appearing in Eq (2) is replaced by a new continuous variable $\hat{P}_{i,k,j}$ so that Eq (2) is transformed into:

$$F_{i,j} = \sum_{k \in K} \hat{P}_{i,k,j} \qquad \forall i \in I, \forall j \in J \tag{15}$$

In order for the above to match Eq (2), the following constraints must be added.

$$\hat{F}_{i,k,j} - \hat{F}^U_{i,k,j}(1 - y_{k,j}) \le \hat{P}_{i,k,j} \le \hat{F}_{i,k,j} - \hat{F}^L_{i,k,j}(1 - y_{k,j}) \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{16}$$

$$y_{k,j} \cdot \hat{F}^L_{i,k,j} \le \hat{P}_{i,k,j} \le y_{k,j} \cdot \hat{F}^U_{i,k,j} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{17}$$

where $\hat{F}^U_{i,k,j}$ and $\hat{F}^L_{i,k,j}$ are upper and lower bounds of continuous variable $\hat{F}_{i,k,j}$.

Eq (3) and Eq (11) can be linearized in a similar way.

Linearization of Eq (3): The mixed integer product appearing in Eq (3) is replaced by a new continuous variable $\hat{Q}_{i,k,j}$. Eq (3) takes the form of:

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$$R_{i,j} = \sum_{k\in K} \hat{Q}_{i,k,j} \qquad \forall i \in I, \forall j \in J \tag{18}$$

$$\hat{R}_{i,k,j} - \hat{R}^{U}_{i,k,j}(1-y_{k,j}) \le \hat{Q}_{i,k,j} \le \hat{R}_{i,k,j} - \hat{R}^{L}_{i,k,j}(1-y_{k,j}) \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{19}$$

$$y_{k,j} \cdot \hat{R}^{L}_{i,k,j} \le \hat{Q}_{i,k,j} \le y_{k,j} \cdot \hat{R}^{U}_{i,k,j} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{20}$$

Linearization of Eq (11): The mixed integer product appearing in Eq (11) is replaced by a new continuous variable $\hat{S}_{i,k,j}$. Eq (11) takes the form of:

$$O\&M\ Cost = \sum_{j\in J}\sum_{k\in K}\sum_{i\in I}(OM_{k,j} \cdot \hat{S}_{i,k,j}) \tag{21}$$

$$\hat{F}^{in}_{i,k,j} - \hat{F}^{in^U}_{i,k,j}(1-y_{k,j}) \le \hat{S}_{i,k,j} \le \hat{F}^{in}_{i,k,j} - \hat{F}^{in^L}_{i,k,j}(1-y_{k,j}) \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{22}$$

$$y_{k,j} \cdot \hat{F}^{in^L}_{i,k,j} \le \hat{S}_{i,k,j} \le y_{k,j} \cdot \hat{F}^{in^U}_{i,k,j} \qquad \forall i \in I, \forall k \in K, \forall j \in J \tag{23}$$

The linearized form of the model is coded in GAMS and solved by employing CPLEX solver using the problem database that was built in Microsoft Excel. The database includes the parameters values which are collected from the literature.

3. Case study – Emirate of Abu Dhabi

The developed optimization model is applied on a case study to identify the optimal processing route for the optimal utilization and management of MSW. A case of the Emirate of Abu Dhabi, United Arab Emirates (UAE) is considered. UAE is placed among top five countries in the MSW generation worldwide, with per capita MSW generation of 2.1 kg/person/day (Paleologos et al., 2016). In UAE, Abu Dhabi Emirate is the largest emirate by area (67,340

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km^2), and has population of approximately 2.784 million (Abu Dhabi e-Government, 2015). MSW generation in the Emirate of Abu Dhabi is roughly 1.3 – 1.7 million tons annually (Statistics Centre, Abu Dhabi, 2016). Majorly, the MSW is disposed in the dumpsites (Statistics Centre, Abu Dhabi, 2016) as shown in Fig. 3, which is not a promising practice for waste disposal. Only 20% of the waste is recycled in year 2015 (whereas in year 2014, only 6% was recycled (Statistics Centre, Abu Dhabi, 2015)). The developed framework can guide us to determine a promising way of waste management.

