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ORIGINAL PAPER

A new framework for assessing the sustainability of municipal solid waste treatment techniques applying multi-criteria decision analysis

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Abstract
In this study, a new multi-criteria decision analysis (MCDA) framework was designed and adopted for assessing the sustainability of solid waste treatment techniques (six treatment techniques) in urban areas of Baghdad (the capital of Iraq). A questionnaire has been developed that contains the four dimensions of sustainability (environmental, economic, social, and technical) and their indicators. These indicators have been studied, analyzed, and evaluated by a group of specialists working on solid waste management. Then the data were modelled adopting the weighted sum model (WSM), weighted product model (WPM) and technique for order preference by similarity to ideal solution (TOPSIS). The main results of the study clearly showed that the sustainability of municipal solid waste treatment in the city of Baghdad is directly related to the four dimensions in variable proportions (weights), and the environmental dimension gained the largest impact (46.9%) while the technical dimension gained the least impact (16.1%) on sustainability. By analyzing the questionnaire data according to the designed framework with reference to the three methods of MCDA (WSM, WPM, and TOPSIS) and in the presence of three Scenarios of the multi-criteria weights, Recycling by Source-Separation (RSS) Technique gained the highest score (0.896) which means that it is the best alternative, while Anaerobic Digestion Technique (AD) gained the lowest score (0.397) which means that it is the worst alternative, other scores are (0.874) for material recycling facility (MRF) Technique, (0.84) for Landfill Technique, (0.813) for Composting Technique, and (0.584) for mass-burn incineration (MBI) Technique.

Keywords MCDA · Multi-criteria weights · MSW treatment techniques · Sustainability · Sustainability dimensions

Introduction

Municipal solid waste (MSW) is a major concern for the economy in third world countries, as MSW management has a clear impact on health, community welfare, and sustainability. Reducing, converting, recycling, and treating solid waste is the series of methods applied in the management of that wastes. In all these methods, the need for waste disposal and treatment has a clear environmental impact on human life (Alam et al. 2022; Wang et al. 2022). The treatment of solid waste and the identification of suitable sites for landfills are difficult tasks faced by government departments because of the dependence on various factors and regulations. Increased population density, limited land availability for burial work, as well as environmental and health impacts have become the major difficulties to overcome (Vyas et al. 2022; Zhang et al. 2022). Environmental factors clearly influence the biophysical characteristics of the landfill in the surrounding area (Su et al. 2021). Solid waste disposal in landfills is the oldest and most practical method (Blair and Mataraarachchi 2021; Zhang et al. 2021). In addition to landfill technology, there are other technical methods used to treat solid waste, such as recycling by source-separation (RSS), material recycling facility (MRF), composting (C), anaerobic digestion (AD), and mass-burn incineration (MBI). Most of the solid wastes in the United States are treated using one of the following methods: Landfill

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(53.8%), MRF (34.5%), and MBI (11.7%) (Eskandari et al. 2016). Aerobic Composting is defined as the biodegradation of organic wastes during aerobic conditions to achieve a stable state of such wastes, which can be used as a soil enhancer (fertilizer), (Graça et al., 2021; Lin et al. 2022). Several researchers (Batista et al. 2021; Liu et al. 2021; Banch et al. 2020; Chowdhury et al. 2021; Schneider et al. 2017; Lim et al. 2016; Ferraro et al. 2019; Vassanadumrongdee and Kittipongvises 2018; Ding et al. 2021; Vyas et al. 2022; Huang et al. 2022; Rasheed et al. 2021; Siqueira and Monteiro Filho 2021) have discussed the advantages, disadvantages and the economic issues of the various MSW treatment techniques. In Iraq, Baghdad Mayoralty which is responsible for MSW management planned to use open dumps or landfills to treat MSW in many cities (more than 70% of Iraqi cities), while about 30% of the solid waste was incinerated by primitive methods in other areas, besides that there is no separation of wastes at the sources, or if it occurs, biodegradable and non-biodegradable wastes are mixed in disposal areas which led to lands and resource degradation and ultimately to environmental pollution and poor health. The lack of land in the urban areas allocated to new dumps reinforced the need to rehabilitate or repair existing landfills (Baghdad 2016).

