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RESEARCH ARTICLE

A multi-stage fuzzy decision-making framework to evaluate the appropriate wastewater treatment system: a case study

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Abstract

Selection of appropriate treatment processes for wastewater treatment (WWT) plants at the design stage involves a careful examination of different economic, environmental, and social parameters. Designers and decision-makers seek a compromise among such conflicting elements, which can be facilitated by decision support tools that are adapted for the ambiguity of individual opinions and decision parameters. This study aims to improve the qualification and efficiency of decision-making in WWT processes. A multi-stage framework is proposed to help select investments, technology, appropriate technology-specific system, and companies that apply such systems. The framework combines the Analytic Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), cash flow analysis, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) within fuzzy logic. The main contribution is the description and formation of an integrated framework to guide businesses and researchers for the evaluation of several WWT decision processes. To the best of the authors' knowledge, no study in the literature fuses multiple stages of this WWT process with the proposed approaches.

Keywords Industrial wastewater · Treatment process · Multiple criteria decision-making · Fuzzy logic · Uncertainty · Decision support systems

Introduction

Businesses and governments increasingly face environmental challenges in their operations, ranging from stricter regulatory compliance, public scrutiny, higher compliance costs, resource availability, climate change, and waste disposal (Büyüközkan et al. 2019; Collivignarelli et al. 2020; Liu et al. 2020). Increased awareness of regulators, suppliers, and clients on environmental issues leads to external pressure to limit environmental footprint related to manufacturing and consumption patterns of offered products and services. Until recently, the standard practice was end of pipe solutions that take action on the side effects of manufacturing activities when and where the actual pollution occurs. For instance, the solution to air pollution created by a thermal power plant was believed to be installing flue gas desulphurization equipment or a WWT plant in the case of a manufacturing facility. This understanding of environmental management is globally transforming. Therefore, selecting the appropriate WWT process at the start is ever more important. To cope with this subject, this paper proposes an integrated model that aims to enhance the process of making decisions in terms of quality and effectiveness for selecting the most appropriate WWT plant investment and technology alternative.

Selecting the most appropriate technology and design for environmentally friendly processes requires a methodological examination of large data sets in terms of environment, economics, and technology. Management of waste and wastewater usually contains conflicting elements regarding economic, environmental, and social aspects, requiring compromise decisions. For this reason, decision-makers need a comprehensive approach that works under uncertainty for deciding on waste management solutions. Such decision problems can be tackled with multi-criteria decision-making (MCDM) approaches (Gherghel et al. 2020). MCDM refers to taking decisions by considering multiple, usually conflicting criteria.

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The concept of uncertainty, which is a natural aspect of decision-makers' judgments, is usually not included in the research of traditional MCDM approaches. In real-world problems, on the other hand, it is not easy to translate decision-makers' judgments into absolute terms of 1-0 or true-false. In simulating real decision processes where phenomena are imprecise and vague, computing based on degrees of truth is more reliable. The fuzzy set theory (Zadeh 1965) can be useful in handling such problems with blurred boundaries. This study follows a multi-stage fuzzy decision-making procedure to create and evaluate the most suitable WWT decision system. For this, AHP (Saaty 1980), TOPSIS (Chen 2000), PROMETHEE (Goumas and Lygerou 2000), and different economic evaluation approaches (Chan et al. 2000) will be combined in a fuzzy environment. The aim is to best reflect the judgments of decision-makers who deal with the selection problem of a WWT investment for a case study.

Although there exist several MCDM studies in this field (Kalbar et al. 2012; Molinos-Senante et al. 2015; Sawaf and Karaca 2018), there is a research gap for developing suitable selection frameworks for WWT systems that incorporate different decision parameters. This paper proposes a decision-making framework to address this gap. This decision problem needs to be handled in a multi-layer decision environment. The contributions of this study to the WWT literature can be summarized as the following:

- It proposes a novel decision-making model by introducing different WWT problems in every phase, as well as by implementing hybrid evaluation techniques.
- It integrates cash flow analysis and three MCDM methods, i.e., AHP, PROMETHEE, and TOPSIS, in a fuzzy decision environment.
- It helps comprehend the theoretical processes of a WWT selection problem to better choose WWT system strategies.

To the best of the authors' knowledge, no study incorporates these different decision processes for the WWT selection problem. This procedure offers practical guidance to the WWT industry for deciding upon appropriate WWT strategies once wastewater elimination, minimization, and recycling are accomplished.

