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# Multi-Criteria Analysis of Waste-to-Energy Technologies in Developed and Developing Countries

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The main objective of this paper is to utilise a multi-criteria analysis (MCA) to evaluate waste-to-energy (WTE) technologies and identify constraints when examining the placement of a WTE facility. From this, the focus is best summarised by determining the optimal WTE technology in developed countries and how the process would change if implemented in developing countries. In this study, incineration, gasification, and pyrolysis technologies were reviewed and evaluated. The MCA evaluated the different WTE technologies based on a variety of criteria considering environmental, financial, social, technical, and waste quality and quantity. Different weighted factors were used for two MCAs and different alternative weighted factor scenarios were produced to perform a sensitivity analysis on the results. Overall, pyrolysis was found to be the preferred option for developed and developing countries in all scenarios. For developed countries, the highest difference in the overall index score (7%) was found in incineration between the baseline and scenario 4. In developing countries, the highest differences in the overall index scores were found in scenario 3 for incineration (9%) and pyrolysis (10%). Although pyrolysis had the highest overall capital cost due to it being the newest technology, the environmental, social, associated risk, and waste benefits were found to be more significant.

**Keywords:** Waste-to-energy, incineration, gasification, pyrolysis, multi-criteria analysis.

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## Introduction

As comprehensive information gathered from the World Energy Council, establishing the present-day status of waste-to-energy (WTE) in developed and developing regions is a critical part of the study being conducted. From recent data, it is predicted that the global market surrounding WTE will continue its steady annual growth of 5.5% into the year 2023 (World Energy Council, 2016). This will represent a total value of roughly 40 billion in US dollars. In 2013, Europe was considered the largest market, encompassing 47.6% of the total market revenue, whereas China was considered the fastest-growing market. Although this data represents summaries from the past, China is planning to install the world's largest incinerator (constructed to burn 5,000 metric tons of waste daily) in Shenzhen, China, by 2020, which only further shows the progress being made on WTE facilities in developed countries (World Energy Council, 2016). The stark contrast that is seen in WTE in developing countries is prominent given that the installation of an incinerator in South Africa in 2017 was the continent's first form of WTE technology. Urbanisation is continuing to increase the output of waste and the gap in WTE facilities in regions around the world is clearly evident (Dhar et al., 2017).

Incineration is currently the most mature as well as most used form of WTE technology in the world (Dong, 2018). This is predominantly due to the lower costs that are associated with the technology. Although the capital costs needed for incinerator, boilers, turbines, and flue gas cleaning systems may be high, the overall operational costs associated with the incineration process are reduced, which makes incineration a favorable WTE system in developing countries (Menikpura et al., 2016). Furthermore, a limitation for using incineration is its impact on the environment (Shareefdeen et al., 2015). However, as stated with flue gas cleaning systems, various technologies have been developed in order to overcome this limitation. In addition, another environmental issue with the incineration process is the bottom ash produced that will also need to be treated appropriately in order to remove the necessary contaminants (Menikpura et

al., 2016). If done properly, the incineration process should cause minimal harm to the environment. Despite the notable reduction in environmental impacts, incinerators still face a strong opposition by the public. On top of all of this, incinerations have a low efficiency of energy recovered; however, segregation of the waste has shown an increase of the overall efficiency (Grosso et al., 2010).

As a relatively clean and environmentally-friendly process, gasification has attracted most energy researchers' attention in recent years (Upham and Shackley, 2007; Shareefdeen et al., 2015). With potential health risks still associated with incinerators, there is considerable interest among these alternative WTE options. The capital cost of a gasification plant is similar to an incinerator plant; however, due to the reduced amount of emitted flue gases, the investment required for the post-processing of flue gases is much lower for gasification (Consonni and Viganò, 2012). The gasification system also shows superior economic performance since the improved super-heated steam facilitates a higher energy recovery efficiency (Li et al., 2018). This economic benefit makes gasification an attractive WTE option for both developed as well as developing countries. However, as in incineration, there still are chemical issues that can cause either technical issues or further environmental problems. For example, a complex mixture of hydrocarbons can often be created that can block installed filters and cause technical obstacles (Arena et al., 2015). One of the most important disadvantages of gasification process is ash fouling, which can lead to economic problems because of the significant reduction in the efficiency of gasification (Anderson et al., 2016). Although these are some limitations compared with an incineration facility, beneficial offsets still include clean fuels produced in the back-end of the catalytic process and the recovery of recyclables such as metals in the up-front sorting process (Al-Salem et al., 2017). Based on a life cycle assessment comparison in Finland of WTE technologies for a gasification plant and a mechanical-grate incinerator, gasification was shown to be the more environmentally-friendly

option (Dong et al., 2018). This was mainly because of the reduction in emissions. The advantages were considered as lower nitrogen oxides and particulate matter as a result of the reduction in excess air, which then leads to easier emission controls.