Sustainable development depends on 3 types of indicators: environmental protection indicators (related to the environmental dimension), economic growth indicators (related to the economic dimension), and strengthening social structures (related to the social dimension). Sustainability is assessed by linking these common indicators to establish and develop the conditions of human dignity and progress towards greater sustainability. The valuation of solid wastes management in terms of sustainability is a complex issue when considering the huge overlap between environmental, economic, and social indicators and the absence of clear data, (Deus et al. 2019; da Silva et al. 2019; Juca et al. 2020; Deus et al. 2020; Paes et al. 2020; Olay-Romero et al. 2020; AlHumid et al. 2019; Fratta et al. 2019; Coşkun et al. 2022).

Therefore, municipal solid waste management should be reconsidered and updated continuously to achieve a balance between solid waste disposal and treatment, and the best sustainability must be the ultimate goal of those responsible for solid waste management. Many studies indicated that waste composition is the main determinant of a waste management strategy, taking into account that each country has its own environmental rules and regulations on solid waste disposal (Kurniawan et al. 2022; Jabeen et al. 2022; Olujobi et al. 2022). Appropriate waste management strategies can only be developed by defining the qualities and quantities of the generated wastes (Cárcamo and Peñabaena-Niebles 2022).

Jeswani and Azapagic, (2016) applied life cycle assessment (LCA) to find the most sustainable option (in terms of electricity generation) out of two options of MSW disposal: incineration and landfilling; the study was performed in the UK. Their results showed that electricity from incineration was lower than that resulting from landfill biogas. (Cobos-Mora et al. 2022) applied a multi-criteria decision analysis using analytical hierarchy process to select a suitable site for transfer stations in a solid waste management system. (Soltani et al. 2015) stated that (MCDA) was the most popular framework to be applied in managing MSW. (Vučijak et al. 2016) confirmed the importance of utilizing multi-criteria decision-making tools to choose the best MSW management scenario among six different choices. (Jovanovic et al. 2016) performed an MCDA on six waste treatment alternatives relying on two (MCDA) methods, strictly speaking the simple additive weighting (SAW) and order preference by similarity to ideal solution (TOPSIS) techniques.

(Coban et al. 2018), utilized multi-criteria decision making methods to evaluate the best (MSW) treatment technique in Turkey, Istanbul, their results indicate that recycling and landfill techniques were the most sustainable. (Wang et al. 2018),in their study on MSW treatment in Chongqing, China, utilizing multi-criteria decision making methods, concluded that (Anaerobic digestion) was the best (MSW) treatment among four alternatives. (Gaur et al. 2022) adopted the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and the (Fuzzy TOPSIS) technique to study, identify, investigate and evaluate six (MSW) management techniques(landfill, incineration, Bio-methane composting, recycling and reuse, and aerobic digestion). Their scenarios relied on nine criteria classified under the major categories of (environmental, social, financial, and profitable). They found that (40% Bio-methane composting + 60% Landfill) was the best scenario.

(Omran et al. 2021) carried out their work to analyze the sustainability of 13 wastewater treatment plants in ten cities, Iraq. Their framework was built using (MCDA) the weighted sum model (WSM).

It is believed, up to our knowledge, that this is the first time a study conducted in Baghdad, Iraq, to evaluate the sustainability of MSW and to develop a designed MCDA framework.

