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Assessment of secondary wastewater treatment technologies for agricultural reuse in Rafah, Gaza Strip: Application of evidential reasoning method

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ABSTRACT

Water scarcity is a global issue confronting the present generation, particularly acute in arid regions such as Palestine. Treated wastewater reuse is recognized as a strategic solution. The challenge in obtaining effluent quality that meets the reuse requirements of the area is how to select the best treatment technology. A multi-criteria decision-making method is necessary for assessing the sustainability of different wastewater treatment technologies. This study selected the most sustainable secondary treatment technology that could produce quality effluent for agricultural reuse at the Rafah wastewater treatment plant in the Gaza Strip. The Evidential Reasoning method was applied to evaluate the sustainability of sand filters, constructed wetlands, activated sludge, and bio-tower technologies. The evaluation was based on four sustainability dimensions and thirty-five indicators. The dimensions and indicators were obtained from a review of related literature and validated by experts. Using a questionnaire, the judgment of local experts (professionals working on the project, selected university professors, and members of the agricultural NGOs) was used to evaluate the dimensions and indicators qualitatively. Data analysis was done using the Intelligent Decision System and Expert Choice software tools. The utility interval-based evidential reasoning ranking technique was used to rank the wastewater treatment options with and without ignorance as follows: constructed wetlands > sand filters > bio-towers > activated sludge. Constructed wetlands ranked as the most sustainable alternative, with a minimum utility of 0.7345. The environmental dimension, with a relative weighting of 60.4%, was the dimension with the greatest influence on ranking the secondary wastewater treatment alternatives.

1. Introduction

The Occupied Palestinian Territory (the West Bank and Gaza Strip) is one of the world's most water-scarce nations (Salem et al., 2021). Available data suggest that only 10% of Gaza's population has access to safe drinking water because 96% of the water resource from the coastal aquifer is unfit for human consumption (UNDP, 2018). This situation is influenced by environmental degradation, climatic change, population growth, growing water demand, and political constraints (Barghouthi and Gerstetter, 2012). There is a need for fresh water to sustain agricultural growth. Recycling wastewater to augment agricultural irrigation is acknowledged as a crucial approach for minimizing water competition (Dziedzic et al., 2022) and to address the rising water shortage in Palestine (Samhan et al., 2010). For wastewater to be reused, it must meet the local reuse standards. Wastewater treatment plants (WWTPs) combine unit operations and processes for removing/reducing contaminants in wastewater to meet water quality regulations. Wastewater treatment methods improve the effluent quality for reuse while increasing the quantity of the resource as an alternative source of freshwater (Gallego-Valero et al., 2021). The purpose of wastewater treatment is to remove or reduce contaminant levels in the water, which may pose a threat to humans and the environment in its present form (Joshua et al., 2017). Wastewater must be treated to satisfy various national level regulations and guidelines before disposal or reuse (Salem et al., 2021). Complete wastewater treatment comprises three major steps: primary (removal of suspended and floating solids), secondary

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(biological degradation of organic matter), and tertiary (nutrient and toxic compounds removal) treatments (Jones et al., 2021). Secondary wastewater treatment technologies include oxidation ponds, aerated lagoons, activated sludge, membrane bioreactors, up-flow anaerobic sludge blanket reactors, anaerobic baffled reactors, expanded granular sludge beds, anaerobic/aerobic filters, constructed wetlands (Anekwe et al., 2022). In Palestine, many wastewater treatment technologies are in use. These include bio-tower (PWA, 2012) activated sludge, membrane bioreactor (MBR) (Taha and Al-Sa'ed, 2017), trickling filter, waste stabilization ponds, sand filters (Al-Sa'ed, 2000), extended aeration, aerated lagoons (Samhan et al., 2010) and constructed wetlands (IRIDRA, 2021).

The technologies selected for WWTP must be cost-effective, meet environmental regulations, and promote community development and public acceptance (Padrón-Páez et al., 2020). To select the best technology for wastewater treatment, it is also essential to use a framework for decision-making that considers sustainability indicators. The multi-faceted nature of sustainability requires a sophisticated multi-criteria decision analysis (MCDA) to choose the most effective technology. In MCDA problems, the decision-maker is presented with several alternatives to weigh against established standards. The alternatives could be prioritized, taking the assessment's objective into account.

Muga and Mihelcic (2008) assessed the sustainability of activated sludge systems with secondary treatment, lagoon (facultative, anaerobic, and aerobic), and land treatment systems (e.g., slow rate irrigation, rapid infiltration, and overland flow). Molinos-Senante et al. (2014) also compared the sustainability of seven WWT technologies (constructed wetlands, pond systems, extended aeration, membrane bioreactor (MBR), rotating biological contactor, trickling filter, and sequencing batch reactor) for secondary treatment in small communities. They found constructed wetlands to be the most sustainable technology. But their assessment was performed using environmental, economic, and social dimensions. Plakas et al. (2015) assessed the sustainability of four intensive technologies for tertiary treatment (powdered activated carbon adsorption coupled with ultrafiltration membrane separation, reverse osmosis, ozone/ultraviolet-light oxidation, and hybrid TiO2/UV-A catalysis– ultrafiltration process) in WWTPs based on data from thirteen WWTPs in Greece. Akhoundi and Nazif (2018) assessed the sustainability of twenty tertiary treatment technologies to meet three wastewater reuse standards in Tehran-Iran. In a similar study, Padrón-Páez et al. (2020) applied an integrated methodology that combines conceptual and mathematical programming approaches to design sustainable WWTPs using municipal wastewater in Mexico City as a case study. They used data available in literature to assess technologies comprising of screening, grit separator, oil-water separation, primary sedimentation, filtration, flotation, coagulation/flocculation combined with primary sedimentation, aerobic process, anaerobic process, aerobic combined with anaerobic process, anaerobic-anoxic-aerobic processes combined, chemical oxidation, chemical precipitation, membrane processes, carbon adsorption, ion exchange, stripping and electrochemical processes. The best WWTP design obtained in their assessment involved treatment techniques made up of screening, grit separator, primary sedimentation, aerobic process, and chlorine disinfection. More recently, Omran et al. (2021) assessed the sustainability of four wastewater treatment technologies (Conventional, Oxidation Ditches, Aeration Lagoons, and MBR) using data from thirteen operating plants in urban areas of Iraq. Their study showed that the sustainability of the treatment technologies in the order of total importance (in descending order) was membrane bioreactor > oxidation ditches > aerated lagoons > conventional treatment. Most of the studies discussed above assessed the sustainability of tertiary WWT technologies, but only a few of them focused on secondary WWT technologies. In addition, the sustainability assessments were all performed on existing secondary wastewater treatment technologies. None of the studies applied the sustainability assessment method to rank and select the best technology before construction.

In assessing the sustainability of WWTPs, several distinct MCDA techniques have been widely used in various studies (Padrón-Páez et al., 2020). More recently, the Evidential Reasoning (ER) method, based on the Dempster–Shafer (D–S) theory of evidence for attribute aggregation, has gained prominence as one of the best methods for MCDA (Ngan, 2015) mainly due to its capacity to handle both qualitative and quantitative indicators in the face of various uncertainties and ignorance (Wang et al., 2006). The D–S theory of evidence for attribute aggregation and the distributed assessment framework (belief decision matrix) were used by the ER method for modeling several characteristics. Through the belief structure, the ER distributed modeling framework offers a consistent framework as well as an efficient and reliable way to handle different human judgments (Akhoundi and Nazif, 2018). Each characteristic is evaluated using a set of grades that are mutually exclusive and exhaustive collectively (Yang et al., 2006).