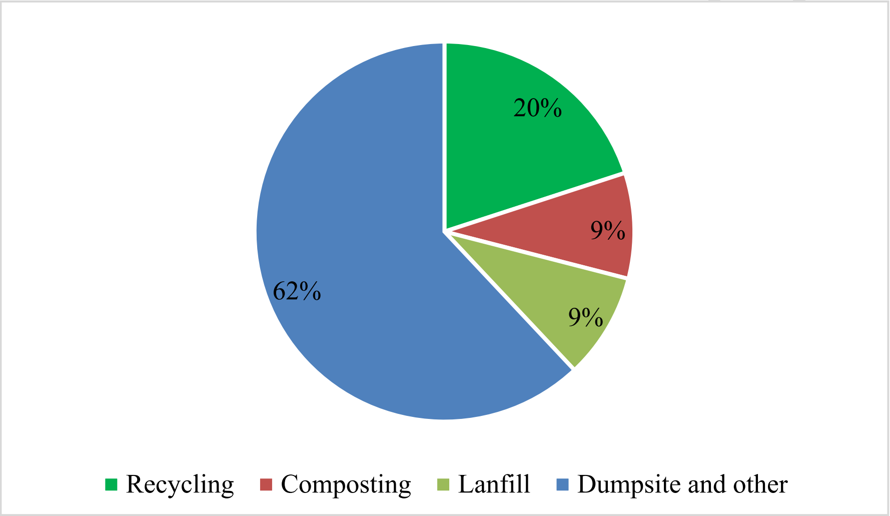

Fig. 3. Distribution of MSW by method of disposal in the Emirate of Abu Dhabi in 2015 (Statistics Centre, Abu Dhabi, 2016)

The MSW can be categorized into various fractions such as food waste, paper, plastic, glass, metal, wood waste, textile, etc. The composition of MSW is given in Table 3. Food waste is the main component of MSW in Abu Dhabi Emirate, representing 49% of the total waste. The allocation of waste to each technology is shown in Table 4. The superstructure is developed for the MSW management as shown in Fig. 1, and explained in section 2.2. The optimization formulation is described in section 2.3. The objective is to identify the optimal processing route

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for the utilization and conversion of MSW into energy and useful products. The input data about the different waste treatment technologies is collected from the literature. Input yield data of products is given in Table 5. The O&M cost and capital cost of different technologies included in the superstructure model is presented in Table 6. The selling price of products is given in Table 7.

For the evaluation and analysis of MSW processing problem (e.g., with respect to net profit maximization), two scenarios are investigated:

Scenario-1: MSW treatment with considering recycling option.
Scenario-2: MSW treatment without considering recycling option.

Table 3. Composition of MSW (Qdais et al., 1997)

Component	**Composition (weight %)**
Food waste	49
Paper	6
Plastic	12
Glass	9
Metal	8
Wood waste	8
Textile	8

Table 4. Allocation of MSW to different technologies

	Recycling	Composting	Anaerobic digestion	Gasification	Plasma arc gasification	Pyrolysis	Incineration	Landfill
Food waste		✓	✓	✓	✓	✓	✓	✓
Paper	✓	✓	✓	✓	✓	✓	✓	✓
Plastic	✓			✓	✓	✓	✓	✓

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Glass	✓						✓	✓
Metal	✓						✓	✓
Wood waste		✓	✓	✓	✓	✓	✓	✓
Textile	✓	✓	✓	✓	✓	✓	✓	✓

Table 5. Input yield data

Product	**Technology**	**Yield (t/t MSW)**	**Reference**
Recycled products	Segregation & MRF	0.90 ^{a} 0.60 ^{b}	Feil et al. (2017); Tan et al. (2014)
Compost	Composting	0.30	Verma (2002)
Electricity	Anaerobic digestion with electricity generation	389 ^{c}	Akbulut (2012); Khan et al. (2016)
Bioethanol	Gasification with bioethanol production	0.255	Jacobs Consultancy (2013); Khan et al. (2016)
Electricity	Gasification with electricity generation	1530 ^{c}	Khan et al. (2016)
Electricity	Plasma arc gasification with electricity generation	816 ^{c}	Young (2010)
Electricity	Pyrolysis with electricity generation	490 ^{c}	Ng et al. (2014)
Electricity	Incineration with electricity generation	340 ^{c}	Ng et al. (2014)
Electricity	Landfill based electricity generation	162 ^{c}	Leme et al. (2014)

a: t/t of individual component in MSW (except plastic)

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b: t of recycled plastic/t of plastic in MSW
c: kWh/t of MSW

Table 6. O&M cost and capital cost of technologies included in the superstructure