The objectives of this study were to assess the sustainability of MSW treatment techniques in Baghdad city, Iraq relying on field surveys by recording the selected values (by specialists) of the different elements and comparing the four dimensions of sustainability (Environmental, Social, Economical, and Technical), evaluating the impact of those dimensions, then to analyze the recorded data (in terms of a matrix) using the MCDA (WSM, WPM and TOPSIS) to decide the most sustainable MSW treatment technique out of the six selected techniques (Landfill, RSS, MRF, Composting, AD, and MBI), and finally to decide whether the framework is applicable to other countries in the world after comparing the results of the study with the literature in the same field of knowledge.

The study was carried out during the period 2018–2020, and the authors have selected the city of Baghdad as a case study for the high performance of its municipalities in managing MSW than other Provinces in Iraq.

Materials and methods

Study area and data collection

Baghdad/Iraq has an area of about 670 km^2. It is divided into 12 districts; 7 districts are located on the eastern bank of the Tigris River, and the other 5 are on the west bank of the river. The total population of Baghdad city in 2016 was 8,400,000 (eight million and four hundred thousand) people. The urban area of the city is about 269.9 km^2, including the industrial area of about 23.376 km^2, the commercial area of 5.643 km^2, and the domestic area of about 240.881 km^2. This means that the domestic area accounts for about 90% of the urban area. There are no clear and consistent determinants of solid waste disposal in and around Baghdad. These disposal methods have resulted in the increased environmental pollution in and around Baghdad. Figure 1 is an aerial map of Baghdad/Iraq (Google Earth).

Sustainability of MSW treatment techniques

Waste can be classified as MSW, medical, hazardous, industrial, or radioactive waste. Therefore, the application of the concept of sustainability of solid waste treatment techniques and the development and analysis of influencing social, economic, and environmental indicators became among the matters that fall within the strategic plans of most countries. In view of the importance of the technical factor of treatment methods, the technical dimension was added in this study as a fourth influential indicator within the analysis and evaluation of the sustainability of solid waste treatment techniques.

In this research, four dimensions of sustainability were used to fulfil all the requirements of sustainability: environmental, social, economic, and technical dimensions. In order