The objectives of the present study were to:

- Develop a systematic framework for assessing the sustainability of secondary WWT technologies based on the Evidential Reasoning method.
- Select and assess the sustainability of secondary wastewater treatment technologies through expert opinion (questionnaire survey) on four sustainability dimensions (economic, technological, environmental, and socio-cultural).
- Rank and select the most sustainable secondary wastewater treatment technology to complete the Rafah WWTP in the Gaza Strip, Palestine, where the treated wastewater would be reused in the surrounding agricultural farms.

The current research aided in selecting the best secondary WWT technology for real-life agricultural reuse applications in Rafah, Gaza Strip-Palestine. To the best of authors' knowledge, this is the first study reported in scientific literature to use the sustainability assessment method to select the best secondary WWT technology at a project planning stage. Unlike other studies where assessments were performed for existing technologies, this study selected the technology before design and construction. In the midst of a lack of quantitative data on the cost (construction, operation, and maintenance) and estimated environmental impacts of the technology alternatives, the ER method used the subjective judgment and opinion of local experts to rank the alternatives.

2. Materials and methods

2.1. Study context

Rafah is a Palestinian city and refugee camp located in the southern Gaza Strip. It occupies a land area of 64 km^2 and is situated between longitudes 34°20′ and 34°25′ east and latitudes 31°16′ and 31°45′ north. The governorate of Rafah is on the Rafah border between Egypt and the State of Palestine. The 2021 population was forecast at 260,117 (PCBS and Statistics, 2021) with a population density of 4064 people per square kilometer. The climate of Rafah is a mix of the semi-humid Mediterranean climate and the semi-arid Sinai Peninsula climate, with hot, dry summers and moderate winters (Shomar, 2006). Rafah area has low rainfall intensity (rarely exceeding 200 mm/year). The mean daily temperature is 25 °C in the summer and 13 °C in the winter (Aish et al., 2021). Over half of the land area (33 km^2) is used for agriculture (Eljamassi and Abeaid, 2013). The Coastal Municipality Water Utilities (CMWU) manages around 80% of the water supply, which is used for household, industrial, and agricultural activities.

2.2. Wastewater treatment in Rafah

The Rafah WWTP collects, transports, and treats the wastewater generated in the governorate. About 65% of the population of Rafah is connected to the existing wastewater system, with the remaining 35% connected to septic tanks. Prior to the implementation of the current project, the existing facility consisted of an anaerobic system with screening and sedimentation and an aerobic lagoon system equipped with mechanical aerators. The Rafah WWTP, managed by the CMWU, treats an average of 10,000–12,000 m^3/day of wastewater, with a peak of 18,000 m^3/day (ICRC, 2013). The treatment facility was expanded from 1800 m^3/day in 1989 to 20,000 m^3/day in 2011. The wastewater effluent quality of the Rafah wastewater treatment plant prior to the implementation of this project is presented in Table 1.

The effluent from the treatment plant had characteristics outside the Palestinian Standard for reuse of wastewater in irrigation (see Table 1), but it is discharged into the Mediterranean Sea (ICRC, 2011). Aside from the environmental ramifications of the practice on the receiving aquatic environment, the beneficial nutrients and water were also wasted. There was the need to introduce a secondary treatment technology into the existing WWTP to recycle the wastewater. The technology to be applied should be able to reduce target contaminants (BOD_5, COD, TSS, Nitrogen, and Phosphorus) to an acceptable standard for agricultural reuse in Palestine.

2.3. Data collection instruments and assessment tools

Data for assessing the sustainability of dimensions and indicators could be qualitative, quantitative, or both. The current project was in the decision-making stage, and no capital or operating cost estimates were readily available for the selected technologies, so all the dimensions and indicators were evaluated qualitatively using the knowledge and judgment of local experts. This was achieved using a questionnaire survey. A questionnaire based on the dimensions and their indicators was pretested on six local university professors with expertise in sustainability assessment and environmental engineering. Inputs from the pre-testing were used to finalize the questionnaire. The questionnaire was distributed to thirty-two local experts, comprising selected local university professors, members of the agricultural NGOs in Rafah Governorate, and those working on the current project. The varied levels of experience and exposure of the experts make the assessment subjective and characterized by uncertainties. The uncertainties could also be due to a lack of information or the vagueness of the meaning of some indicators (Wang et al., 2006). The Dempster–Shafer (D–S) theory of evidence for attribute aggregation and the belief decision matrix used by the ER method accommodates experts' subjective judgments (Yang et al., 2006).

The questionnaire was divided into two parts. In the first part, the respondents assigned a degree of importance (in percentage) to the sustainability dimensions (economic, technological, environmental, and socio-cultural) and first-level indicators for the technological dimensions. In the second part, the respondents specified the degree of desirability of each second-level indicator by assigning a number from 1 to 5 (5 being desirable and 1 being unfavorable). Where the respondents had no idea about an indicator, they were requested to leave the cell blank. The results from the survey were used at various stages of the ER process to assess the sustainability of the technology alternatives.

Table 1
Effluent quality of Rafah wastewater treatment plant before implementation of the current project.

Parameter	Unit	Effluent quality	Palestine Standard[a]
pH	–	8.2	6–9
Biochemical oxygen demand (BOD_5)	mg/L	110	20–60
Chemical oxygen demand (COD)	mg/L	250	50–150
Total dissolved solids (TDS)	mg/L	2976	1200–1500
Total suspended solids (TSS)	mg/L	137	30–90
Total Kjeldahl Nitrogen (TKN)	mg/L	108	50
Phosphorus (P)	mg/L	18	30
Ammonium (NH_4)	mg/L	127	5–15
Nitrate (NO_3)	mg/L	0.23	20–40
Fecal coliform	CFU/100 ml	620,000	<1000/100 ml

[a] PSI (2012).
Source: Adapted from El Hamarneh (2018).

2.4. Selection of secondary wastewater treatment alternatives

The selection of technologies was based on the concept of "Appropriate Technology". Appropriate technologies are inexpensive, have minimal negative effects on the environment, and can be managed by local communities with little expertise (Feige and Vonortas, 2017). Through a review of related literature (government documents, project reports, and scientific articles), a list of wastewater treatment technologies was prepared in consultation with local experts working on the project. Four (4) secondary wastewater treatment technology alternatives were chosen: sand filter, constructed wetland, activated sludge, and bio-tower technologies. These technologies have been used in wastewater treatment projects in different areas of Palestine. Specific areas of application are bio-tower technology at Gaza WWTP (PWA, 2012), an activated sludge system at Nablus and Al-Bireh WWTPs (Taha and Al-Sa'ed, 2017), constructed wetlands at Sarra-Nablus WWTP (IRIDRA, 2021), and sand filters in rural areas of Aba, Aba School, Jericho, and Beit Doggo (Al-Sa'ed, 2000). A comparison of the selected treatment technologies is shown in Table 2.