Pyrolysis has recently gained critical importance due to its favourable advantages towards environmental pollution in light of increasing production of solid wastes involving plastics (Vergara and Tchobanoglous, 2012). This form of WTE minimises the emissions of carbon monoxide and carbon dioxide greatly when compared with combustion and gasification (Al-Salem et al., 2017). Pyrolysis has an extremely high energy efficiency with an output-input ratio of 13.2 (Shu-Kuang et al., 2013). However, as pyrolysis does treat plastics, it requires waste segregation; otherwise, its efficiency will decrease (Alston et al., 2011). Financially, pyrolysis produces a fuel that could be easily marketed and used in gas engines to produce electricity and heat. This financial benefit is also apparent in operational examinations since the technology does not require as many feedstock pre-treatment steps as compared with incineration and gasification (Al-Salem et al., 2017). Overall, pyrolysis still has a much lower maintenance cost required to maintain the facility in comparison with the other discussed WTE technologies. Due to pyrolysis being a relatively new technology, there is no real public opinion on the facility due to the lack of widespread available knowledge (Vergara and Tchobanoglous, 2017).

Applications of multi-criteria analysis (MCA) to environmental engineering as a decision support system have been successfully established (Halog, 2004; Xi et al., 2010; Madadian et al., 2012). Munda (2005) showed that multi-criteria decision analysis is an adequate approach for dealing with sustainability conflicts at both micro and macro levels of analysis. MCA is an interdisciplinary and a powerful framework for the implementation of the incommensurability principle that encounters participation of a wide spectrum of stakeholders. Accordingly, the goal of this paper is to determine the optimal WTE in a developed region based on defined multi-criteria analysis, and then analyse the obstacles and necessary changes for WTE implementation in developing countries based on the constraints imposed.

## Methods

The processes that were used across this research were focused on developing a complete and chronological approach to establishing how an MCA can be used to a degree far greater than just evaluating various technology alternatives (Chadderton et al., 2017). The research focuses on the review of three well-known WTE technologies: incineration, gasification, and pyrolysis. For each WTE facility, a ranking index was determined by an expert panel comprised of 25 experts from different related sectors, including academia, industries and regulatory entities. Care was taken not to exclude certain decision-makers from any part of the process and also to ensure that there was a substantial overlap of expertise that could have implications for the level of ownership and commitment. Definitely, the multitude of expertise and the interdisciplinary nature of the panel would positively affect the credibility and reduce the uncertainty of this work. Moreover, the panel leveraged the information and values described in previous studies and similar research works related to the specific technologies. As a result, ranking indices of 2, 3 and 4 were used when a category feature was determined to be rather similar for all technologies in order to minimise increased error and/or biases in the results. The methodology used to determine the ranking indices varied between categories and are summarised in Table 1. Based on a case study on how to manage the opinions that originate from stakeholders against those that have other technical backgrounds, a scale of 1 to 5 was considered (Vučijak et al., 2016). This helps to limit the large range of disagreements that often occur throughout the decision process.

Weighting factors were determined depending on the type of nation (developed and developing) considered in the analysis, which will be discussed in-depth later. An index score for each corresponding method was evaluated using Equation 1 and the most suitable technology was confirmed with the use of Equation 2 (Jóźwiakowski et al., 2015; Plakas et al., 2016; Livingston and Abbassi, 2018). Particular attention was given to the alarming threat of climate change, as well as to severe impacts of atmospheric pollution on human health and natural ecosystems.