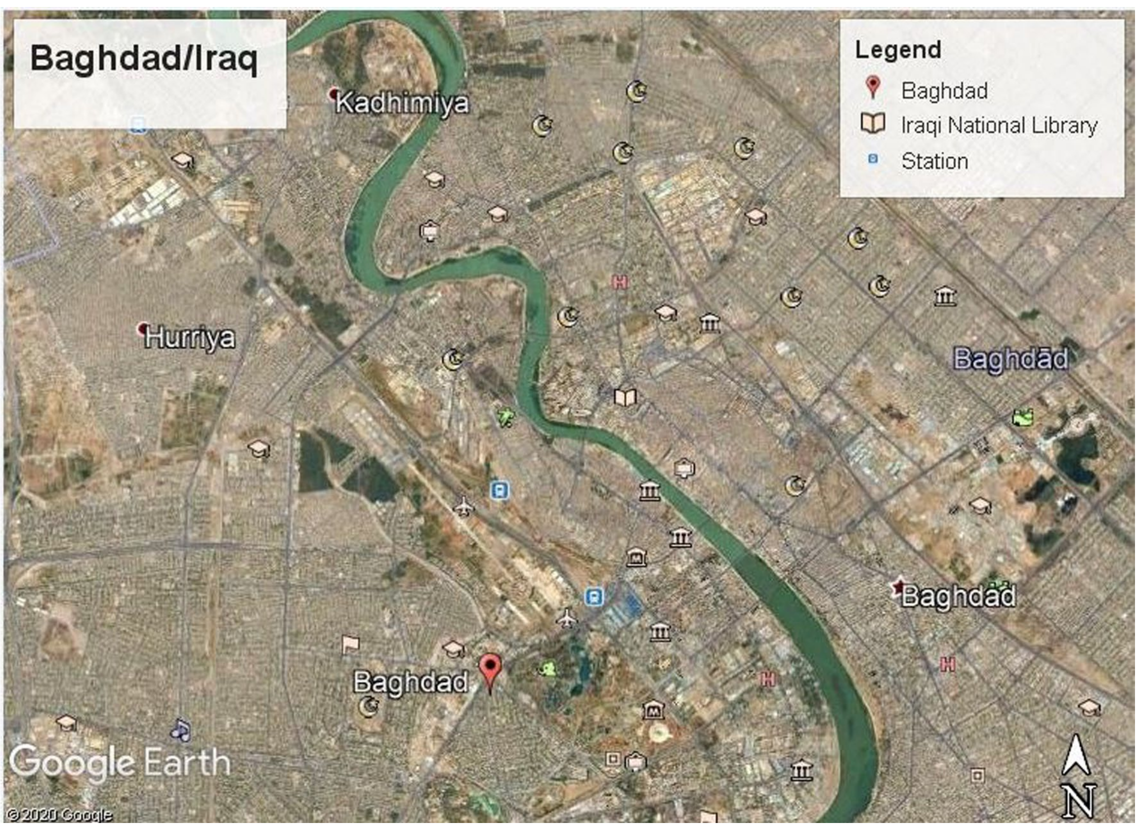

Fig. 1 Google Earth map of Baghdad/Iraq

to achieve a comprehensive vision of sustainability and to select the appropriate technique for the treatment of solid waste, several indicators were used for each dimension to assess the sustainability conditions of treatment techniques.

Multi-criteria decision analysis (MCDA)

MCDA comprises several techniques. In this research paper, three methods were relied on, the weighted sum model (WSM), the weighted product model (WPM) and the technique for order preference by similarity to ideal solution (TOPSIS) (Simsek et al. 2022; Jovanovic et al. 2016; Sadhya et al. 2022). Following is a brief description of these methods:

MCDA/weighted sum model (WSM)

Assuming that the criteria under study are benefit criteria, i.e., the higher the values are, the better it is, then the general model is:

$$A_i^{WSM} = \sum_{j=1}^{n} W_j r_{ij} \tag{1}$$

where: A_i^{WSM} = the total importance of alternative A_i, when all the studied criteria are considered simultaneously. W_j = the relative weight of importance of the criterion C_j.

$$r_{ij} = \frac{a_{ij}}{\left(a_j\right)_{\max}}. \tag{2}$$

For i = 1,2, 3, …………., m, j = 1,2, 3……, nwhere:
a_{ij} = matrix of the alternatives (m) versus the criteria(n) ,
r_{ij} = normalized matrix. ,
$\left(a_j\right)_{\max.}$ = maximum element in the specified criterion.

It is to be noted that a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j.

In order to maximize A_i^{WSM}, then the best way is to choose the value which yields the maximum total performance (Simsek et al. 2022; Jovanovic et al. 2016).

Weighted product model (WPM)

Normalization is accomplished to the matrix (a_{ij}) using Eq. 2 (as stated in Sect. 2.5.1), then:

$$P\left(A_i\right) = \prod_{j=1}^{n} \left(r_{ij}\right)^{Wj} \tag{3}$$

for i = 1, 2,……, m.where: $P\left(A_i\right)$ = weighted product of the ith alternative. r_{ij} = normalized matrix. W_j = the relative weight of importance of criteria j.

Technique for order of preference by similarity to ideal solution (TOPSIS)

The matrix (a_{ij}) is normalized to (r_{ij}) using the following formula:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{n} a_{ij}^2}} \tag{4}$$

for i = 1, 2, …., m, j = 1, 2……, n

Then t_{ij} is calculated using the equation:-

$$t_{ij} = r_{ij} * W_j \tag{5}$$

for i = 1, 2, …., m, j = 1, 2…, nwhere: t_{ij} = weighted normalized matrix

$$W_j = \frac{\sum_{i=1}^{m} a_{ij}}{\sum_{j=1}^{n} \sum_{i=1}^{m} a_{ij}} \tag{6}$$