Technology	**Capacity (base case) (t/y)**	**Capital cost (US$)**	**O&M cost (US$/t of MSW)**	**Reference**
Segregation & MRF	130,000	5,687,500	34.80	Daskalopoulos et al. (1998); Santibañez-Aguilar et al. (2015)
Composting	365,000	45,000,000	12	Hareen (2009); Ng et al. (2014)
Anaerobic digestion with electricity generation	406,975	95,000,000	45.90	Khan et al. (2016); Ng et al. (2014)
Gasification with bioethanol production	588,235	263,000,000	113.11	Khan et al. (2016)
Gasification with electricity generation	341,275	80,532,000	71.16	Khan et al. (2016); Klein and Themelis (2003)
Plasma arc gasification with electricity generation	182,500	101,538,800	41	Young (2010)
Pyrolysis with electricity generation	182,500	86,936,900	8.82	Cekirge et al. (2015); Young (2010)
Incineration with electricity generation	420,000	191,436,000	29.68	Murphy and McKeogh (2004)
Landfill based electricity generation	230,680	5,937,432	31.20	Leme et al. (2014)

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Table 7. Selling price of products

	Price (US$/t)	**Reference**
Compost	30	Antler (2012); Khan et al. (2016)
Bioethanol	849.18	Khan et al. (2016); Nasdaq (2015)
Electricity	0.08 (US$/kWh)	Khan et al. (2016)
Recycled paper	210.9	Santibañez-Aguilar et al. (2013)
Recycled plastic	204.16	Tan et al. (2014)
Recycled glass	45.08	Tan et al. (2014)
Recycled metal	229.01	Tan et al. (2014)
Recycled textile	45.08	Tan et al. (2014)

4. Results and discussion

The optimization results are investigated for each scenario and discussed in this section. The solution statistics summary is given in Table 8, and the optimization results are presented in Table 9. These results are reported based on 100 t of MSW, for the sake of simplicity. In this study, the transportation cost is not included in the economic analysis. The idea is to determine the optimal or promising technological alternatives for handling and processing of MSW into value-added products.

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Table 8. Summary of solution statistics

	Scenario-1	**Scenario-2**
Description	Waste treatment with recycling option	Waste treatment without recycling option
Objective function	Maximization of net profit	Maximization of net profit
Solver used	CPLEX	CPLEX
Number of equations	14,790	14,790
Number of continuous variable	6,698	6,698
Number of binary variables	44	44
Number of iterations	39	2,985
Optimality gap	0	0
CPU time (s)	0.172	0.219

Table 9. Optimization results (reported on 100 t of MSW basis)

	Recycled products (t)					**Bioethanol (t)**	**Profit (US$)**
	Recycled paper	Recycled plastic	Recycled glass	Recycled metal	Recycled textile		
Scenario-1	5.4	7.2	8.1	7.2	7.2	19.5	5,238.9
Scenario-2	-	-	-	-	-	25.5	5,209.7

4.1. Scenario-1: MSW treatment with recycling option

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Scenario-1 integrates the recycling of recyclable components in the MSW with the further treatment and conversion of the rest of the waste into useful products. The optimal processing route obtained in this scenario is represented by Fig. 4. It is composed of segregation (1,2) of mixed MSW into its constituents, MRF (1,3) for the recycling of recyclable components, gasification (4,4) of the rest of the waste, and catalytic transformation (4,5) of syngas into bioethanol. As shown in Table 9, the maximum profit for scenario-1 is found to be US$ 5,238.9 per 100 t of MSW, which shows the economic feasibility of the MSW management system. The yield of all recycled products and bioethanol is found to be 35.1 t /100 t of MSW and 19.5 t /100 t of MSW, respectively.