2.5. Defining the sustainability dimensions and indicators

The quality and reliability of sustainability assessment results depend on selecting the correct sustainability dimensions and indicators. Different authors apply different sustainability dimensions based on the objective of the assessment. Nkuna et al. (2022) and Dixon et al. (2003) applied environmental and economic dimensions to evaluate the sustainability of wastewater treatment technologies. However, most sustainability assessments are performed to cover the three sustainability pillars, namely, economic, environmental, and social dimensions. Padrón-Páez et al. (2020) used the three dimensions to assess the sustainability of a wastewater treatment plant in Mexico City. In Greece, Plakas et al. (2015) also used the three dimensions to assess the sustainability of tertiary wastewater treatment technologies. In another study, Omran et al. (2021) added a fourth dimension (technical aspect) to assess the sustainability of wastewater treatment techniques in urban areas of Iraq.

In this study, four sustainability dimensions (economic, technological, environmental, and socio-cultural) were applied. The dimensions were assessed using sustainability indicators. The indicators are a quantifiable aspect of the dimensions that are helpful for assessing changes in the system attributes that are important for maintaining both human and environmental well-being (Fiksel et al., 2012). Harger and Meyer (1996) assert that the sustainability indicators should be simple, extensive (in terms of scope), easily quantifiable, capable of capturing performance patterns, adaptable to changes, and easy to determine performance trends.

After a comprehensive review of related literature (research articles and scientific magazines), the indicators used by Akhoundi and Nazif (2018) were adapted for the present study. This decision was influenced by two factors: (1) similarity in socio-economic, cultural, religious, and environmental traits between Palestine and Iran; and (2) precedence in the assessment of WWTP effluent reuse alternatives. The dimensions and associated indicators were shared with the experts for their input. Based on the inputs from the experts, two indicators under the technological dimension that were not relevant to the present study were removed. But two new indicators (one each under the technological and environmental dimensions) were introduced. A total of thirty-five indicators

Table 2
Comparative analysis of the advantages and disadvantages of selected wastewater treatment technologies.

Treatment alternatives	Capacity to treat contaminants	Advantages	Disadvantages
Activated Sludge	High removal of BOD_5 and removal of nitrogen.	• Low land requirement • Low installation cost • Excellent quality effluent	• Operation cost is high. • Sludge disposal is needed on a large scale.
Bio-tower technology	Removal of organic matter	• Long-life span • Large specific surface areas to accommodate large microbial growth. • Good wetting, continuous air movement, and thinner biological growths eliminate the fly nuisance.	• Requires regular operator attention. • The incidence of clogging is high. • Requires low loadings depending on the medium.
Constructed Wetlands	BOD_5; Suspended solids; Nitrogen and phosphorous can be converted into biomass	• Simple operation and low capital • Lower energy consumption • The presence of vegetation improves the treatment efficiency, producing an effluent suitable for various reuse applications (e.g., irrigation). • High-value products can be extracted from the biomass generated.	• A large area for storage is needed. • Long time to obtain the expected effect.
Sand filters	Removal of Suspended solids and bacteria. Removal of turbidity.	• The simplicity of design and installation. • No chemical addition is needed.	• Frequently clogging of the filter beds. • Loss of productivity during the long filter skimming and ripening periods.

were categorized under the four dimensions as follows: technological (21), economic (3), environmental (7), and socio-cultural (4). The twenty-one indicators for the technological dimension were distributed under five first-level indicators. A list of the sustainability dimensions and indicators used for the assessment is presented in Table 3.

2.6. Procedure for evidential reasoning method

The procedure for performing the ER method, in this case study, followed four (4) main steps, as illustrated in Fig. 1(a). The procedure for determining the relative weight of indicators is shown in Fig. 1(b).

2.6.1. Determination of relative weights of indicators using analytic hierarchy process (AHP)

The relative weights of the sustainability indicators were established by applying the analytical hierarchy process (AHP) using the *Expert Choice software (version 11)*. The AHP model organizes the indicators into a hierarchical structure. The procedure for determining the relative weighting of the dimensions and indicators is presented in Fig. 1 (b). AHP began by making a pairwise comparison matrix $\boldsymbol{A}$ of $m \times m$ entries, where m is the number of considered evaluation criteria on a preference scale presented in Table 4. A pairwise comparison reveals how frequently one alternative is more significant (better) than the other

Table 3
The selected dimensions and indicators for sustainability assessment of secondary wastewater treatment technology alternatives.

Dimension	First level indicator	Second level indicator
Technological	Adaptability to the external environment	Rainfall compatibility
		Temperature compatibility
		Land slope suitability
		Soil suitability
		Preserving the natural view
	Technological conceivability	Water recovery ratio
		Sensitivity to toxic substances
		Mechanical reliability
		Ease of O&M
		Energy consumption
		Frequency of O&M
		Need for skilled operators
	Expandability	Ease of future expansion
		Economies of scale
		Constant operating efficiency after expansion
	Adaptability to existing infrastructure	Availability of operational resources
		Need for pre-treatment
	Sludge management	Suitability as fertilizer
		Suitability for use in industries
		Sludge production (with other reuse potential)
		Sludge disposal in landfill
Economic		Capital cost
		Operating cost
		Maintenance cost
Environmental		Estimated environmental impacts
		Impacts on the marine environment
		Providing a natural habitat
		Landscape development
		Noise pollution
		Odor nuisance
		Rodents and insect nuisance
Socio-cultural		Need for public awareness
		Risk to the public health and safety
		Employment creation
		Creating possibilities for study

(Szabo et al., 2021).

The entry a_{ij} of matrix $\boldsymbol{A}$ denotes the importance of the i-th criterion relative to the j-th criterion. Once matrix $\boldsymbol{A}$ was built, matrix $\boldsymbol{A}_{norm}$ (the normalized pairwise comparison matrix) was acquired. Finally, the relative weight of each criterion was calculated by averaging the entries in the row corresponding to those criteria in $\boldsymbol{A}_{norm}$. The criteria weight vector $\boldsymbol{w}_j$, which was an m-dimensional column vector, was built following Eq. (1).

$$\boldsymbol{w}_j = \frac{\sum_{k=1}^{m} \overline{a}_{jk}}{m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 1}$$

The only conflicting issue that had to be addressed was consistency. It typically arises when many pairwise comparisons are performed. Inconsistencies open the window for knowledge, which changes preferences in order to be admitted (Saaty, 1987). The validity of calculated weights was determined using the consistency ratio (CR) computed from Eq. (2).

$$CR = \frac{CI}{RI} < 0.1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 2}$$

The consistency ratio was used to determine the value of probability, and the judgment matrix was created randomly. The CR compares the consistency index (CI) with the randomness index (RI), and its value ranges from 0 to 1 (Saaty, 1987). A CR of up to 0.1 indicates a reasonable level of consistency (Malczewski, 1999). A consistency ratio greater than