Then, determine the worst alternative (tw_j) for the jth criteria and the best alternative (tb_j) for the jth criteria. Calculate d_{iw} and d_{ib} from:

$$d_{iw} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj}\right)^2} \tag{7}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{bj}\right)^2} \tag{8}$$

for i = 1, 2, …., mwhere d_{iw} and d_{ib} are L2-norm (which is called the Euclidean norm) distances from the target alternative (A_i) to the worst and best conditions, respectively. Finally, calculate the similarity to the worst condition:

$$S_{iw} = \frac{d_{iw}}{\left(d_{iw} - d_{ib}\right)} \tag{9}$$

for i = 1, 2, …., m S_{iw} = 1 if (A_i) has the best condition. S_{iw} = 0 if (A_i) has the worst condition.

Figure 2 is a flow chart designed to show the main steps of the sustainability assessment of MSW.

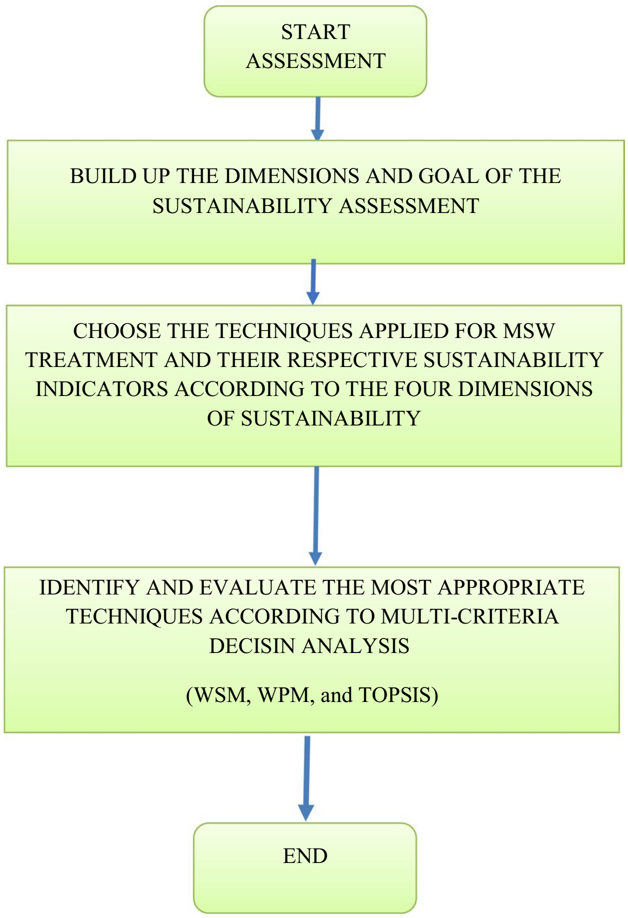

Fig. 2 MSW Sustainability Assessment Flow Chart according to MCDA

Results and discussion

A questionnaire sheet was built containing the four dimensions and their indicators, as shown in Tables 1, 2, 3, and 4. These indicators were studied, analyzed, and evaluated by a group of specialists working in the management of solid waste in the Ministry of Municipalities and Public Works (MMPW). The survey included landfills, secondary, and major transformational stations located within the geographical area of the city of Baghdad, which is the administrative and economic capital of Iraq. In the questionnaire sheet, three assessments were considered: the most sustainable, moderate, and least sustainable for each indicator. Within the research and evaluation methodology, a scale from 1 to 3 was used, given a score of 2 for a moderate sustainability status, 3 for the most sustainable, and 1 for the least sustainable. Specialization and experience of the experts were considered as an important basis for the evaluation process of the solid waste treatment techniques. The questionnaire was answered by 36 specialists in this field. The summary of Tables 1, 2, 3, and 4 represents the sustainability of each MSW treatment technique which is clearly shown in Table 5.