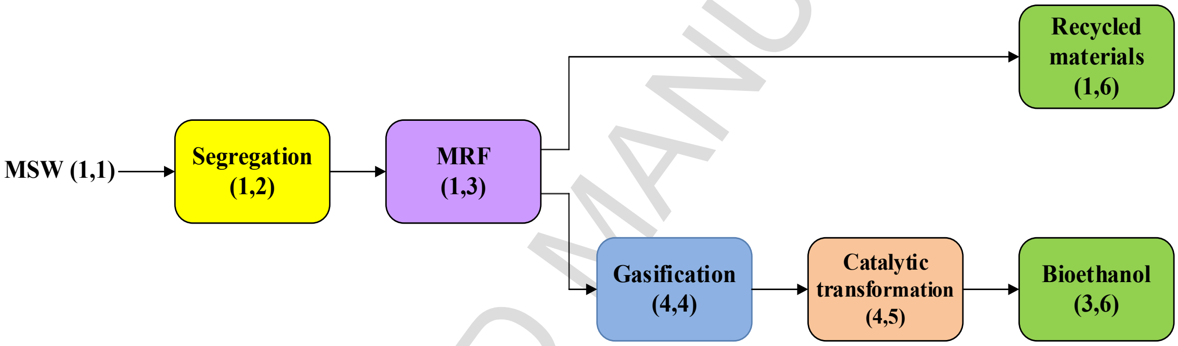

Fig. 4. Optimal processing route for scenario-1

Scenario-1 describes the promising options for MSW management in a profitable and sustainable manner, *i.e.*, recycling of recyclable components in the waste along with the production of bioethanol from MSW via gasification followed by catalytic transformation. Despite their high operational and capital cost, gasification and catalytic transformation are chosen mainly because of their high conversion of MSW into bioethanol as well as high product value. Because, bioethanol offers a high product value, and it can also be used as a potential

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alternative to gasoline. The production of biofuels through gasification of biomass has been investigated by many researchers, however, relatively limited studies are available on the potential of MSW for biofuels production via gasification. Smith et al. (2015) also identified in their analysis that production of bioethanol from MSW via gasification offers potential economic benefits. The results obtained in scenario-1 can guide the researchers and municipality planners to focus on these potentially economical technological alternatives for the sustainable management of MSW in a profitable way in the Emirate of Abu Dhabi. As per the current practice in the emirate (as shown in Fig. 3), mostly the waste is sent to the dumpsites. Therefore, a complete and comprehensive roadmap needs to be devised in order to switch from the current practice towards a promising and sustainable ones.

4.2. Scenario-2: MSW treatment without recycling option

Scenario-2 deals with the treatment and conversion of mixed MSW into useful products without considering the segregation and recycling option. The optimal processing route obtained for scenario-2 is represented by Fig .5. In this scenario, segregation (1,2) and MRF (1,3) has not been selected, and all of the MSW is sent for the treatment. The purpose of this scenario is to explore the economic potential of mixed MSW for the production of energy products, however, from the environmental perspective, it may not be a good practice. The optimal processing route obtained for this scenario is composed of gasification (4,4) of MSW followed by the catalytic transformation (4,5) of syngas into bioethanol.

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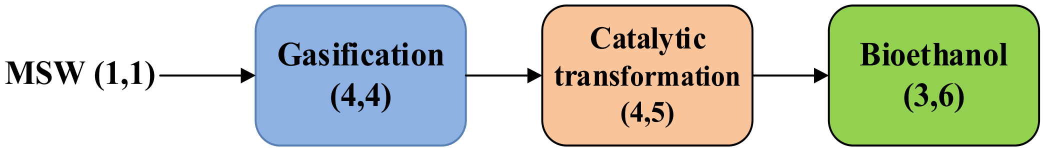

Fig. 5. Optimal processing route for scenario-2

The maximum profit and bioethanol yield obtained in this scenario is US$ 5,209.7 and 25.5 t per 100 t of MSW, respectively. Despite more bioethanol is produced here than in scenario-1, the net profit obtained in this scenario is lower than found in scenario-1. The potential reason is that the recyclable components present in the MSW might not be processed or utilized as per their full potential, when sent for the treatment option only instead of recycling and treatment option. The results obtained imply that economically it is a better choice to recycle the recyclable components first, and then the treatment of the rest of the waste for bioethanol production. These results also indirectly suggest the high product value of the recycled products, therefore, recycling option cannot be bypassed. Furthermore, the integration of recycling with the waste treatment technologies (findings obtained in scenario-1) is also in-line with the very common MSW management hierarchy that suggests to: reduce the waste, reuse and recycle, treatment with heat recovery, and disposal (Finnveden et al., 2005). Therefore, the treatment of MSW without considering recycling option is not recommended.

4.3. Sensitivity analysis

Sensitivity analysis is carried out to investigate the influence of key economic and technical parameters on the net profit obtained as well as the optimal processing route. As shown in table

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10, a total of 31 parameters are evaluated. The evaluated parameters are categorized as yield coefficient for the conversion of MSW into products, selling price of the products, O&M cost, and capital cost. To perform this analysis, the value of each parameter is varied individually and then its influence on the optimal results (both net profit and optimal design) is examined, while keeping all other parameters constant. The optimal design and value of net profit obtained in scenario-1 is used as a reference.