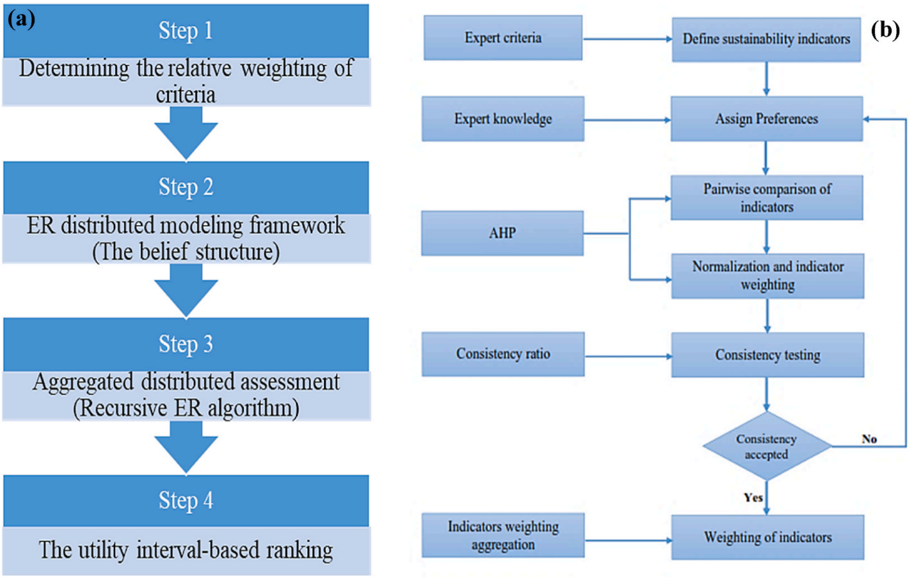

Fig. 1. Methodological procedure for ER method (a); and determining the relative weighting of indicators (b).

Table 4
Preference scale for pairwise comparison (Saaty, 1987).

Intensity	Definition	Explanation
1	Equal importance between both elements	Two activities contribute equally to the objective
2	Equally to moderately more important	Experience and judgment slightly favor one activity over the other
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over the other
5	Strong importance	Experience and judgment very strongly favor one activity over the other
7	Very strong importance	Experience and judgment very strongly favor one activity over the other
9	Absolute importance	Experience and judgment very strongly favor one activity over the other
2, 4, 6, 8	Intermediate values between adjacent scales	Used to represent the compromise between the priorities listed above

0.1 requires that the comparison process be repeated by reviewing the inconsistent decision matrix of the indicators (Akhoundi and Nazif, 2018). *RI* is the random index, which is the consistency index of matrix ***A,*** where its entries are all random. The random average consistency indexes for various ***m*** were reported by Saaty (1987), as presented in Table 5.

The consistency index (CI) was calculated by first determining the scalar ***x,*** which represents the average of the elements of the vector, whose *j-th* element represents the ratio of the *j-th* element of the vector ***A. w*** to the corresponding element of the vector ***w***. Then, CI was determined using Eq. (3).

$$CI=\frac{x-m}{m-1}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 3}$$

When $CI = 0$, a perfectly consistent decision-making is obtained. However, small values of inconsistencies were also tolerated when Eq. (3) was less than unity.

Table 5
The random average consistency indexes for various m (Saaty, 1987).

m	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

2.6.2. *The ER distributed modeling framework (the belief structure) for secondary wastewater treatment alternatives*

The ER distributed modeling framework used in this study was based on that developed by Yang (2001). Fig. 2 presents the procedure for ranking the alternatives using the utility interval-based ER method.

Assuming the sustainability assessment had L alternatives represented by $a_l(l = 1,\ldots,L)$, and B indicators represented by $c_b(b = 1,\ldots,B)$. Each indicator had its own influence and degree of importance different from the others. A relative weight was assigned to each indicator using the AHP method. The relative weights of the indicators were given by $\omega_b = \{\omega_1,\omega_2,\ldots,\omega_B\}$, where ω_b was normalized to satisfy the condition presented in Eq. (4).

$$\sum_{b=1}^{B}\omega_b=1,(0\leq\omega_b\leq1)\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 4}$$

Assuming that there were N mutually exclusive and collectively exhaustive (Wang et al., 2006) set of assessment grades (presented in Table 6) for evaluating each alternative on all the indicators, represented by H_n $(n = 1,\ldots,N)$, where H_n is the ***n*** th assessment grade. The assumption was that H_{n+1} was preferred to H_n,

$$H=\{H_n,n=1,\ldots,N\}\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 5}$$

The sustainability assessment of the alternatives was modeled using Eq. (6) for alternatives a_l $(l= 1,\ldots,L)$ on indicators $c_b(b = 1,\ldots,B)$:

$$S(c_b(a_l))=\left\{\left(H_n,\beta_{n,b}(a_l)\right),n=1,\ldots,N;\ b=1,\ldots,B;\ l=1,\ldots,L\right\}\ldots\ldots\ldots \quad \text{Eq.6}$$

where $\beta_{n,b}(a_l)\geq0$, $\sum_{n=1}^{N}\beta_{n,b}(a_l)\leq1$; $\beta_{n,b}(a_l)$ represent a degree of belief.

An expectation for c_b and a_l reads that an indicator (c_b) at an alternative (a_l) was evaluated to a grade H_n, with a degree of belief of $\beta_{n,b}(a_l)$ $(n = 1,\ldots,N)$. For each treatment technology alternative, the assessment outcome of an indicator was denoted by the belief decision matrix given in Eq. (7).

$$\begin{bmatrix} S_{1,l} \\ \vdots \\ S_{N,l} \end{bmatrix}=\begin{bmatrix} \omega_{1,1} & \cdots & \omega_{1,M} \\ \vdots & \ddots & \vdots \\ \omega_{N,1} & \cdots & \omega_{N,M} \end{bmatrix}\begin{bmatrix} \beta_{1,l} \\ \vdots \\ \beta_{M,l} \end{bmatrix}\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 7}$$

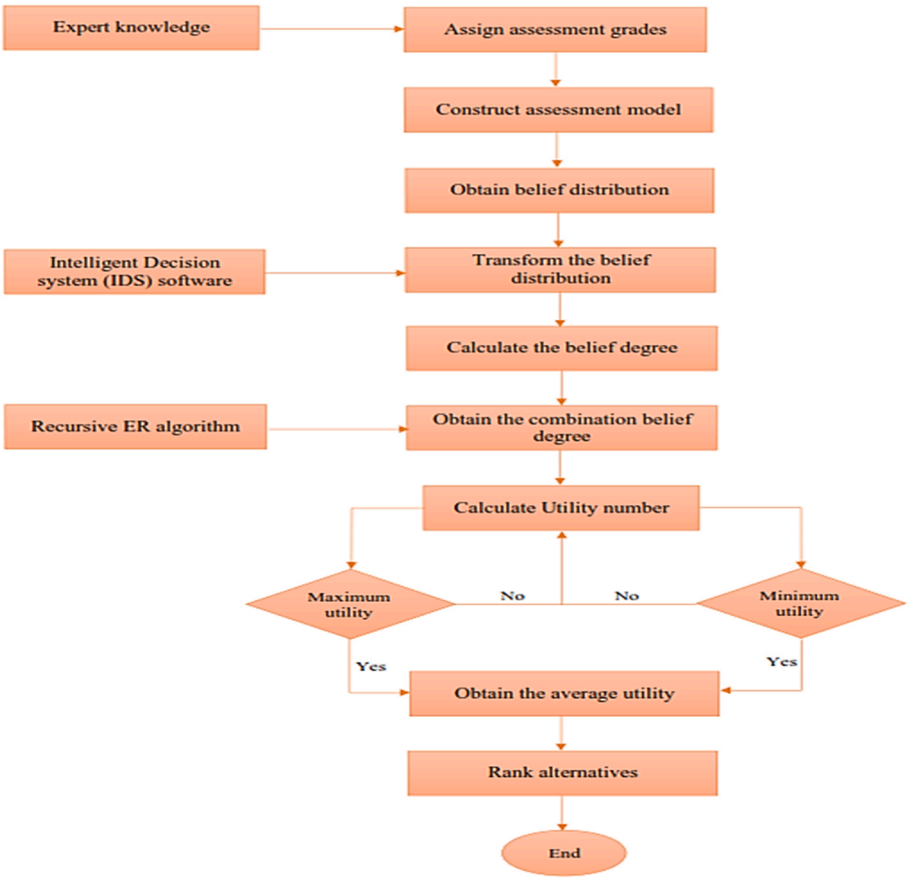

Fig. 2. The procedure for ranking alternatives using the utility interval-based ER method.