The next section of the study offers an overview of literature about the application area and briefly presents the WWT problem of the case company. The "Materials and methods" section presents the proposed multi-stage fuzzy MCDM approach and its computational procedure. The "Results and discussion" section illustrates the application of the proposed framework on a case company, ABC based in Istanbul. Finally, the "Managerial implications" section gives managerial insights, and the "Conclusion" section concludes the paper.

Literature review on the selection of WWT systems

WWT technologies have shown significant progress since the middle of the twentieth century. As far as WWT operations are concerned, the concepts of long-term sustainability, cost-effectiveness, resilience, reliability, and resource consumption are of primary importance. Similar to other fields, different alternatives should be examined and evaluated to decide on the most appropriate solution, also for environmental management programs. Quantitative models and software simulations are frequently used for wastewater management. Studies and applications in the literature concerning WWT problems usually discuss the experimental design dimension or carry out statistical analyses to search for optimal settings (e.g., intake and outflow of the plant, the outflow water quality) to attain a higher WWT performance.

Few of these articles focus on comparing different WWT technologies or processes from a decision-making perspective with several parameters. Having said that, the evaluation of wastewater technologies and processes is attracting attention. Kalbar et al. (2016) presented an alternative selection method for selecting an appropriate WWT technology. Their study involves environmental, economic, and social aspects as an evaluation framework with a life cycle sustainability approach for assessing different technologies. It studies two real-life case applications using TOPSIS. Another method is proposed by Mahjouri et al. (2017a) for selecting WWT technologies in the steel industry. A combined AHP and TOPSIS method based on fuzzy logic is used to evaluate those treatment systems. They found high system efficiency and environmental protection compliance to be important in treatment technology. Table 1 presents a summary of recent articles that deal with WWT technology/process evaluation and suggests that MCDM and programming approaches are frequently used in these studies.

The state of the art given in Table 1 shows a research gap for systematic approaches for deciding on WWT systems. To the best of the authors' knowledge, there is not any study in the literature for carrying out a holistic WWT decision process, starting with the investment phase, proceeding to choosing the WWT technology, and eventually closing with selecting the company that supports the preferred technology. While literature generally focuses on specific parts, such as WWT alternative selection, this research uses multi-stage modelling and multi-criteria analysis for this decision-making problem. Also, a real case study is proposed to offer insights into how these processes function.

Materials and methods

Multi-stage fuzzy decision-making methodology

Wastewater management is a multi-dimensional, complicated problem that is closely related to sustainable development. To

Table 1 Several WWT technology/process evaluation studies in recent years

Author	Topic	Methodology	Dimensions
Zeng et al. (2007)	Selection of WWT alternatives	AHP, GRA	Economic, technical, administrative
Kalbar et al. (2012)	Selection of WWT technology	TOPSIS	Environmental, economic, social
Kalbar et al. (2013)	Selection of WWT alternatives	AHP	Environmental, economic, sustainability
Molinos-Senante et al. (2015)	Selection of WWT technology	ANP (Analytic Network Process)	Environmental, economic, social
Sadr et al. (2015)	Selection of WWT technology	Fuzzy TOPSIS	Technical, economic, environmental, social
Aydiner et al. (2016)	Selection of WWT technology	AHP	Technical, economic, environmental
Castillo et al. (2016)	Selection of WWT process concepts	Knowledge-based systems and mixed-integer non--linear programming	Technical, economic, environmental
Dursun (2016)	Selection of WWT alternatives	Fuzzy VIKOR (VIseKriterijumska Optimizacija i kompromisno Resenje)	Environmental, economic, social
Kamble et al. (2017)	Selection of WWT technology	Fuzzy Delphi, Fuzzy AHP and Fuzzy TOPSIS	Technical, economic, environmental, social
Mahjouri et al. (2017b)	Selection of WWT technology	Fuzzy Delphi and Fuzzy AHP	Technical, economic, environmental
Ren and Liang (2017)	Selection of WWT technology	Intuitionistic fuzzy set theory-based group multi-attribute decision analysis	Environment, economy, society-politic, technology
Al Sawaf and Karaca (2018)	Evaluation of WWT technology	AHP, Simple Additive Weighing (SAW)	Technical, economic, environmental, social
Chen et al. (2018)	Selection of municipal sewage treatment technology	Multi-objective programming	Economic, environmental
Gómez et al. (2018)	Evaluation of the eco-efficiency of WWT plants	Data envelopment analysis (DEA)	Economic, environmental
Promentilla et al. (2018)	Selection of sewage treatment technology	Stochastic Fuzzy Analytic Hierarchical Network Process	Technical, economic, environmental, social, space
Triantafyllidis et al. (2018)	Evaluation of WWT technology	Agent-Based Modelling, Mixed-Integer Linear Programming	Technical, social, economic
Zhou et al. (2018)	WWT plans selection	Intuitionistic Fuzzy TOPSIS	Economic, technical, management, sustainability
Gherghel et al. (2020)	WWT plants design	SAW, Paired Comparison Technique	Economic, environmental
Yao et al. (2020)	Evaluation of WWT technology	Incomplete interval type-2 fuzzy preference relations based MCDM	Technical, economic, environmental, societal
Cossio et al. (2020)	Sustainability assessment of WWT systems	EVAluation of Sustainability (EVAS) decision tool	Technical, economic, environmental, social, institutional
Lizot et al. (2020)	Selection of WWT systems	Expressing the Reality (ELECTRE II)	Technical, economic, environmental, social
Wei et al. (2020)	Selection of biological technology for WWT	AHP	Technical, economic, environmental, administrative
Zhang et al. (2020a)	Evaluation of WWT technology	Fuzzy AHP and evidence theory	Technical, economic, environmental, social