**Table 1.** Categories considered in the MCA and methods used to determine ranking indices

Category	Feature	Determination of Ranking Index
Financial	Capital Cost <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
	Operation and maintenance cost <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
Environmental	Production of hazardous residue <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
	Emissions (air) <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
Technical	Efficiency-energy generation <sup>1 Max</sup>	Ordered by performance and given a score of 2, 3, 4
	Complexity of installation <sup>2 Min</sup>	Ordered by performance and given a score of 1, 3, 5
Social Environment	Social acceptance <sup>2 Max</sup>	Ordered by performance and given a score of 1, 3, 5
	Noise <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
	Dust/Odour <sup>1 Min</sup>	Ordered by performance and given a score of 1, 3, 5
	Visual impact <sup>2 Min</sup>	Ordered by performance and given a score of 2, 3, 4
Waste Q/Q	Quality <sup>2 Max</sup>	Ordered by performance and given a score of 1, 3, 5
	Quantity <sup>1 Max</sup>	Ordered by performance and given a score of 2, 3, 4
Risk	Financial <sup>1 Min</sup>	Ordered by performance and given a score of 2, 3, 4
	Environmental <sup>1 Min</sup>	Ordered by performance and given a score of 1, 3, 5

Type: <sup>1</sup> quantitative, <sup>2</sup> qualitative. Objective: <sup>Min</sup> minimisation, <sup>Max</sup> maximisation

$$OIS = \sum_{j=1}^M \sum_{i=1}^N r_{ij} * f_i * c_j \quad (1)$$

Where:  $r$  – ranking indices for each feature;  $f$  – feature weighting factor;  $N$  – number of features within each category;  $c$  – category weighting factor;  $M$  – number of categories;  $OIS$  – overall index score.

$$BT = MAX(OIS_n) \quad (2)$$

Where:  $BT$  – best technology;  $n$  – treatment technology (1, 2, 3, 4).

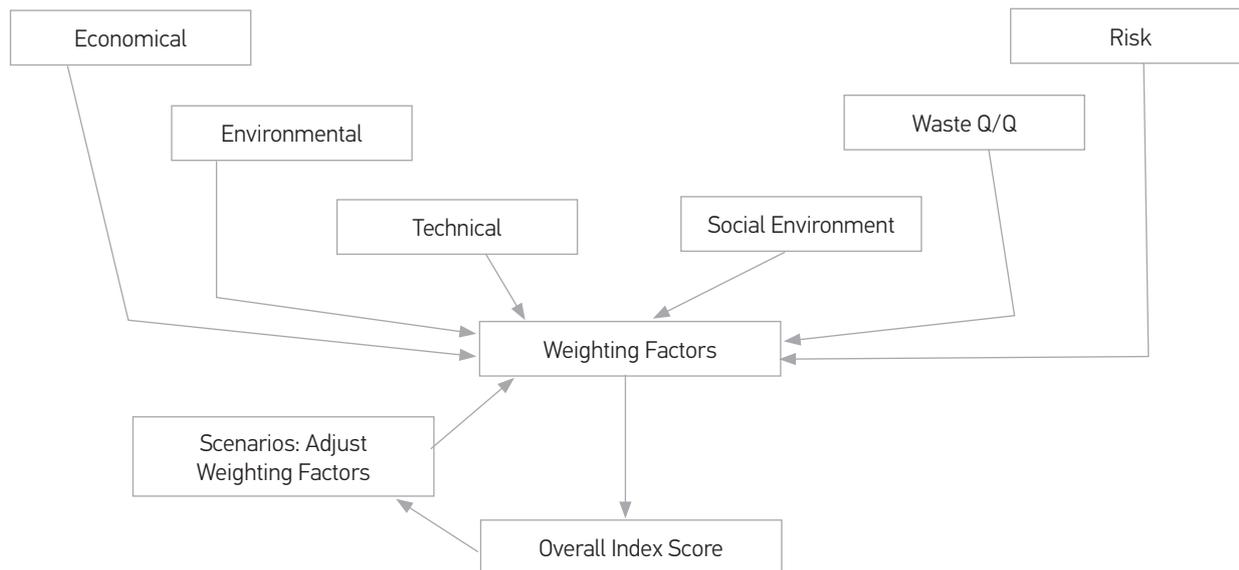
### Sensitivity Analysis

Due to the nature of the MCA algorithm, which depends on subjective scoring in some cases, sensitivity analysis was performed to account for the implication of the MCA results on decision-making strategies and to test the robustness of the model. Once the

primary MCA (based on a developed region) was performed with the determined weighting factors for each category and features, further MCAs were then conducted under five alternative scenarios. This was performed through a sensitivity analysis and was carried out in order to strengthen the results of the study. The sensitivity analysis was executed by varying the weighting factors for any chosen category while the remaining categories are unchanged. Figure 1 details the processes that are often used when conducting a multi-criteria decision analysis (Livingstone and Abbassi, 2018).