The (Total Score) in Table 5 reflects the effect of sustainability dimensions on the evaluation of treatment techniques. The contribution of dimensions is as follows:—Environmental Dimension (46.9%), Social Dimension (19.9%), Economic Dimension (17.1%), and Technical Dimension (16.1%).

This contribution can be ranked in a descending order as follows:—Environmental Dimension > Social Dimension > Economical Dimension > Technical Dimension.

Consider the following: -

Table 1 Sustainability of the environmental dimension

Indicator	Treatment Method					
	MSW landfill Technique	RSS Technique	MRF Technique	Composting Technique	AD Technique	MBI Technique
Area required for treatment	1	2	2	3	1	2
Emission of polluting gases to the air	1	3	2	2	1	1
Energy consumption reduction	3	1	1	3	2	1
Pollutants removal rate	3	2	2	2	2	2
Stabilization of solid wastes	3	1	1	3	3	2
Emission of unpleasant odors	1	2	2	1	1	1
Noise and disturbance	3	1	1	2	2	1
Use of chemicals	2	2	2	1	1	3
Solid waste volume	1	3	3	2	2	3
Leachate organic load	1	2	2	2	1	3
Biogas volume	1	2	2	3	1	3
Rapid biogas production	1	3	3	2	1	3
Total Score	21	24	23	26	18	25

Table 2 Sustainability of the social dimension

Indicator	Treatment Method					
	MSW landfill technique	RSS technique	MRF technique	Composting technique	AD technique	MBI technique
Social and cultural acceptance	1	3	3	2	1	1
Safety conditions available	3	2	2	2	1	1
Provides job opportunities	3	2	2	2	1	2
Competence requirements and on-site training	3	2	2	1	1	1
Contribute to the development of the community	2	3	3	2	2	2
Total Score	12	12	12	9	6	7

Table 3 Sustainability of the economical dimension

Indicator	Treatment method					
	MSW landfill technique	RSS technique	MRF technique	Composting technique	AD technique	MBI technique
The cost of land and construction	1	3	3	2	1	1
The cost of operation and maintenance	2	1	1	2	1	1
The cost of mechanical and electrical equipment	2	1	1	2	1	1
Salaries and wages of workers in the project	2	3	3	2	1	1
The cost of providing health and safety conditions	2	3	3	2	1	1
The selling cost of treatment products	2	2	2	3	2	1
Total Score	11	13	13	13	7	6

Table 4 Sustainability of the technical dimension

Indicator	Treatment method					
	MSW landfill technique	RSS technique	MRF technique	Composting technique	AD technique	MBI technique
The durability of hardware and equipment	2	3	3	2	1	2
Reliability and flexibility of the treatment method	3	3	3	2	1	2
The simplicity of construction and installation of equipment	3	2	2	2	1	1
The simplicity of operation and maintenance	3	1	1	1	1	2
Total Score	11	9	9	7	4	7

C_1 = Environmental criteria, C_2 = Social criteria,

C_3 = Economical criteria, and C_4 = Technical criteria.

A_1 = Landfill technique alternative, A_2 = RSS technique alternative,

A_3 = MRF technique alternative, A_4 = Composting technique alternative,

A_5 = AD technique alternative, and A_6 = MBI technique alternative.

W_1 = weight of the environmental criteria, W_2 = Weight of the social criteria,

W_3 = weight of the economic criteria, and W_4 = Weight of the technical criteria.

To increase the confidence in the results of the multi-criteria evaluation, hence increasing the accuracy of the decision taken, three Scenarios of the multi-criteria weights were taken into account.

These three scenarios were chosen arbitrarily as follows: -

Scenario No. 1 ($W_1 = 47\%$, $W_2 = 20\%$, $W_3 = 17\%$, $W_4 = 16\%$).

Scenario No. 2 ($W_1 = 25\%$, $W_2 = 25\%$, $W_3 = 25\%$, $W_4 = 25\%$).