deal with the WWT decision-making problem, an integrated model is proposed to compare the suitability of different alternatives. Fuzziness is unavoidable in the WWT technology selection due to its uncertain nature. This makes MCDM a suitable method for the objective of this paper. In the literature, MCDM techniques are used for several waste-themed studies. Eskandari et al. (2016) proposed a fuzzy AHP model for selecting solid waste disposal sites by considering landslide risks. More recently, Khoshand et al. (2019) used a fuzzy AHP approach to assess different alternatives for e-waste collection and processing by using a case in Iran. Another article by Zhang et al. (2020b) presented a fuzzy AHP and fuzzy comprehensive evaluation for the risk grade evaluation of sudden water pollution and demonstrated their method on the Yongding River as a case study.

The proposed MCDM approach includes four consecutive phases, in which different decision techniques are utilized. The method is presented in Fig. 1. The summary of the main calculation steps is provided below. The technical details and formulations are available in Supplementary Materials. Readers may refer to the indicated references for additional information on the techniques used in the article.

Phase I—Decision on investment At this initial phase, the decision of "to invest" or "not to invest" in the WWT system is made. Once the decision goal is defined, a group of experts is formed, and the available alternatives and evaluation criteria sets are identified. This group of experts can consist of the personnel, experts, consultants, or managers of different departments, such as research and development, quality, and engineering. Each decision-maker is expected to independently express his or her opinion.

The importance of the evaluation criteria is determined with the fuzzy AHP algorithm. AHP, first developed in 1980 by T.L. Saaty (1980), is a numerical approach for putting a complex multi-attribute issue into a hierarchical perspective. It is an objective technique for handling decision problems among a defined set of possible alternatives. The method of fuzzy AHP is basically an integration of the AHP technique and fuzzy set theory together to describe the decision-making process more accurately. Once the evaluation criteria weights are found, the alternatives are evaluated with the help of the fuzzy PROMETHEE (F-PROMETHEE) method according to the description provided by Goumas and Lygerou (2000).

Phase II—Decision on technology In this second phase, the ultimate aim is to select the most appropriate WWT system among various technology options. At this phase, the technology selection algorithm described by Chan et al. (2000) is utilized to calculate the advantages in a fuzzy environment. The same algorithm also includes a fuzzy cash flow analysis with an economic assessment perspective.

Phase III—Decision on system type This phase aims to decide on the "system type for the technology which is selected in phase II" with the help of the fuzzy AHP method. The notation and calculation steps are given in phase I with formulae (1)-(7).