In this work, a weighted factor analysis was utilised in order to overcome the possible subjectivity brought by MCA as well as to reflect different priorities by different stakeholder groups (Feili et al., 2014). The weighted factors for each category differed between the MCAs created for developed and developing countries. This was due to the different constraints that are often imposed in a developing country; however,

**Fig. 1.** Overview of the weighting approach for MCA



often constraints may not even have a score if they are not able to be surpassed. For example, the panel gave higher weight to the environmental category (priority group) for developed countries compared with developing countries. The numerical weights of priority groups and their associated discriminating features are explained in the Results and Discussion section. Five weighting scenarios giving different

levels of consideration to each category were used in this analysis, allowing for the calculation of six index scores for each technology. The index score for each technology could then be directly compared with the best technology being selected (the greatest index score). This same procedure can be utilised in order to compare scoring features and outcomes between developed and developing countries.

## Results and Discussion

### Multi-Criteria Analysis of Developed Countries

Criteria ratings were provided based on each one's relative significance to the other criteria. The sum of all criteria rating will equate to one since this represents the total distributed percent. Based on this, environmental criteria were given the highest rating with a value of 0.25. This was done due to increased environmental awareness in developed countries, which often consider this category as the most crucial in consideration of global sustainability and the potential health risks associated with the habitants near the facilities. The MCA was then further specified into assessments, which are the specific aspects

of the criteria that need to be considered. For environmental assessments, these were broken down into the production of residue and released emissions. Once again, these assessments were weighted with respect to each other. Like for the criteria ratings, the sum of all assessment ratings for each respective criterion must sum to a value of one. The quality of air was prioritised in this study due to the amount of pollutants that are released from these facilities; thus, emissions were given a rating of 0.65. Furthermore, the ratings were evaluated for each WTE technology as shown by the ranking index in Table 1. For example, pyrolysis was given a rating of 4 for emissions due to the higher quality of

flue gas produced. Lastly, the final scores for each facility were given by multiplying the criteria rating by the assessment rating and the technology factor rating. These were then summed in order to find the

WTE facility that is most suitable and realistic for developed countries. The MCA for developed countries that were used to select this optimal WTE technology is shown in Table 2.

**Table 2.** MCA of WTE technologies in developed countries

Criteria Category	Rating	Assessment	Weighting	Factor Rating Site*			Final Scores for Sites*		
				I	G	P	I	G	P
Financial	0.2	Capital cost	0.4	4	3	2	0.32	0.24	0.16
		Operation and maintenance cost	0.6	2	3	4	0.24	0.36	0.48
Environmental	0.25	Production of hazardous residue	0.35	2	3	4	0.18	0.26	0.35
		Emission (air)	0.65	2	3	4	0.33	0.49	0.65
Technical	0.2	Efficiency/ Energy generation	0.8	2	3	4	0.32	0.48	0.64
		Complexity of installation	0.2	5	3	1	0.20	0.12	0.04
Social Environment	0.1	Social acceptance	0.05	1	3	5	0.01	0.02	0.03
		Noise	0.1	4	3	2	0.04	0.03	0.02
		Dust/Odour	0.5	1	3	5	0.05	0.15	0.25
		Visual Impact	0.35	2	3	4	0.07	0.11	0.14
Waste Q/Q	0.15	Quality	0.65	1	3	5	0.10	0.29	0.49
		Quantity	0.35	4	3	2	0.21	0.16	0.11
Risk	0.1	Financial	0.4	4	3	2	0.16	0.12	0.08
		Environmental	0.6	1	3	5	0.06	0.18	0.30
Total							2.27	3.00	3.73

\*I: Incineration, G: Gasification, P: Pyrolysis

Table 2 show that pyrolysis (score = 3.73) was the optimal selected WTE technology for developed countries based on the defined criteria and assessments. Gasification was ranked second (score 3.00), whereas incineration showed the lowest final score (2.27). MCA variations were then chosen under six different weighting scenarios to conduct a sensitivity analyses on the results. This sensitivity analysis indicates the findings would be impacted if the proposed criteria ratings for

the MCA were changed and whether certain criteria are more heavily relied upon. A summary of the category ratings and the six different scenarios as suggested by the expert panel are shown below in Table 3.

