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Water Practice & Technology Vol 00 No 0
doi: 10.2166/wpt.2021.013

Sustainability assessment of wastewater treatment techniques in urban areas of Iraq using multi-criteria decision analysis (MCDA)

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Abstract

Sustainable development is based on environmental, social, economic, and technical dimensions. In this study, the sustainability of wastewater treatment techniques in urban areas of Iraq was assessed using a multi-criteria decision analysis (MCDA)/the weighted sum model (WSM). The analysis was performed on 13 operating wastewater treatment plants in 10 provinces, Iraq, using a questionnaire sheet with the assistance of 52 specialists in the Ministry of Municipalities and Public Works, Iraq. Four types of wastewater treatment techniques (Conventional Treatment, Oxidation Ditches, Aeration Lagoons, and membrane bio-reactor (MBR)) were assessed. The environmental, social, economic, and technical dimensions were represented by 11, 5, 7, and 4 indicators, respectively. The main results of this study indicate that the sustainability of MBR recorded the highest total importance; the order of the total importance from the highest to the lowest was: MBR > Oxidation Ditches > Aeration Lagoons > Conventional Treatment. The environmental dimension proved its dominance in the four studied treatment techniques' sustainability as it recorded the maximum contribution to sustainability. While the technical dimension recorded the least contribution to sustainability, the order from the highest to the lowest was: Environmental Dimension > Economic Dimension > Social Dimension > Technical Dimension.

Key words: MBR, MCDA, sustainability, sustainability dimensions, wastewater treatment techniques, WSM

Highlights

- A multi-criteria decision analysis (MCDA) was used to assess the sustainability of 13 WWTP.
- The weighted sum model (WSM) was to validate the analysis.
- Chemical Treatment, Oxidation Ditch, Aeration Lagoon, and membrane bio-reactor (MBR) were studied.
- 31 environmental (En), social (S), economical (E), and technical (T) indicators were analysed.
- The effects of these indicators on sustainability of the WWTP was: En > E > S > T

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doi: 10.2166/wpt.2021.013

INTRODUCTION

The theme of sustainability has gained considerable attention in recent years via environmental organizations and departments worldwide, particularly with regard to the issues of addressing the pollution of the basic elements of the environment (water, air, soil) and the sustainability required for treatment techniques (Furley *et al.* 2018). For instance, water bodies are facing severe deterioration due to the discharge of wastewaters, which results in a remarkable increase in heavy metals (Abdulla *et al.* 2020; Abdulraheem *et al.* 2020), coloring agents (Abdulhadi *et al.* 2019; Aqeel *et al.* 2020), nutrients (Alenezi *et al.* 2020; Al-Marri *et al.* 2020; Khalid *et al.* 2020a, 2020b), phenols (Emamjomeh *et al.* 2020a, 2020b), Gesomin (Ryecroft *et al.* 2019), fluoride (Alhendal *et al.* 2020), organic pollutants (Abdulhadi *et al.* 2021; Alyafei *et al.* 2020; Zanki *et al.* 2020), viruses and bacteria (Hashim *et al.* 2020a, 2020b; Hashim *et al.* 2021; Khalid *et al.* 2020a, 2020b), turbidity (Alenazi *et al.* 2020; Alnaimi *et al.* 2020) and other pollutants (Emamjomeh *et al.* 2020a, 2020b; Hashim *et al.* 2020a, 2020b; Kadhim *et al.* 2020b; Mohammed *et al.* 2020). Air quality is also deteriorating due to the increasing emissions from human activities (Grmasha *et al.* 2020; Kadhim *et al.* 2020a; Shubbar *et al.* 2020a, 2020b), such as cement industries (Majdi *et al.* 2020; Shubbar *et al.* 2020a, 2020b), which resulted in an increase in global temperature (Salah *et al.* 2020a, 2020b, 2020c, 2020d; Zubaidi *et al.* 2020a, 2020b), and an increase in the rain intensity (Salah *et al.* 2020a, 2020b, 2020c, 2020d; Zubaidi *et al.* 2020a, 2020b). The term sustainable development was introduced for the first time through the adoption of the strategic concept for the protection and sustainability of biodiversity by the International Union for the Conservation and Protection of Nature (IUCN) of 1980, which noted that sustainable development should take into account social, environmental and economic factors when considering the aspects of human life. The concept of sustainable development is based on the main point that economic, environmental, and social factors cannot be separated from each other. Some sources have shown that sustainable development is the one that meets the needs of the current generation without compromising the ability of future generations to meet their own needs (Song *et al.* 2019).