As presented in Table 10, only 10 parameters (out of 31 parameters) affect net profit, while the remaining parameters have shown no influence. The effect of these 10 parameters on net profit is presented in Fig. 6. Out of these 10 parameters, 6 parameters (yield of gasification + catalytic transformation, yield of gasification + electricity generation, selling price of bioethanol, selling price of electricity, O&M cost of gasification + catalytic transformation, and capital cost of gasification + catalytic transformation) affect both net profit and optimal design, whereas the other 4 parameters (yield of recycling, selling price of recycled products, O&M cost of recycling, and capital cost of recycling) affect the net profit only.

Net profit is found to be the most sensitive to the selling price of bioethanol. With 50% increase in bioethanol selling price, the net profit is increased by 154%. It also results in the change of optimal design when its value is reduced by 30% and more; the new optimal design involves the electricity generation from syngas instead of bioethanol production. The second most influential parameter is the yield of gasification and bioethanol production process. With 50% increase in the yield of gasification + catalytic transformation, the net profit is increased by 143%. Similarly, it also results in the change of optimal design when the value is reduced by 30% and more. O&M cost and capital cost of gasification + catalytic transformation are also

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found to be very sensitive to both net profit and optimal design. With 50% decrease in O&M cost and capital cost of gasification + catalytic transformation, the net profit is increased by 70% and 49%, respectively; the variations of these parameters also change the optimal design towards electricity generation when the values are increased by 50%. However, if the yield of gasification + electricity generation is increased by 30%, the optimal design again switches towards the electricity generation from syngas instead of bioethanol production. A similar change in the optimal design is also noted at 30% increase in selling price of the electricity.

The parameters related to the recycling process such as yield of the recycling, selling price of the recycled products, O&M cost, and capital cost of recycling do not affect the optimal design but affect the net profit only. Selling price of the recycled products, yield of the recycling, and O&M cost of recycling show significant effect on the net profit value, whereas the capital cost of recycling show less effect on the net profit, only 3.8% at 50% variations in the capital cost. With 50% increase in selling price of the recycled product and 50% decrease in O&M cost of the recycling, the net profit is improved by 47% and 33%, respectively. If the yield of recycling is reduced by 50%, the net profit will be decreased by 35%.

To summarize, the findings of the sensitivity analysis reveal that both the technical and economic parameters related with the recycling and gasification + bioethanol production process are very sensitive to both optimal solution as well as the objection function value. This is mainly due to the high yield of the respective technologies along with the high product value of the products obtained from them. These parameters are directly related with the process improvements and further developments except the selling price of the products which is more associated with the market aspects. The improvements in these parameters can further increase

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the economic benefits while handling and managing the MSW in a systematic and sustainable manner.

Table 10. List of evaluated parameters and their effect on optimal solution

Parameters evaluated		**Effect on profit (Yes/No)**	**Effect on optimal pathway (Yes/No)**	**Optimal pathway**
Yield coefficient	Yield of recycling	Yes	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of composting	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of anaerobic digestion + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of gasification + bioethanol production	Yes	Yes (on -30% and -50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	Yield of gasification + electricity generation	Yes	Yes (on +30% and +50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	Yield of plasma arc gasification + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of pyrolysis + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of incineration + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Yield of landfill +	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6

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	electricity generation			
Selling price of products	Price of compost	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Price of bioethanol	Yes	Yes (on -30% and -50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	Price of electricity	Yes	Yes (on +30% and +50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	Price of recycled products	Yes	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
O&M cost	O&M cost of recycling	Yes	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of composting	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of anaerobic digestion + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of gasification + bioethanol production	Yes	Yes (on +50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	O&M cost of gasification + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of plasma arc gasification + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of pyrolysis + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of incineration + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	O&M cost of landfill + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6

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Capital cost	Capital cost of recycling	Yes	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of composting	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of anaerobic digestion + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of gasification + bioethanol production	Yes	Yes (on +50 % variations)	1,1 1,2 1,3 4,4 **5,5** 1,6 **4,6**
	Capital cost of gasification + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of plasma arc gasification + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of pyrolysis + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of incineration + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6
	Capital cost of landfill + electricity generation	No	No	1,1 1,2 1,3 4,4 4,5 1,6 3,6

Numbers in bold represent the differences in the selected alternatives with respect to the base case.