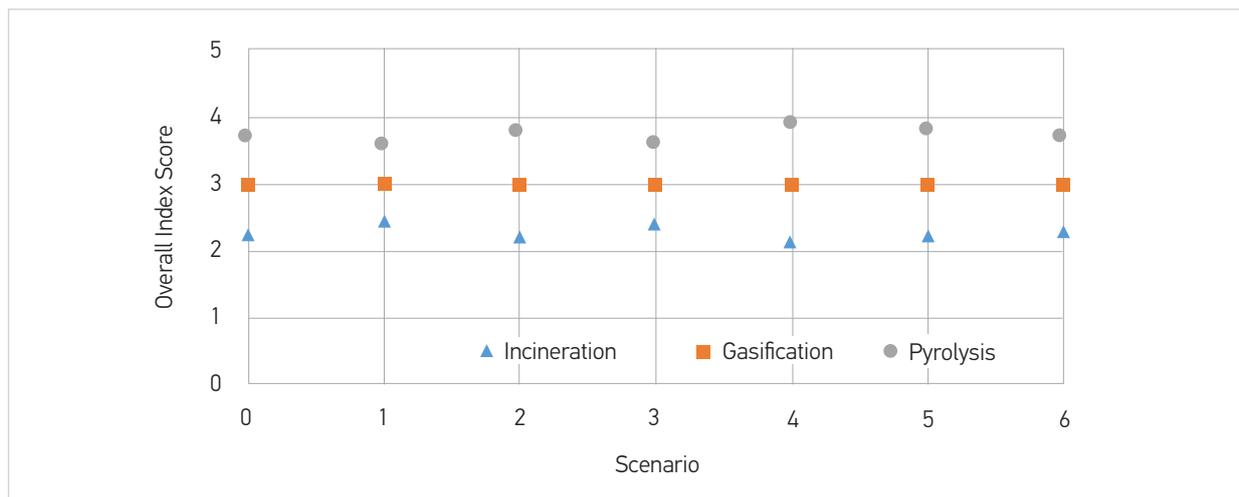
The MCA resulted in an index score for each technology across the six different scenarios set out in Table 3. The resulting index scores are presented in Figure 2. Across the six category weighting scenarios (sensitivity analysis) pyrolysis always received the highest

**Table 3.** Sensitivity analysis on MCA in developed countries

Scenario	Financial	Environmental	Technical	Social Environment	Waste Q/Q	Risk
1	0.45	0.20	0.15	0.05	0.10	0.05
2	0.15	0.50	0.15	0.05	0.10	0.05
3	0.15	0.20	0.45	0.05	0.10	0.05
4	0.15	0.20	0.15	0.35	0.10	0.05
5	0.15	0.20	0.15	0.05	0.40	0.05
6	0.15	0.20	0.15	0.05	0.10	0.35

index score. Insignificant difference in the overall index scores was found between the baseline scenario and the other six scenarios for all WTE technologies. However, the highest difference in the overall index score (7 %) was found in incineration between the baseline and scenario 4. Pyrolysis is still considered a relatively new form of WTE technology and has significant environmental benefits while also effectively

reducing the large volumes of solid waste. Although there is a high cost associated with the technology due to its equipment and its increased complexity compared to gasification and incineration, the overall environmental benefit far outweighs these other parameters. Pyrolysis is ultimately a clean process and has been chosen as the optimal technology for each scenario.