The Wastewater Management System is a foundation for the protection of public health and the modern environment. The system also makes sustainability more visible and achieves best practices for building standard specifications for wastewater transfers from piping networks and treating them within treatment plants. The sustainability of wastewater treatment projects is determined by achieving the best assessment of operational, economic, and environmental efficiency (Muga & Mihelcic 2008).

Indicators affecting sustainability were based on their suitability to different wastewater treatment technologies and their ability to identify or move towards balanced sustainability. Under the assumption of equal weights for the specific dimensions (environmental, social, economic, and technical) of the assessed process, a set of indicators have been proposed to achieve the dimensions required to achieve the overall sustainability of treatment system technologies that treat different discharges of wastewater. Many scientific sources relied on the construction of indicators of these dimensions, as shown below (Arroyo & Molinos-Senante 2018; Delanka-Pedige *et al.* 2020):

Environmental dimension

Its constructed indicators were: -1- Exploitation of land, 2- Air Pollution, 3- Energy, 4- Pollutants removal, 5-Toxic substances, 6-Odor emission, 7-Nuisance, and noise, 8-Use of chemicals, 9-Sludge production, 10-Sludge quality, 11-Urbanization.

Social dimension

Its constructed indicators were: -1-Cultural acceptance (Awareness, Cultural heritage, Quality of life, Public participation, Responsibility, and Community size served), 2-Public safety, 3-Creation of employment, 4- Competence and training requirements, 5- Local development.

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Economic dimension

Its constructed indicators were: 1-Construction cost, 2-Operation, and maintenance cost, 3-Land cost, 4-Cost of resources used (mechanical and electrical types of equipment and any value-added), 5-Salaries and wages of labors, 6-Expenditure on health and safety, 7- Economic performance of production and waste management.

Technical dimension

Its constructed indicators were:(1) Durability, (2) Reliability and Flexibility, (3) Ease of construction, and (4) Complexity.

The sustainability of wastewater treatment technologies in Egypt was assessed by Ahmed *et al.* (2017). There proposed weights of the three dimensions of sustainability were (Environmental 30%, Economic 40%, and Social 30%).

An assessment of wastewater treatment technologies in the petrochemical industry was conducted by Meerholz & Brent (2013). They used multi-criteria decision analysis (MCDA) as a decision-making tool to compare and evaluate the different wastewater treatment technologies in the petrochemical industry (Adem & Geneletti 2018). According to their study, the calculated MCDA for different wastewater treatment technologies was ranked as follows: High-performance compact reactor (HCR) < Pure Oxygen Dosing < Activated Sludge < Membrane Bioreactor (MBR) < Biological Aerated Filters (BAF) < Alternate Aeration Technology < Moving Bed Biofilm Reactor (MBBR) < Retrofit MBBR. They concluded that Retrofit MBBR was the most feasible wastewater treatment technology, while HCR was the least desired technology.

A proposed sustainability assessment framework for the prioritization of urban sewage treatment technologies was suggested by Ren *et al.* (2020). They studied four urban sewage treatment technologies and concluded that the anaerobic–oxidation ditch technology performed the highest sustainability for urban sewage treatment.

Yao *et al.* (2020) developed a novel multi-criteria group decision-making framework to evaluate four types of wastewater treatment techniques (WTTS), (Anaerobic-Anoxic-Oxic, Triple-Oxidation Ditch, Anaerobic-Single-Oxidation Ditch, and Sequencing-Batch-Reactor Activated Sludge). They concluded that suitable WTT might differ according to the city's size in developing or developed countries.

Kalbar *et al.* (2012) showed that it was challenging to select the most appropriate wastewater treatment alternative under the 'no scenario' condition and that the decision-making methodology effectively identifies the most appropriate wastewater treatment alternative for each of the scenarios.

Lizot *et al.* (2020) developed a multi-criteria methodology based on the analytical hierarchy process (AHP) and ELECTRE II methods to select the best wastewater treatment systems. They designed a methodology with 20 alternatives and 12 criteria for this application; the adopted dimensions of sustainability were economic, social, technical, and environmental.

Hadipour *et al.* (2016) developed a multi-criteria decision-making model (MCDM) for the selection of the best wastewater reuse system in Iran. Their model manages four criteria, 16 sub-criteria and five alternatives.