Phase IV—Decision on technology supporting company This phase aims to select the "most appropriate company which will provide the wastewater system construction service." For this purpose, fuzzy TOPSIS is utilized to compare

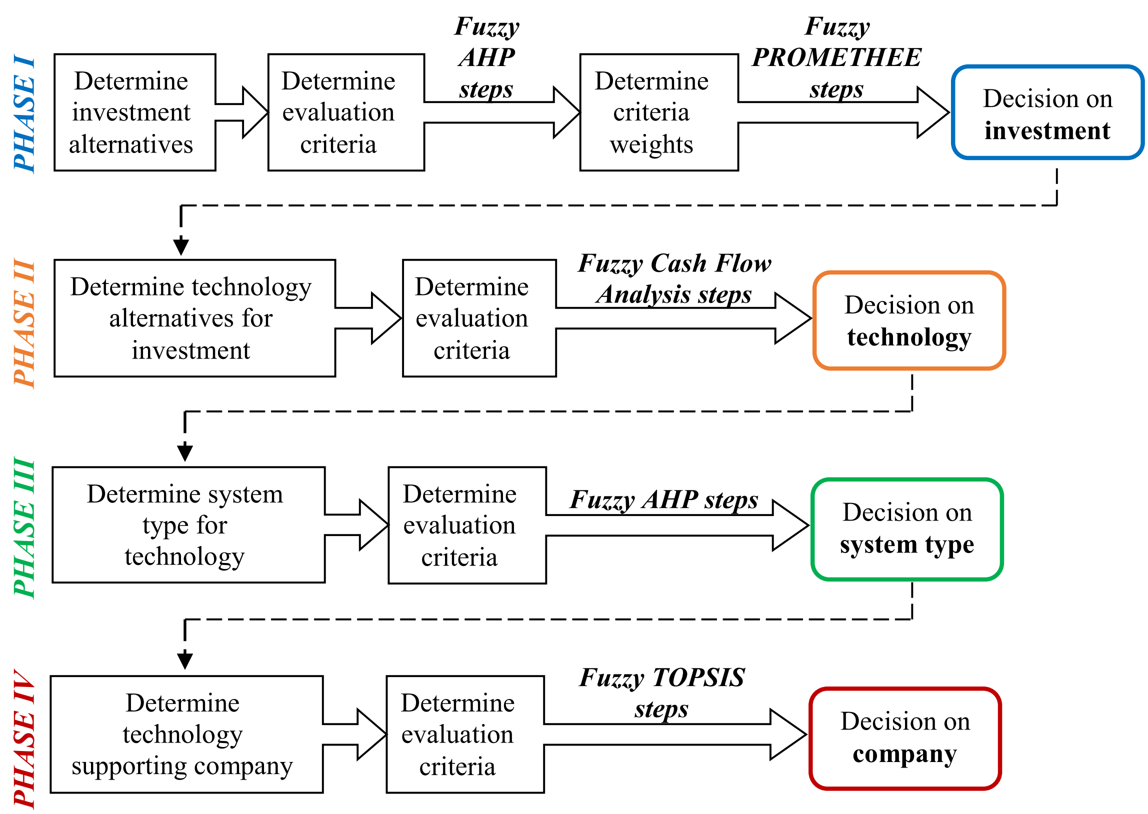


Fig. 1 Four-phase evaluation model

available technology providing companies, as explained by Chen (2000).

Problem definition and data for the case study

The application of the framework will be demonstrated on a case company, ABC, based in Istanbul, Turkey. ABC Company has been a leading player in innovation and forms the future of the domestic electronics industry. Since its establishment in 1847, ABC Company is a reliable industry partner which manufactures control equipment, other facilities of control, and telephone wires. Some of the processes, such as the shaping of metals and duroplasts that are used as inputs for further processing stages, are carried out in workshops. Some other assembly components are imported. Environmental issues are of key importance, also reflected in its certification with ISO 14001. Similar to the usual practices in the electric and electronics industry, ABC Company recycles metal waste, plastic, as well as glass, paper, and batteries. Special attention is paid to toxic waste recycling, such as oil, dye waste, and mud that are generated from the bath of galvanizations, and aerosol boxes. The galvanization workshop creates toxic waste (heavy metals and other toxic chemical components) in the forms of wastewater, which must be treated before discharging it to the sewage system. To decrease the concentration of heavy metals, ABC Company sediments and precipitates its wastewater. Following the sedimentation, two material streams are obtained, a sludge with toxic remains and purified water, which is directly discharged to the sewage system. The sludge contains metal hydroxides and other metals and stays in the sedimentation basin to be cleaned. The composition of the sludge mostly depends on the type of processes; however, various kinds of metals can be found that must be separated. ABC Company collects and stores this sludge, after which it is sent to IZAYDAS, a hazardous waste disposal company, for incineration, leading to the following problems:

- Very high water consumption, remarkably increasing operational costs
- Increase in electricity and chemical consumption
- High discharge and disposal fees for the mud generated in the basins
- Need for a continuous monitoring system, complicating the management structure

The literature mentions additional functions expected from WWT plants for a circular economy, such as effective local recovery of water, sludge, and nutrients (Cossio et al. 2020). Heavy metals can be highly toxic and even fatal to humans and aquatic organisms (Chen et al. 2021). As also suggested by the Environmental Management Department of ABC Company, improved water treatment can be an effective solution to such problems. Poor design or selection of improper technology for WWT plants can be another reason for failure, which is also a concern in the literature (Cossio et al. 2020). Therefore, selection processes should be performed systematically.

Application

The expert group formed for the case study consists of five decision-makers, who are the managers and assistant managers of the Environmental Management and Quality Departments of ABC Company, as well as the executive vice president, who is responsible for these units. These experts are employed by ABC Company and therefore know the ongoing problems sufficiently well. The experts are selected such that each member has many years of relevant experience. This makes the decision committee sufficiently knowledgeable and experienced for this decision problem. Each decision-maker is treated equally. The importance of the evaluation criteria, which are found by the group, is obtained by comparing the criteria pair by pair. These experts make use of linguistic variables in evaluating the alternatives. Consensus of the experts will be sought. The evaluations are made based on evaluation criteria. Based on a literature survey, the authors have initially proposed a list of evaluation criteria for this problem. Using the feedback of the expert group about these criteria, the evaluation criteria are adapted and finalized, as explained below.

Phase I: Decision on investment

At this phase, the expert group considers economic and environmental criteria (Kalbar et al. 2012; Molinos-Senante et al. 2015; Arroyo and Molinos-Senante 2018; Sawaf and Karaca 2018; Gherghel et al. 2020) to take the decision "A1 - Not to invest" or "A2 - To invest" in the WWT system. The detailed model of phase I is presented in Fig. 2.

Economic criterion—C1 This criterion covers the incurred costs. Water (C11), electricity (C12), discharge (C13), and chemical (C14) costs constitute the operating costs of the investment. Considering that WWT achieves 90% water savings, the investment is expected to fare well for this criterion. The frequency of monitoring (C15) represents the number of controls carried out during an entire day. When an operation transforms from a continuous to a discontinuous one, this monitoring frequency will naturally decrease. These criteria can change depending on the issues that the companies are taking forward (such as the cost of labor).

Environmental criterion—C2 This criterion includes subcriteria that are related to the environmental impacts caused by current practices and by the WWT system in question.

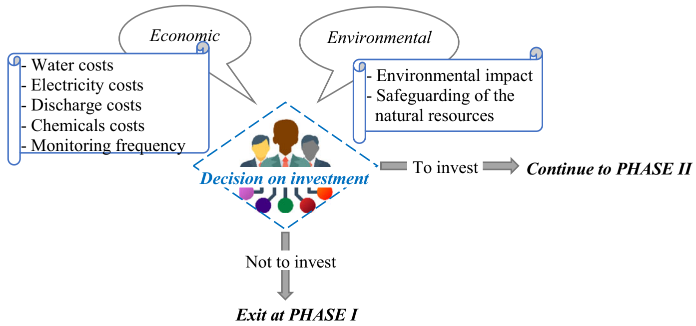


Fig. 2 Overview of phase I

Environmental impact (C21) considers the amount of generated toxic waste, and C22 assesses how the existing system and the WWT benefit natural resources.

At this point, experts give linguistic evaluation inputs between criteria using the scale given in Step 1.1 of phase I. Linguistic evaluation matrix of C11–C15 is given in Table 2 as a sample evaluation. Table 2 gives the linguistic evaluations of experts, and Table 3 shows their fuzzy number equivalents. Evaluations of criteria C21–C22 and C1–C2 are found to be identical, and linguistic data from decision-makers is provided as "L" when C1 is compared to C2. Consequently, the weights are found as C1= (0.471, 0.667, 0.816) and C2= (0.272, 0.333, 0.471) (Tables 4 and 5).