Table 6
Assessment grades applied in describing the indicators.

Assessment grade	Description	Degree of desirability on survey questionnaire	Utility number
+B	Positive	5	1
+A	Slightly positive	4	0.75
N	Neutral	3	0.50
-A	Slightly negative	2	0.25
-B	Negative	1	0

2.6.3. Aggregating distributed assessment information (The recursive ER algorithm) for secondary treatment alternative

The belief decision matrix was combined with the D-S theory of evidence to obtain the aggregated distributed assessment information. This was achieved by transforming the belief degrees into basic probability masses by combining the relative weights and the degrees of belief using Eq. (8) and Eq. (9) (Wang et al., 2006):

$$m_{n,b} = \omega_b \beta_{n,b}(a_l), n = 1, \ldots, N; \quad b = 1, \ldots, B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 8}$$

$$m_{H,b} = 1 - \sum_{n=1}^{N} m_{n,b} = 1 - \omega_b \sum_{n=1}^{N} \beta_{n,b}(a_l), b = 1, \ldots, B \ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 9}$$

where $m_{n,b}$ represents the basic probability mass of a_l being assessed to the assessment grade H_n on the indicator, c_b.

The basic probability masses were combined using the recursive ER algorithm presented in Eq. (10) to Eq. (14) (Wang et al., 2006). The recursive ER algorithm combined various pieces of evidence on a one-by-one basis.

$$\{H_n\} : m_{n,I(b+1)} = K_{I(b+1)} \left[m_{n,I(b)} m_{n,b+1} + m_{n,I(b)} m_{H,b+1} + m_{H,I(b)} m_{n,b+1} \right], \ldots\ldots\ldots\ldots \qquad \text{Eq. 10}$$

$$n = 1, \ldots, N$$

$$\{H\} : m_{H,I(b+1)} = K_{I(b+1)} \left[m_{H,I(b)} m_{H,b+1} \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 11}$$

$$K_{I(b+1)} = \left[1 - \sum_{t=1}^{N} \sum_{j=1}^{N} m_{t,I(b)} m_{j,b+1} \right]^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 12}$$

$$b = 1, \ldots, B - 1$$

$$\beta_H(a_l) = \sum_{b=1}^{B} \omega_b \left(1 - \sum_{n=1}^{N} \beta_{n,b}(a_l) \right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 13}$$

$$n = 1, \ldots, N$$

$$\beta_n(a_l) = \frac{1 - \beta_H(a_l)}{1 - m_{H,I(B)}} m_{n,I(B)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Eq. 14}$$

where $m_{n,b} = m_{n,1}$ $(n = 1, \ldots, N)$ and $m_{H,I(1)} = m_{H,1}$.

β_n was the combined degree of belief that the dimension was assessed to the grade H_n. When all B indicators were assessed, β_n was assigned to any single evaluation grade as the degree of belief. Then, the degree of incompleteness in the assessment was represented using β_H. According to Yang and Xu (2002b)

$$\sum_{n=1}^{N}\beta_n(a_l)+\beta_H(a_l)=1$$

2.6.4. *The utility interval-based evidential reasoning method with uncertainties*

In the case of an incomplete assessment (with uncertainties), to rank L alternatives based on B indicators, a utility interval comprising the maximum, minimum, and average utilities (Yang, 2001) had to be defined. The least desirable assessment was related to the lowest utility, whereas the most desirable assessment grade was related to the highest utility.

The aggregated assessment for a_l was represented by Eq. (15).

$$S(y(a_l))=\{(H_n,\beta_n(a_l)),n=1,\ldots,N\}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 15}$$

When the utility of an evaluation grade H_n is represented as $u(H_n)$, then the expected utility of the aggregated assessment $S(y(a_l))$ is given by Eq. (16).

$$u\left(S\left(y(a_l)\right)\right)=\sum_{n=1}^{N}\beta_n(a_l)u(H_n)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 16}$$

The lower bound of the likelihood to which a_l is assessed to H_n, is represented by the belief degree $\beta_n(a_l)$ while $\beta_n(a_l)+\beta_H(a_l)$ represented the upper bound of the likelihood (Yang and Xu, 2002a). The lower and upper bounds of the likelihood allowed for the establishment of a utility interval. The minimum, maximum, and average utilities of a_l were evaluated using Eq. (17) to Eq. (19) (Yang, 2001).

$$u_{min}(a_l)=\left(\beta_1(a_l)+\beta_H(a_l)\right)u(H_1)+\sum_{n=2}^{N}\beta_n(a_l)u(H_n)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 17}$$

$$u_{max}(a_l)=\sum_{n=1}^{N-1}\beta_n(a_l)u(H_n)+\left(\beta_N(a_l)+\beta_H(a_l)\right)u(H_N)\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 18}$$

$$u_{average}(a_l)=\frac{u_{max}(a_l)+u_{min}(a_l)}{2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. 19}$$

The utility intervals are used to rank two alternatives a_l and a_k. As suggested by Wang et al. (2006), a_l is preferred to a_k if and only if $u_{min}(a_l)>u_{max}(a_k)$. The two alternatives a_l and a_k are considered the same if, and only if $u_{min}(a_l)=u_{min}(a_k)$ and $u_{max}(a_l)=u_{max}(a_k)$. A more reliable ranking between a_l and a_k would be achieved by reducing imprecision or incompleteness in the original assessment (Wang et al., 2006).

In ranking the secondary treatment alternatives based on the utility interval-based method without uncertainties, the assessment grades were assumed to be linearly correlated with the utility numbers. The least favorable assessment grade (-B) was assigned a utility number of zero, whereas the most favorable assessment grade (+B) was assigned a utility number of 1. Based on the assumed linear relationship, the other assessment grades were assigned utility numbers between zero and 1, as indicated in Table 6.

2.7. *ER assessment tools*

The relative weights of the sustainability assessment indicators were established by applying the analytical hierarchy process (AHP) using the *Expert Choice software (version 11)*. The software makes it possible to compare each pair of alternatives based on each indicator and rate alternatives based on these comparisons. The ER method was performed using the Intelligent Decision System (IDS) software based on the frameworks and algorithms described in the previous sections.

3. Results and discussions

In this section, the proposed method is implemented to assess and rank the four secondary wastewater treatment technologies alternative for Rafah WWTP according to the sustainability dimensions and indicators introduced in Table 3. The case study was based on data acquired from the literature and validated by experts' views.