To the best of the authors' knowledge, this is the first time the sustainability of wastewater treatment techniques in Iraq, has been studied relying on the MCDA framework.

The objectives of this study are:

1. To assess the sustainability of wastewater treatment techniques in urban areas of Iraq through a field survey by recording the appropriate values of the different elements comprising the four dimensions (Environmental, Social, Economic and Technical) of sustainability.

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2. To analyze the recorded data using the MCDA to decide the most sustainable (in terms of total importance) wastewater treatment technique out of the four selected techniques (Conventional, Oxidation Ditches, Aeration Lagoons, and MBR).

This study was performed on (13) thirteen operating plants located within ten provinces of Iraq for the period (1/1/2017) to (31/12/2017), with the assistance of 52 specialists in the Ministry of Municipalities and Public Works/Iraq (MMPW). Wastewater treatment plant capacities ranged between (45,000–100,000) m^3/day.

MATERIALS AND METHODS

Wastewater treatment systems

The selection of technical systems used in wastewater treatment projects is based on several factors, the most important of which is to achieve the environmental, technical and economic feasibility of such projects. The design of technical systems is one of the difficult tasks of engineering agencies to determine the levels of treatment required to meet environmental requirements, taking into consideration the socio-economic conditions of countries (Da Silva *et al.* 2020).

The suspended growth process (aeration basins) was the most widely used in the designed applications as it was convenient to a wide range of wastewater discharges, especially the large ones, while the attached growth film process was convenient for small discharges.

The traditional Activated Sludge Treatment (conventional treatment) and Extended Aeration are good examples for the application of the suspended growth process (Metcalf 2003).

Extended aeration and its modifications

There are several modifications of this method, including:

1. Oxidation Ditches.
2. SBR method (Sequencing Batch Reactor).
3. ISAM method (Integrated Surge Anoxic Mix).
4. MBR method (Membrane Bio-Reactor).
5. RBC method (Rotating Biological Contactor).

The above modifications are inconvenient for large discharges; the USA specifications show that these modifications are suitable only for discharges less than 10,000 m^3/day; in general, the specifications of the Environmmetal Protection Agency (EPA) do not recommend using these methods to discharges more than 20,000 m^3/day. To solve this problem, many designs and consulting companies for wastewater treatment projects in large cities have tended to divide the work of treatment plants into several stages to meet the EPA's requirements (Wexford 1997; Metcalf 2003).

Oxidation Ditches are the most widely used method in wastewater treatment projects in Iraq, while the MBR Method (Membrane Bio-Reactor) has become familiar recently for its competence with limited use.

The method of treatment by extended aeration is easy to implement for the treatment units in addition to simplicity in operation and flexibility.

Applications of treatment methods in Iraq

In Iraq, the departments responsible for the management of wastewater treatment works have tended to use extended aeration systems to treat wastewater in many cities (more than 85% of Iraqi cities).

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While the use of conventional treatment systems (old existing projects) was limited to cities characterized by high population densities (city centers) such as Baghdad, Karbala, Mosul, and Basra, knowing that the current designs for Waste Water Treatment Plants (WWTPs) in these cities have also used the extended aeration system in wastewater treatment for its districts and sub-districts, the above facts being documented by the MMPW.

Reuse of treated wastewater

The reuse of treated wastewater is becoming an attractive method of increasing the utilization of water resources, particularly in hot climate regions, like the countries of the Middle East region (for example, Iraq). Its application improves the soil and increases the value of the crops. The characteristics of treated wastewater have the capability for irrigation and fertilization of the soil. The treated wastewater can be used to irrigate trees like palms and other non-sensitive plants (Kennedy & Tsuchihashi 2005; Toze 2006; Omran *et al.* 2019).

Sustainability of WWTP

Various assessment tools were used to demonstrate the sustainability of wastewater treatment technologies such as economic analysis, environmental analysis, energy analysis, and life cycle assessment (Salvador *et al.* 2014).

These wastewater treatment techniques include the Conventional Treatment, Oxidation Ditches, Aeration Lagoons, and MBR method.

The identification of indicators depends on a variety of factors such as community culture, civilization development of the community, the geographical location of the country, population, and characteristics of their daily activities (Chen *et al.* 2020).

Some studies have used several indicators in the assessment process, but only one treatment technique was evaluated, and one dimension was used to assess sustainability, such as the assessment of environmental or economic impacts only (Padilla-Rivera *et al.* 2016).