**Fig. 2.** Results of MCA under six weighting scenarios for developed countries

### Multi-Criteria Analysis of a Developing Countries

An analysis of numerous case studies on waste-to-energy facilities in developing countries was conducted and concluded that waste-to-energy still has potential but is struggling for implementation (Vujic, 2015;

Adebe, 2018; Kristiansen, 2018; Qazi et al., 2018). Based on this complete investigation and critical criteria examined, the research study could highlight limiting factors/constraints. There are four main reasons for the difficulty of WTE implementation in the

developing countries that have been covered and they are as followed:

- \_ High financial costs (financial criteria)
- \_ Gap in technical skills that translate to complexity of installation (technical criteria)
- \_ Lack of regulations regarding waste streams (waste Q/Q criteria)
- \_ High risk related to financial and political terms (social acceptance and risk criteria)

Based on these constraints, a second MCA was created to determine how the criteria ratings would affect the optimal WTE technology in a developing country. As a result, the criteria ratings were altered for the financial, environmental, technical, social environment, waste Q/Q and risk. It was deemed that environmental criteria for the WTE facility were not as much of a concern in developing countries since the main objective was to simply provide landfill diversion. Financial criterion was linked to the lack of funding and, therefore, had an increased score to highlight its large impact. The technical criterion was also increased due to the lack of technical skills and how this may prove to be a decisive factor. As such, it is implied that less complicated designs and technologies would possess a better chance of being implemented. In addition, the criteria rating for the social environment was also increased due to the influence the general public has shown to have on a nation's implementation of various technologies. The final criteria rating that was also increased was the risk assessment. This was ultimately executed because of the lack of financial stability that is prevalent in developing countries. In order to increase the weight of a majority of these criteria, the overall criteria rating of the environment was reduced substantially since it was not concluded to be a constraint. Since each criteria ratings also have various assessment ratings, some of these values were adjusted as well. This can be seen in the social environment criteria as the social acceptance parameter was significantly increased. Case studies have shown that the general public have occasionally prevented the implementation of an incinerator because of its negative perception (Jamie et al., 2016). Other assessments such as quality of the waste were

also increased due to the lack of laws regarding segregation of different types of waste in developing countries. The developed MCA can be seen below in Table 4. These weightings have been increased to simply show their higher impact on the MCA and how they have to be thoroughly considered in a developing country.

Even with the altered criteria weightings for developing countries, pyrolysis was still an optimal WTE technology based on the defined criteria and assessments. Similarly to the MCA study of developed countries', gasification was ranked second (score 2.87), whereas incineration showed the lowest final score (2.58). In order to account for uncertainties in the weighted scores, a sensitivity analysis was conducted under different weighting scenarios. In the case of the developing countries, the environmental criteria were determined to be the same in each scenario since the overall use of the technology to reduce large volumes of solid waste was deemed to be more significant than the environmental effects of the technology. The summary of the category ratings and the five different scenarios as suggested by the expert panel are shown below in Table 5.

The MCA resulted in an index score for each WTE across the five different scenarios set out in Table 5. The resulting index scores are presented in Figure 3. Although pyrolysis was still the chosen option, Figure 3 shows that there is a reduced gap in the WTE scores in scenario 2. Furthermore, in scenario 5, the three WTE technologies returned practically the same index scores. This is due to the large capital costs associated with pyrolysis and, therefore, the large risk with the project, which helped to make it a less desirable option in a developing country. Like for developed countries, Figure 3 shows an insignificant difference in the overall index scores between the baseline scenario and the other five scenarios for all WTE technologies in developing countries. However, the highest differences in the overall index scores were found in scenario 3 for incineration (9%) and pyrolysis (10%). Overall, the constraints did help to limit the gap between pyrolysis and the other WTE options in developing countries when compared with MCA of developed countries.