3.1. *Relative weights of sustainability dimensions and indicators*

The level of influence of a dimension on the rank of a technology alternative was determined by the total relative weight of the dimension. The relative weights of the environmental, economic, technological, and socio-cultural dimensions were 60.4%, 20.1%, 12.1%, and 7.4%, respectively. The environmental dimension had the greatest influence (60.4%) on the ranking of a technology alternative (Fig. 3). The socio-cultural dimension had the least influence (relative weight of 7.4%) on the ranking of the alternatives. The relative weight of each sustainability dimension, and the relative weights of all indicators, are presented in Fig. 4.

For the technological dimension, 'sludge management' had the greatest influence with a relative weight of 25.8%, followed by both 'ability to adapt to the physical environment' and 'adapting to the existing infrastructure' indicators, each with a level of influence of 12.9%. The indicator with the least influence on the aggregated technological dimension was technological conceivability, with a relative weight of 11.0%.

The weights of the first-level indicators for the technological dimension signify the importance of the indicators to the aggregated technological dimension (Abdella et al., 2021). The weights of indicators for the economic, environmental, and socio-cultural dimensions and the second-level indicators for the technological dimension were all considered equal.

As Yang (2001) indicated, the validity of the computed weights had

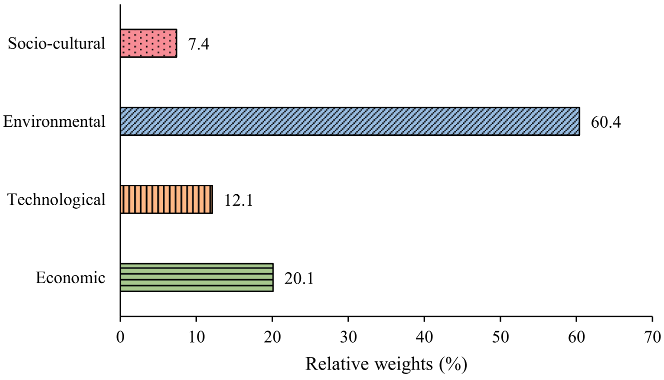

Fig. 3. Relative weights of dimensions based on the pairwise comparison.

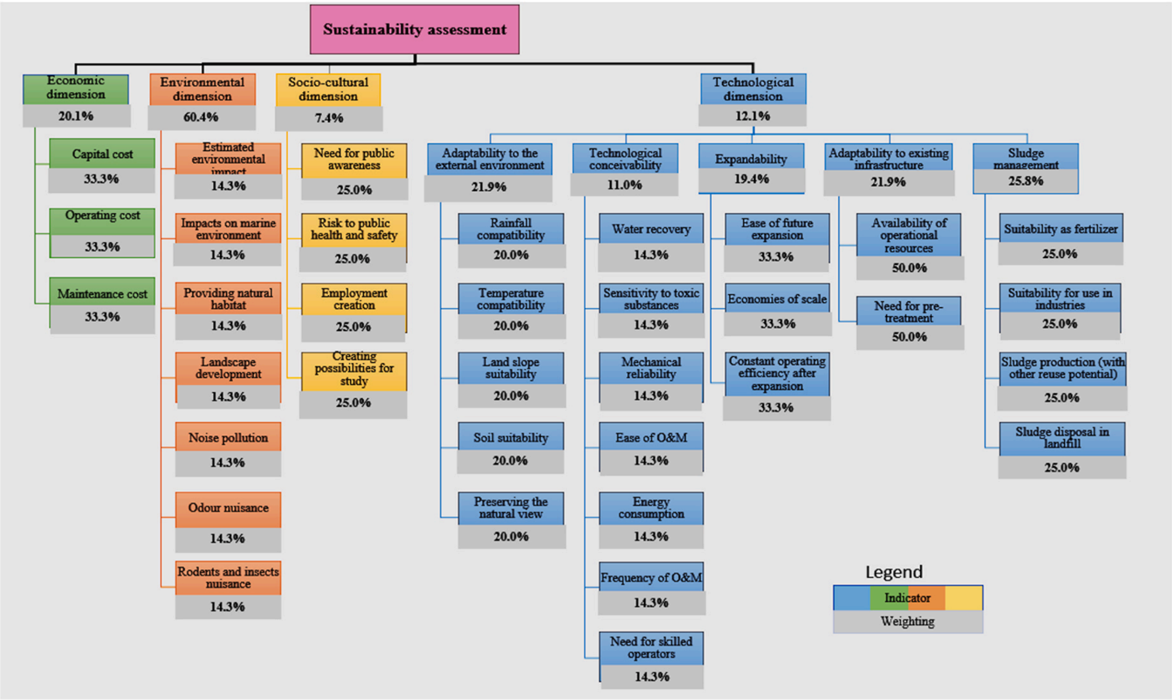

Fig. 4. Weighting of sustainability dimensions and indicators.

to be determined using the consistency ratio (CR). The consistency ratio (CR) was obtained as 0.02 for the dimensions and 0.01 for the first-level indicators of the technological dimension. The computed CR was within the tolerable level of consistency (CR < 0.1) (Malczewski, 1999). The CR for economic, environmental, and socio-cultural dimensions and second-level indicators for technological dimensions were all taken as zero because their weights were considered equal, as has already been indicated.

3.2. *ER distributed assessment modeling framework (the belief structure)*

The ER method was implemented using the *Intelligent Decision System (IDS) software*. The qualitative criteria were all assessed by the 32 experts on the grades [-B, -A, N, +A, +B] as defined in Table 6. All the assessment grades were considered mutually exclusive and collectively exhaustive (Wang et al., 2006). The assessment information for each alternative, presented in the form of a distributed assessment, is presented in Table 7 for the environmental dimension (see Tables S–1 of the Supplementary Material for the distributed assessment for the remaining dimensions and indicators).

The distributed assessment consists of an assessment grade and a corresponding decimal number which indicates the percentage of experts who were awarded the assessment grade. Taking the indicator "estimated environmental impacts" of the Environmental dimension for constructed wetland (Table 7) as an example, the distributed assessment {(-A, 10), (N, 0.10), (+B, 0.80)} means that 10% of the experts assessed the indicator as -A, 10% as N, and 80% as + B. Since all thirty-two experts filled in the questionnaire, the assessment was complete. Using the ER method, it was possible to assess unknown data in the form of a degree of ignorance (Wang et al., 2006) in the sustainability assessment. The degree of ignorance comprises uncertainty, missing data, unknown data, etc. In assessing a dimension that is indicated, for example, by {(+A, 0.20), (+B, 0.60)}, the degree of ignorance would be 0.20 because 20% of the experts did not assess that dimension.

3.3. *Aggregated distributed assessment information (recursive ER algorithm)*

Using the ER algorithm, the distributed assessment of each indicator under a dimension (as shown in Table 3) was aggregated into a distributed assessment for the sustainability dimension. The distributed assessment for the dimensions was then aggregated to produce an overall assessment of the treatment alternative, as presented in Table 8. The overall belief degree for each treatment alternative is shown in Fig. 5. All the experts assigned a neutral grade to the economic dimension. This was expected because it was quite difficult to grade the alternatives without quantitative data on the capital, operating and maintenance costs of each technology alternative.