Other studies were limited to assessing the environmental and economic dimensions of sustainability and did not address the social dimension and its impact on assessing the sustainability of wastewater treatment technologies (Dixon *et al.* 2003), which did not fully absorb the required sustainability that is supposed to balance between economic, environmental, and social considerations.

In this research, a fourth dimension representing the technical aspect of treatment systems was added to meet all the requirements of comprehensive sustainability.

All environmental, economic, social, and technical visions should be integrated in order to achieve a comprehensive vision of sustainability and the choice of appropriate technology for wastewater treatment.

Multi-criteria decision analysis (MCDA)

This analysis comprises many methods; the appropriate method chosen here in this research article is the weighted sum model (WSM) (Ben-Arieh 2002), or weighted linear combination (WLC) (Malczewski & Rinner 2015), or simple additive weighting (SAW) (Gherghel *et al.* 2020). Following is a brief description of the WSM method:

For an MCDA problem defined on (m) alternatives and (n) decision criteria, if it is assumed that all the criteria are benefit criteria, that is, the higher the values are, the better it is, then suppose that w_j denotes the relative weight of importance of the criterion C_j and a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j. The total importance of alternative A_i

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(i.e., when all the criteria are considered simultaneously), denoted as $A_i^{\text{WSM-score}}$ is defined as follows:

$$A_i^{\text{WSM}-\text{score}} = \sum_{j=1}^{n} w_j a_{ij} \tag{1}$$

For I = 1,2, 3, ;…………., m

To reach the maximization case, the best alternative is to choose the one that yields the maximum total performance value (Ben-Arieh 2002).

RESULTS AND DISCUSSION

A questionnaire containing the assessment of dimensions (Environmental, Social, Economic and Technical), and their indicators has been prepared. It was evaluated by a number of specialists in wastewater treatment plants in the MMPW. The survey included thirteen operating plants located within the ten provinces of Iraq. The evaluation included the use of three assessments: most sustainable, moderate sustainable, and least sustainable. Within the research methodology and evaluation axes, a scale of 1–3 was used, where 2 represents the state of moderate sustainability, 3 is the most sustainable, and 1 is the least sustainable. Specialization and experience were considered as the basis for the evaluation process within the treatment plants selected to answer the questionnaire. Four specialists were selected at each treatment plant to answer the questionnaire, and the total number of specialists included in the survey was fifty-two. Figure 1 is a flow chart showing the main steps of sustainability assessment in this study.

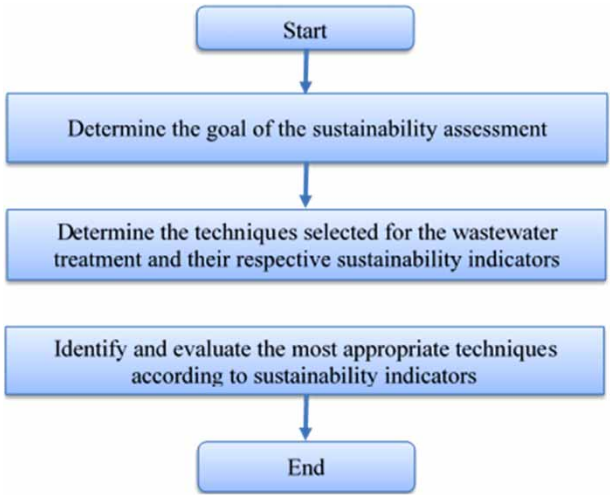

Figure 1 | Flow chart of sustainability assessment.

Table 1 illustrates the results of different indicators (11 indicators) of the environmental dimension of sustainability in terms of studied treatment techniques, together with the total score.

Table 2 illustrates the results of different indicators (5 indicators) of the social dimension in terms of studied treatment techniques, together with the total score.

Table 3 illustrates the results of different indicators (7 indicators) of the economic dimension in terms of studied treatment techniques, together with the total score.

Table 4 illustrates the results of different indicators (4 indicators) of the technical dimension in terms of studied treatment techniques, together with the total score.

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Table 1 | Assessment of environmental dimension of sustainability

Indicator \ Treatment method	Conventional treatment	Oxidation ditches	Aeration lagoons	MBR*
Land exploitation	2	2	1	3
Air pollution	1	3	2	3
Energy consumption	3	1	1	2
Pollutants removal	2	2	2	3
Toxic substances	2	2	2	3
Odor emission	1	3	2	3
Nuisance and noise	2	2	2	3
Use of chemicals	2	3	2	3
Sludge production	1	2	2	3
Sludge quality	3	3	3	3
Urbanization	1	3	1	3
Total score	20	26	20	32

*MBR, Membrane Bio-Reactor.