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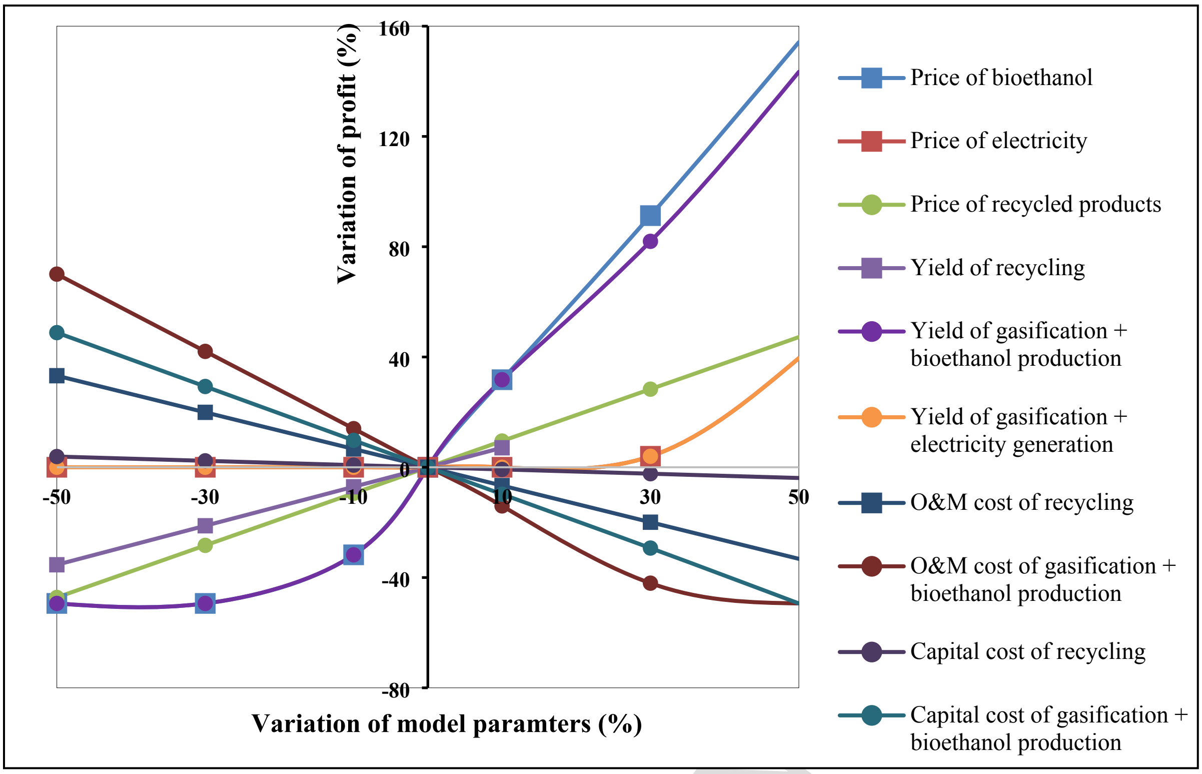

Fig. 6. Sensitivity analysis of key model parameters

5. Conclusions

In this study, an MINLP model has been developed to synthesize the promising / optimal MSW processing route for the handling and conversion of MSW into energy and valuable products. Optimization results show the economic feasibility of MSW management system by integrating the recycling of recyclable components with the production of bioethanol via gasification of the waste followed by the catalytic transformation of syngas into bioethanol. This integrated pathway can provide a maximum net profit of US$ 5,238.9 per 100 t of MSW processed, thus promotes the MSW recycling and waste-to-bioethanol as a promising alternative for MSW management. The sensitivity analysis reveal that the selling price of bioethanol as well as the parameters associated with gasification and catalytic transformation

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are very sensitive, and show significant influence on both the net profit value and optimal design. Both technical and economic parameters associated with gasification and catalytic transformation can be targeted for the possible improvements to enhance the economic competitiveness of MSW management system.

Computationally, the developed optimization framework is very efficient. Due to its generalized representation, it can be implemented to any case study of MSW management with capability of providing valuable insights about the handling and processing of the waste. For future work, some potential research directions have been identified such as:

- Extending the modeling framework to formulate the supply chain optimization model by modeling the transportation cost from the waste collection station to the processing site as well as the transportation cost for the distribution of products from the processing site to the potential market.
- Extending the framework to perform the environmental analysis of MSW processing network to determine the environmental gain that can be obtained by sustainable management of the waste.
- The model is sensitive to technical and economic parameters. A stochastic model can be formulated to find a robust treatment layout for the handling of MSW.

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