Considering only the socio-cultural dimension (see Table 8), the technological alternative believed to be the best was the sand filter, with a belief degree of 54%. However, when technological and environmental dimensions were included, constructed wetland obtained the highest degree of belief of 86% (technological), 72% (environmental), and 46% (socio-cultural) for positive. Using the information from Fig. 5, only two technologies (constructed wetland and sand filter) were believed to be the best technologies based on the dimensions and their indicators. The constructed wetland was rated the best treatment alternative, with a belief degree of 36%, as against 6% for a sand filter. In terms of rating an alternative as 'Good,' constructed wetland again had the highest belief degree at 24.36%, as against a belief degree of 22.8% for a sand filter. None of the technology alternatives were believed to be the worst by the experts. Based on the degree of belief, the constructed wetland was believed to be the best treatment alternative.

3.4. *Ranking of treatment alternatives through the utility interval-based ER ranking method without uncertainty*

The utility score for each treatment alternative and the rank is reported in Table 9.

The alternative with the highest utility score and ranked first among the four alternatives for wastewater reuse in agriculture was constructed wetland, with a utility score of 0.7399. The other treatment technology

Table 7
The distributed assessment for the environmental dimension of the secondary wastewater treatment alternatives.

Wastewater Treatment Alternatives	Assessment Criteria (Environmental dimensions)	Degrees of Belief				
		-B	-A	N	+A	+B
Sand Filter	Estimated environmental impacts	–	–	0.50	0.50	–
	Impact on marine environment	–	–	0.50	0.50	–
	Providing a natural habitat	–	0.20	0.30	0.50	–
	Landscape development	–	0.50	0.50	–	–
	Noise pollution	0.10	–	0.10	0.40	0.50
	Unpleasant odor	–	0.20	0.70	0.10	–
	Rodents and insects' appearance	0.10	–	0.50	0.40	–
Constructed Wetland	Estimated environmental impacts	–	0.10	0.10	–	0.80
	Impact on marine environment	0.10	0.10	–	–	0.80
	Providing a natural habitat	–	–	–	0.50	0.50
	Landscape development	–	–	–	0.50	0.50
	Noise pollution	0.10	–	–	0.40	0.50
	Unpleasant odor	–	–	0.20	0.40	0.40
	Rodents and insects' appearance	–	–	0.50	0.50	–
Activated Sludge	Estimated environmental impacts	–	0.20	0.30	0.50	–
	Impact on marine environment	–	0.20	0.80	–	–
	Providing a natural habitat	0.10	0.20	0.70	–	–
	Landscape development	0.20	0.80	–	–	–
	Noise pollution	–	0.20	–	0.80	–
	Unpleasant odor	0.20	0.60	0.20	–	–
	Rodents and insects' appearance	–	0.50	0.50	–	–
Bio-tower	Estimated environmental impacts	–	0.20	0.80	–	–
	Impact on marine environment	0.10	0.10	0.80	–	–
	Providing a natural habitat	–	0.50	0.50	–	–
	Landscape development	0.20	0.30	0.50	–	–
	Noise pollution	0.10	–	0.90	–	–
	Unpleasant odor	–	0.50	0.50	–	–
	Rodents and insects' appearance	–	0.10	0.90	–	–

alternatives were ranked in the following order: sand filter > bio-tower > activated sludge. The utility score for constructed wetland was 38% higher than the next ranked technology (sand filter) and up to 83% higher than the least ranked technology (activated sludge). This signifies that constructed wetland was the most sustainable secondary treatment alternative based on expert views. This was also confirmed by the distributed assessments in Table 6 and belief degrees in Fig. 5.

3.5. *Ranking of treatment alternatives through the utility interval by assuming an ignorance degree*

The maximum, minimum, and average utilities were used to rank the alternatives with incomplete assessments (Yang et al., 2006). The assessment for all the indicators was complete without an ignorance degree. But economic dimension and estimated environmental impact indicators could be evaluated as quantitative criteria through life cycle costing (LCC) and life cycle assessment (LCA). A small degree of ignorance was allowed in evaluating their impact on the ranking of the alternatives. Consequently, the grades of economic dimension and estimated environmental impacts in the distributed assessments were reduced simultaneously by 50% and 10%. The reductions were then assigned to the ignorance degree. In Fig. 6, the maximum, minimum, and average utility numbers for the technology alternatives are presented.

The best technology alternative was constructed wetland, with the highest utility numbers, followed by sand filters, bio-towers, and activated sludge. The utility number for constructed wetland was about 38%, 73%, and 83% higher than the utility numbers for sand filter, bio-tower and activated sludge. According to Wang et al. (2006), for an alternative a_l to be preferred to a_k, $u_{min}(a_l) > u_{max}(a_k)$. The minimum utility number (u_{min}) for constructed wetland was higher than the maximum utility number (u_{max}) for sand filter, activated sludge, and bio-tower alternatives, making constructed wetland the best alternative. Similarly, the u_{min} for sand filter was greater than the u_{max} for activated sludge, and bio-tower. This makes sand filter the next preferred treatment alternative to constructed wetland. The alternative with the least utility interval, for that matter, the least preferred treatment alternative was activated sludge. The maximum, minimum, and average utility numbers show that the results of the secondary treatment alternative were the same as the results obtained when no ignorance degree was considered.

3.6. *Assessing alternatives using pairwise rating method*

The Expert Choice software was used to compare each pair of alternatives based on each indicator and then rated alternatives based on a pairwise comparison. The ratings were presented in the form of scores. The treatment alternative with the highest score was considered the most sustainable. Fig. 7 shows the results of this evaluation by assigning a score to each alternative.

The most sustainable secondary wastewater treatment alternative was constructed wetland with a score of 32.5%. The other three treatment alternatives scored between 21 and 25 percent. Scoring constructed wetland as the most sustainable confirms the results obtained using the degree of belief and utility intervals. However, the only significant difference was that bio-tower technology was ranked third by the pairwise comparison method, while it was ranked fourth using the utility interval with and without uncertainty. This is because, in comparing the indicators between two alternatives through pairwise comparison, the key consideration was the number of indicators with higher assessment, grades regardless of the weighting of the indicators. The bio-tower technology alternative had more indicators with higher assessment grades compared to activated sludge, as shown in Table 7 and Tables S–1 of Supplementary Material.

In assessing the sustainability of seven WWT technologies for secondary treatment in small communities through environmental, economic, and social dimensions, Molinos-Senante et al. (2014) found constructed wetlands to be the most sustainable. With the introduction of the technological dimension in this study, the outcome of the assessment still points to constructed wetlands as the most sustainable secondary WWT technology. Selecting a set of indicators depends on a particular community's geographic and demographic context (Muga and Mihelcic, 2008). Evaluating the sustainability of WWT technologies is situational. Even within the same country, the set of indicators to be used and the sustainability evaluation could vary from community to community and region to region based on the types of stakeholders involved. It is recommended that in such studies, the opinions and preferences of all groups be considered. Molinos-Senante et al. (2014) identified two main groups: (1) standard stakeholders involved in preparing and managing the process (such as decision makers, experts,

Table 8
Aggregated distributed assessments for the secondary treatment alternatives.