Table 2 | Assessment of social dimension of sustainability

Indicator \ Treatment method	Conventional treatment	Oxidation ditches	Aeration lagoons	MBR
Cultural acceptance	1	3	2	3
Public safety	1	3	3	3
Employment creation	2	3	3	3
Competence and training requirement	2	2	2	3
Local development	2	3	3	3
Total score	**8**	**14**	**13**	**15**

Table 3 | Assessment of economic dimension of sustainability

Indicator \ Treatment method	Conventional treatment	Oxidation ditches	Aeration lagoons	MBR
Construction cost	1	2	2	3
Operation and maintenance cost	3	2	2	1
Land cost	3	2	2	3
Cost of resources used	1	2	2	1
Cost of salaries and wages of labors	1	2	2	1
Expenditure on health and safety	1	3	2	3
Economic performance of production and waste management	1	3	3	3
Total score	**11**	**16**	**15**	**15**

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Table 4 | Assessment of technical dimension of sustainability

Indicator \ Treatment method	Conventional treatment	Oxidation ditches	Aeration lagoons	MBR
Durability	2	3	2	3
Reliability and flexibility	2	3	2	3
Ease of construction	1	3	3	1
Complexity	2	3	3	1
Total score	**7**	**12**	**10**	**8**

Table 5 illustrates the sustainability of wastewater treatment techniques taking into account the 4 dimensions (Environmental, Social, Economic, and Technical).

Table 5 | Sustainability of wastewater treatment techniques taking into account all dimensions

Treatment method \ Dimension	Environmental dimension	Social dimension	Economic dimension	Technical dimension
Conventional treatment	20	8	11	7
Oxidation ditches	26	14	16	12
Aeration lagoons	20	13	15	10
MBR	32	15	15	8
Total score	**98**	**50**	**57**	**37**

Referring to Table 5, it is obvious that the environmental dimension gained the maximum contribution to sustainability while the technical dimension gained the minimum contribution to sustainability. The contribution of dimensions to sustainability followed the following order: - (Environmental Dimension) > (Economic Dimension) > (Social Dimension) > (Technical Dimension).

Figure 2 is a pie chart that depicts the contribution (%) of the 4 dimensions to sustainability.

According to Equation (1), assuming that the weights are common for all dimensions (25% each), and that:

$A_1^{WSM-score}$ = the total importance of the Conventional Treatment technique.
$A_2^{WSM-score}$ = the total importance of the Oxidation Ditches technique.
$A_3^{WSM-score}$ = the total importance of the Aeration Lagoons technique.

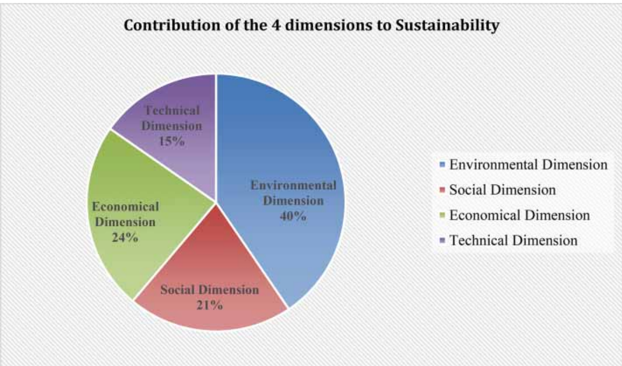

Figure 2 | Contribution (%) of the four dimensions to sustainability.

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$A_4^{WSM-score}$ = the total importance of the MBR technique.
W_1 = weight of environmental dimension, W_2 = weight of social dimension,
W_3 = weight of economic dimension, and W_4 = weight of technical dimension

Then:

$$A_1^{WSM-score} = 0.25*(20 + 8 + 11 + 7) = 11.5$$
$$A_2^{WSM-score} = 0.25*(26 + 14 + 16 + 12) = 17.0$$
$$A_3^{WSM-score} = 0.25*(20 + 13 + 15 + 10) = 14.5$$
$$A_4^{WSM-score} = 0.25*(32 + 15 + 15 + 8) = 17.5$$

Other combinations of weights (scenarios) and the resulting treatment technique with the maximum sustainability are presented in Table 6.