Table 5 Sustainability matrix of MSW treatment techniques

	Technique (alternative)		Dimension (criterion)	
	Environmental dimension ($j=1$)	Social dimension (j=2)	Economic dimension ($j=3$)	technical Dimension ($j=4$)
MSW landfill Technique ($i=1$)	21	12	11	11
RSS technique ($i=2$)	24	12	13	9
MRF technique ($i=3$)	23	12	13	9
Composting technique ($i=4$)	26	9	13	7
AD technique ($i=5$)	18	6	7	4
MBI technique ($i=6$)	25	7	6	7
Total score	137	58	50	47

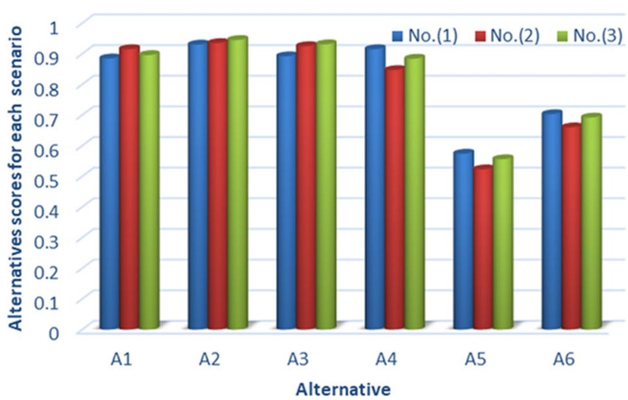

Fig. 3 Alternatives Scores for each Scenario resulting from WSM method

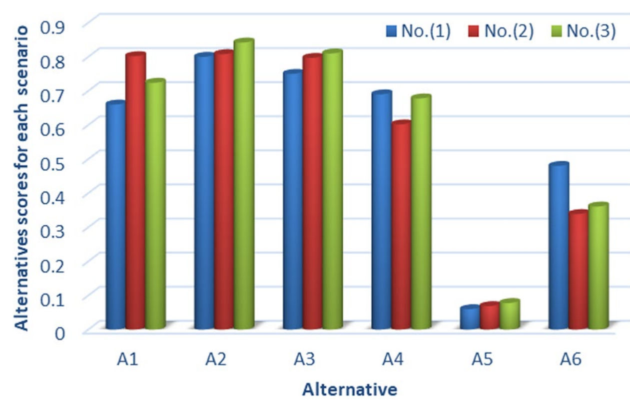

Fig. 5 Alternatives Scores for each Scenario resulting from TOPSIS method

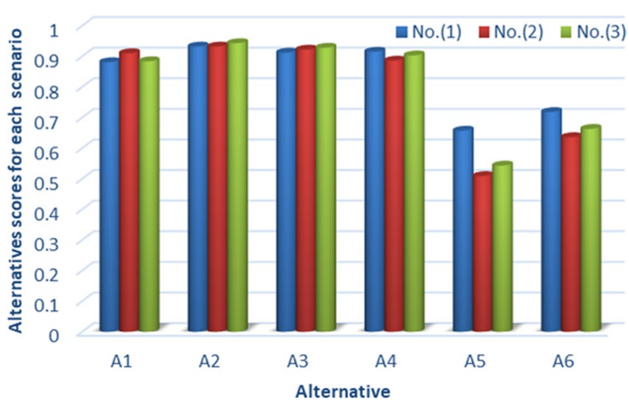

Fig. 4 Alternatives Scores for each Scenario resulting from the WPM method

Scenario No. 3 ($W_1=35\%$, $W_2=25\%$, $W_3=25\%$, $W_4=15\%$).

MCDA/WSM method

Applying Eq. 2 to the matrix presented in Table 5(and after the substitution of characters) results a normalized matrix (NM), for the interested reader this matrix is displayed in Appendix 1 as an attachment. Applying Eq. 1 to the (NM) and the weights in scenarios 1, 2, and 3 results in the alternatives scores according to scenarios as depicted in Fig. 3.