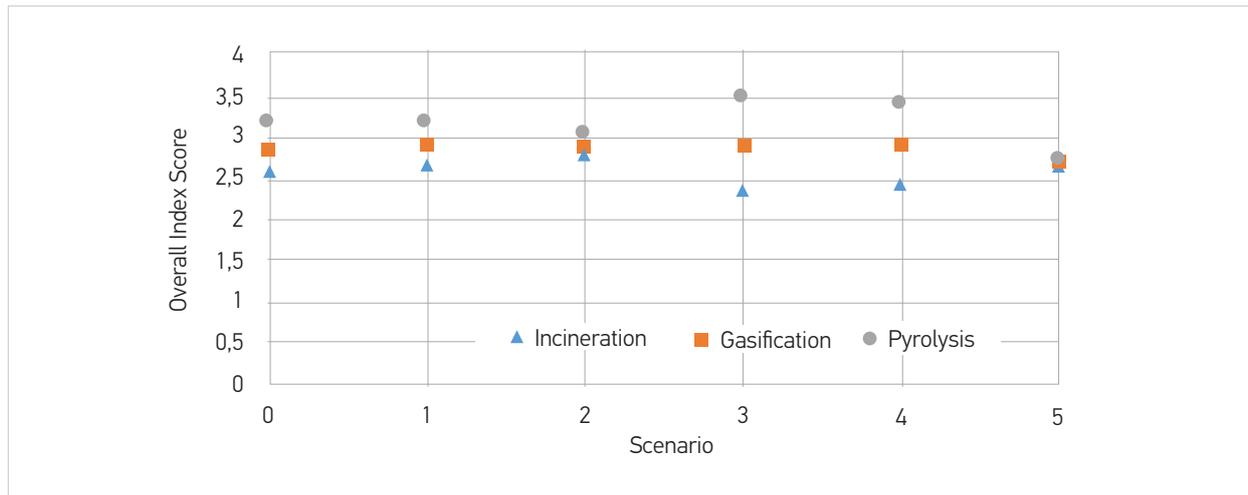
**Table 4.** MCA of WTE technologies in developing countries

Criteria Category	Criteria Rating	Assessment	Assessment Weighting	Factor Rating Site*			Final Scores for Sites*		
				I	G	P	I	G	P
Financial	0.25	Capital Cost	0.4	4	3	2	0.40	0.30	0.20
		Operation and Maintenance Cost	0.6	2	3	4	0.30	0.45	0.60
Environmental	0.05	Production of Hazardous Residue	0.35	2	3	4	0.04	0.05	0.07
		Emission (Air)	0.65	2	3	4	0.07	0.10	0.13
Technical	0.25	Efficiency/ Energy Generation	0.55	2	3	4	0.28	0.41	0.55
		Complexity of Installation	0.45	5	3	1	0.56	0.34	0.11
Social Environment	0.15	Social Acceptance	0.5	1	3	5	0.08	0.23	0.38
		Noise	0.15	4	3	2	0.09	0.07	0.05
		Dust/Odour	0.25	1	3	5	0.04	0.11	0.19
		Visual Impact	0.1	2	3	4	0.03	0.05	0.06
Waste Q/Q	0.15	Quality	0.7	1	3	5	0.11	0.32	0.53
		Quantity	0.3	4	3	2	0.18	0.14	0.09
Risk	0.15	Financial	0.7	4	3	2	0.42	0.32	0.21
		Environmental	0.3	1	3	5	0.05	0.14	0.23
Total							2.58	2.87	3.16

\*I: Incineration, G: Gasification, P: Pyrolysis

**Table 5.** Sensitivity analyses on multi-criteria analyses for developing countries

Scenario	Financial	Environmental	Technical	Social Environment	Waste Q/Q	Risk
1	0.45	0.05	0.20	0.10	0.10	0.10
2	0.20	0.05	0.45	0.10	0.10	0.10
3	0.20	0.05	0.20	0.35	0.10	0.10
4	0.20	0.05	0.20	0.10	0.35	0.10
5	0.20	0.05	0.20	0.10	0.10	0.35

**Fig. 3.** Results of MCA under five weighting scenarios for developing countries

## Conclusions

The MCA was found to be effective in evaluating the different WTE technologies based on environmental, financial, social, technical, and waste quality and quantity aspects for both developed and developing countries. Based on the review of WTE technologies in developed countries, pyrolysis was proven to be the most reliable option even when the sensitivity analysis was implemented. This means that potential biases and subjectivity that may have been incorporated into the choice of ratings for assessment features was eliminated. Based on the MCA created for developing countries, it was seen that pyrolysis was still the most valuable option; however, based on sensitivity analysis, this finding remained constant, but the gap

between the index scores was reduced or eliminated in some cases, which showed the effect of the constraints. Generally, the sensitivity analysis indicated a reasonable weighted score as a result of insignificant differences in the final scores of the technologies at different scenarios. For both developed and developing countries, gasification was ranked second, whereas incineration showed the lowest final score. MCA has proved to be not only a decision support tool but also a base scenario in which future constraints can be developed. Incorporating MCA with other tools, like life cycle assessment (LCA), would be one potential improvement to the decision support systems.

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