Treatment Alternatives	Sustainability dimensions	Degrees of Belief				
		-B	-A	N	+A	+B
Sand Filter	Economic dimension	0.0000	0.0000	1.0000	0.0000	0.0000
	Technological dimension	0.0000	0.0438	0.5008	0.4457	0.0096
	Environmental dimension	0.0000	0.1207	0.6177	0.2616	0.0000
	Socio-cultural dimension	0.0000	0.2308	0.2308	0.5385	0.0000
Constructed wetland	Economic dimension	0.0000	0.0000	1.0000	0.0000	0.0000
	Technological dimension	0.0000	0.0000	0.1449	0.4944	0.3607
	Environmental dimension	0.0000	0.0000	0.2756	0.2756	0.4488
	Socio-cultural dimension	0.0000	0.0000	0.5385	0.2308	0.2308
Activated Sludge	Economic dimension	0.0000	0.0000	1.0000	0.0000	0.0000
	Technological dimension	0.0000	0.1161	0.8172	0.0667	0.0000
	Environmental dimension	0.0000	0.5919	0.4081	0.0000	0.0000
	Socio-cultural dimension	0.0000	0.0000	0.8043	0.1957	0.0000
Bio-tower	Economic dimension	0.0000	0.0000	1.0000	0.0000	0.0000
	Technological dimension	0.0000	0.0552	0.4624	0.4824	0.0000
	Environmental dimension	0.0000	0.6177	0.2616	0.1207	0.0000
	Socio-cultural dimension	0.0000	0.0000	0.5000	0.5000	0.0000

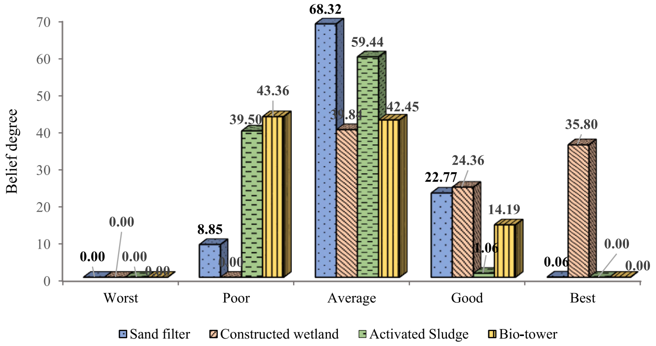

Fig. 5. Belief degree of secondary treatment alternatives.

Table 9
The utility score and rank of each alternative.

Treatment alternative	Utility score	Ranking
Sand Filter	0.5351	2
Constructed wetland	0.7399	1
Activated Sludge	0.4039	4
Bio-Tower	0.4271	3

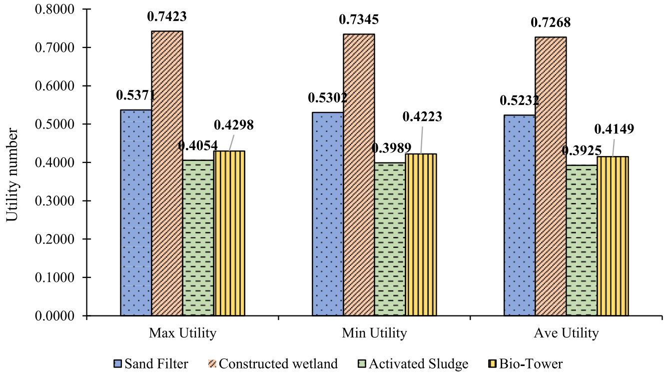

Fig. 6. Maximum, minimum, and average utility interval with uncertainty.

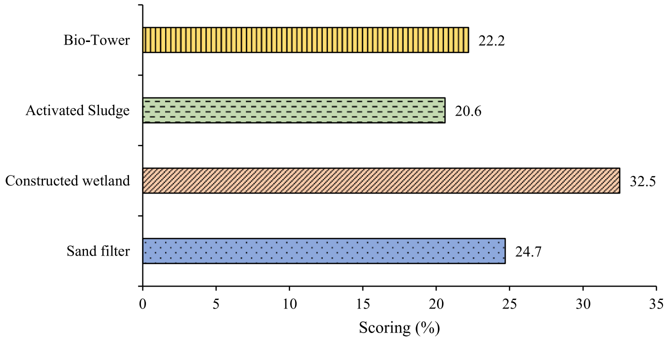

Fig. 7. Scores of secondary treatment alternatives based on the pair-wise comparison.

planners, and analysts) and (2) interest groups (such as political parties, civic organizations, and residents in the area in which there will be an impact). In this study, only the views of standard stakeholders were considered. Future studies should include the views of interest groups and compare the ranking of sustainable WWT technologies based on the preferences of both groups.

The outcome of this study contributes to the scientific discourse on the ease of incorporating the opinions and preferences of local experts into assessing the sustainability of WWT alternatives. The methodology applied in this study presents results in a form that decision makers could easily interpret. This study confirms the possibility of selecting the most sustainable WWT technology from a set of alternatives during the project planning stage. This requires a better understanding of the study area and the selection of stakeholders with the right expertise. The indicators' diversity and the varied experiences of the experts show that constructed wetlands could be used as secondary WWT technology in regions and countries with similar socio-cultural and environmental conditions.

4. Conclusions

The ER method was used in this study to rank and select the best secondary treatment option for wastewater reuse in agriculture. The sustainability assessment considered four secondary wastewater treatment alternatives (sand filter, constructed wetland, bio-tower, and activated sludge technologies). Four sustainability dimensions (economic, technological, environmental, and socio-cultural), five first-level indicators for the technological dimension, and a total of 35 indicators were used to assess the technology alternatives. The AHP method was applied to establish the relative weights of the indicators based on local experts' opinions. The primary sources of uncertainties that the ER method effectively handled were ignorance owing to the subjectivity of qualitative data and a lack of specific knowledge on the cost of the secondary WWT technologies. The results indicate that, among the four secondary wastewater treatment alternatives considered in this study, constructed wetland was the most sustainable for achieving quality effluent for reuse in agriculture in the City of Rafah, Gaza Strip. Sand filter was the second sustainable alternative to constructed wetland. The utility numbers for the constructed wetland with and without uncertainty were 0.7399 and 0.7345–0.7423 (on a scale of 0–1). Similarly, based on the pairwise comparison, constructed wetland had the highest score of 32.5%, making it the most sustainable from the experts' point of view. The environmental dimension, with a relative weight of 60.4%, had the highest influence on the ranking of the secondary treatment alternatives and the selection of the most sustainable alternative. In sustainability assessment using the ER method, the qualitative data (as used in the current study) should be supported with quantitative data for the economic dimension and estimated environmental impact to reduce the level of uncertainty. That notwithstanding, the ER method confirmed its reliability in assessing sustainability and ranking alternatives involving either or both qualitative and quantitative data, with or without uncertainty.

Author contributions

Sara Pennellini: Conceptualization, Supervision, Data Curation, Validation, Formal Analysis, Writing – Original Draft. **Eric Awere:** Data Curation, Validation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **Narges Kakavand:** Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft. **Alessandra Bonoli:** Funding acquisition, Project administration, Conceptualization, Methodology, Supervision, Writing – Review & Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eric Awere reports financial support was provided by Italian Agency for Development Cooperation.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2023.100611.

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