MCDA/WPM method

Applying Eq. 3 to the (NM) mentioned in the (**MCDA/WSM method)** section yielded the alternatives scores according to the scenarios resulting from the WPM method. Figure 4 depicts these scores.

MCDA/ TOPSIS method

Applying Eq. 4 to the matrix presented in Table 5 (and after the substitution of characters) results the normalized matrix (r_{ij}), this matrix is presented in Appendix 1 as an attachment.

Applying Eqs. (5,7, 8 and 9) to the data presented in the normalized matrix (r_{ij}) and varying the weights according to the three scenarios resulted in the similarity to the worst condition(Sample Calculations are presented in Appendices 2 and 3). Similarity to the worst condition in Scenario No.1 for all treatment techniques is as follows: -

$S_{1W} = 0.66$, $S_{2W} = 0.80$, $S_{3W} = 0.75$, $S_{4W} = 0.69$, $S_{5W} = 0.06$, $S_{6W} = 0.48$.

The above results of similarity indicate that the second alternative (RSS treatment technique) is far away from the worst condition, while the fifth alternative (AD treatment technique) is very close to the worst condition. Figure 5 depicts the results for the 3 Scenarios.

The calculated average values of scores for the 3 methods and the 3 Scenarios are summarized as follows: -

$A_1 = 0.84$, $A_2 = 0.896$, $A_3 = 0.874$, $A_4 = 0.813$, $A_5 = 0.397$, and $A_6 = 0.584$.

Figures 3, 4 and 5 and the calculated average values of scores (for the 3 methods and the 3 Scenarios) agree that alternative (A_2), RSS treatment technique is the most sustainable alternative in Iraq, and that alternative (A_5), the AD treatment technique is the worst alternative in Iraq. Also, it is obvious that (A_3), the MRF technique is a good substitute for the RSS treatment technique here in Iraq.

Comparing the above results with the results of references, (Wang et al. 2018; Gaur et al. 2022; Coban et al. 2018), as prescribed in the [Introduction/page 3], it is evident that these studies reached to a different option of MSW treatment techniques. This is anticipated as the frame work procedure of MCDA in the current study differs from other studies, also the four dimensions with their indicators and the characteristics of MSW vary according to the geographic location around the world. To be specific the Technical Dimension was not studied by most of the recent literature.

The results also show that the current plans and actions utilised by the Mayoralty of Baghdad (Baghdad 2016), through using landfills to treat MSW(as prescribed in the Introduction/page 2) must be substituted with the RSS treatment or MRF treatment techniques.

Conclusion

The results indicate that sustainability of MSW treatment in Iraq/Baghdad is directly related to the (Environmental, Social, Economic, and Technical) Dimensions, in a variable contribution: [(46.9%) for Environmental, (19.9%) for Social, (17.1%) for Economic, and (16.1%) for Technical], and that the environmental dimension gained the largest impact, technical dimension gained the least impact on sustainability, noting that the technical term has proved its impact on sustainability. For the selected sample (in Iraq/ Baghdad), out of the six studied MSW treatment techniques the scores[resulting from the three methods of MCDA (WSM, WPM, and TOPSIS) and in the presence of three scenarios of the multi-criteria weights] were summarized as follow: RSS (0.896), MRF (0.874), Landfill (0.84), Composting (0.813), MBI (0.584), and AD (0.397), it was concluded that the RSS technique was the most sustainable, while the AD technique was the least sustainable, that MRF technique might become a good substitute to the RSS technique. The authors recommend that Mayoralty of Baghdad must change the plans of MSW management and to migrate the use of Landfill treatment technique to RSS treatment or MRF treatment techniques, to carry out the study on a larger sample with more than three scenarios (covering more than one Governorate in Iraq) to increase the confidence limits of the results, reducing the error term, which will enhance the decision making, finally the authors recommend to apply the framework to Countries around the World (especially the neighbours of Iraq).

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