Table 6 | Different scenarios of weights combinations to decide the treatment technique with the highest sustainability (total importance)

Scenario	Weight combination	Total importance	Rank
1	$W_1 = 0.40$	$A_1^{WSM-score} = 13.37$	4
	$W_2 = 0.21$	$A_2^{WSM-score} = 18.98$	2
	$W_3 = 0.24$	$A_3^{WSM-score} = 15.83$	3
	$W_4 = 0.15$	$A_4^{WSM-score} = 20.75$	1
2	$W_1 = 0.25$	$A_1^{WSM-score} = 11.5$	4
	$W_2 = 0.25$	$A_2^{WSM-score} = 17.0$	2
	$W_3 = 0.25$	$A_3^{WSM-score} = 14.5$	3
	$W_4 = 0.25$	$A_4^{WSM-score} = 17.5$	1
3	$W_1 = 0.2$	$A_1^{WSM-score} = 10.6$	4
	$W_2 = 0.2$	$A_2^{WSM-score} = 16$	1
	$W_3 = 0.2$	$A_3^{WSM-score} = 13.6$	3
	$W_4 = 0.4$	$A_4^{WSM-score} = 15.6$	2

Figure 3 is a pictorial representation of the results presented in Table 6, and Figure 4 depicts the average total importance (for 3 scenarios) of the 4 treatment techniques.

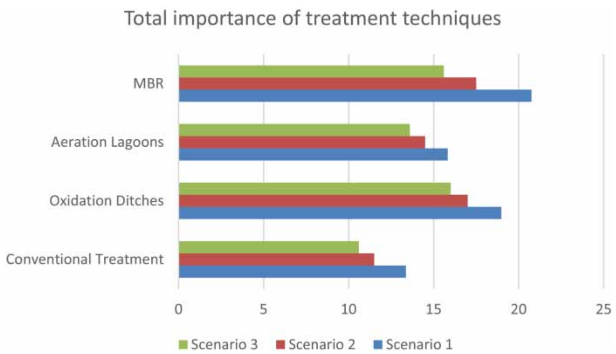

Figure 3 | Total importance of treatment techniques.

It is evident from the above results that MBR wastewater treatment gained maximum sustainability. It is to be noted that MBR gains the maximum sustainability when the environmental dimension is

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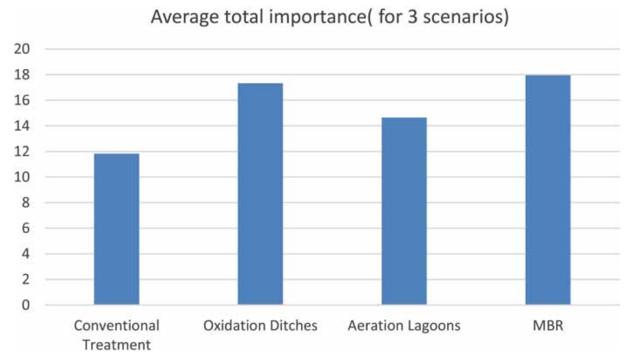

Figure 4 | Average total importance (for 3 scenarios).

dominating other dimensions (which is the real case as shown in Figure 2), for the case when the technical dimension is dominating, then (Oxidation Ditches) will gain the maximum sustainability as shown in Table 6 (Scenario 3); this is in accordance with the results documented by Yao *et al.* (2020). The sustainability of wastewater treatment techniques followed the following order: (MBR) > (Oxidation Ditches) > (Aeration Lagoons) > (Conventional Treatment).

CONCLUSIONS

The findings of the study clearly showed that the sustainability of wastewater treatment in Iraq is directly related to the four dimensions (environmental, social, economic, and technical). The environmental dimension proved its dominance in the sustainability of the 4 studied treatment techniques as it recorded the maximum contribution to sustainability, while the technical dimension recorded the least contribution to sustainability. Out of the 4 studied wastewater treatment techniques, the MBR treatment method was the most sustainable for the selected sample in Iraq as far as the environmental dimension is dominating, while Oxidation Ditches will gain maximum sustainability if the technical dimension is dominating. It is advisable to carry out the same study on a larger sample to increase the confidence limits of the results, which will refine the decision making, and to compare between different methods of MCDA like weighted product method (WPM), AHP, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method.

ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to the staff of the General Manager for Sewage Works in Iraq and the Ministry of Higher Education and Scientific Research for their complete cooperation and offering assistance and help during the course of this research.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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doi: 10.2166/wpt.2021.013

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