As an example for fuzzy AHP steps, linguistic evaluation of C11 against other criteria are shown in Table 3, with the following fuzzy values: C11–C11 = C11 – C12 = C11 – C13 = C11 – C14 = C11 – C15 = (1,2,3). The triangular fuzzy weight of criteria C_{11} can be calculated (Lockström et al. 2010; Tuzkaya and Önüt 2008; Tuzkaya et al. 2009):

$$w_1^l = \frac{(1\times1\times1\times1\times1)^{1/5}}{(1\times2\times2\times2\times2)^{1/5}+(1/2\times1\times1/2\times3\times2)^{1/5}+(1/2\times2\times1\times2\times3)^{1/5}+(1/2\times1/3\times1/2\times1\times1/2)^{1/5}+(1/2\times1/2\times1/3\times1/2\times1)^{1/5}}$$

$$w_1^m = \frac{(1\times2\times2\times2\times2)^{1/5}}{(1\times2\times2\times2\times2)^{1/5}+(1/2\times1\times1/2\times3\times2)^{1/5}+(1/2\times2\times1\times2\times3)^{1/5}+(1/2\times1/3\times1/2\times1\times1/2)^{1/5}+(1/2\times1/2\times1/3\times1/2\times1)^{1/5}}$$

$$w_1^u = \frac{(1\times3\times3\times3\times3)^{1/5}}{(1\times2\times2\times2\times2)^{1/5}+(1/2\times1\times1/2\times3\times2)^{1/5}+(1/2\times2\times1\times2\times3)^{1/5}+(1/2\times1/3\times1/2\times1\times1/2)^{1/5}+(1/2\times1/2\times1/3\times1/2\times1)^{1/5}}$$

The weight is calculated as $\widetilde{w}_1 = \left(w_1^l, w_1^m, w_1^u\right) = (0.184, 0.319, 0.442)$.

The consistency of the obtained results is checked with the CR to verify if the pair-wise comparisons are consistent among themselves. For this purpose, the priority vector and Principal Eigenvalue (λ_{max}) are needed. The priority vector is calculated by taking the average across each of the rows of the normalized matrix. The Principal Eigenvalue is obtained from the average of the divisions between *the multiplication of each element of the priority vector and evaluation matrix* and *priority vector*. Normalized evaluation matrix and priority vector are also shown in Table 3.

The priority vector is multiplied with the reciprocal evaluation matrix, and the values obtained are 1.69, 1.08, 1.37, 0.68, and 0.51. After the division with the priority vector, values are equal to 5.36, 5.34, 5.37, 5.17, and 5.19. Their average gives the Principal Eigenvalue, $\lambda_{max} = 5.285$. The random consistency index (RI) for n=5 is 1.12 according to Saaty's scale.

Table 2 Linguistic evaluation matrix for criteria C11–C15

	C11	C12	C13	C14	C15	Weight
C11	1	L	L	L	L	(0.184, 0.319, 0.442)
C12		1		FL	L	(0.136, 0.199, 0.302)
C13		L	1	L	FL	(0.169, 0.263, 0.376)
C14				1	L	(0.090, 0.121, 0.199)
C15					1	(0.072, 0.097, 0.160)
						Consistency: 0.064

Table 3 Fuzzy evaluation matrix for criteria C11–C15

Reciprocal evaluation matrix						Priority vector
	C11	C12	C13	C14	C15	(defuzzified weights)
C11	1	(1,2,3)	(1,2,3)	(1,2,3)	(1,2,3)	0.31
C12	(1/3,1/2,1)	1	(1/3,1/2,1)	(2,3,4)	(1,2,3)	0.20
C13	(1/3,1/2,1)	(1,2,3)	1	(1,2,3)	(2,3,4)	0.26
C14	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	1	(1,2,3)	0.13
C15	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	1	0.10

$$CI = (5.285-5)/(5-1) = 0.071$$

$$CR = CI/RI = 0.071/1.12 = 0.064 < 0.10 \text{ (i.e., consistent)}.$$

Following the identification of the weights of the evaluation criteria, the F-PROMETHEE technique is applied to evaluate the two available alternatives. Table 4 shows the evaluation data of the expert group and the results. Based on the evaluations, the leaving flows ϕ^{+} and entering flows ϕ^{-} are calculated. According to the outranking rule of F-PROMETHEE given in Step 2.3 of phase II, A2 ("to invest") is by a far margin the preferred decision ($\phi^{+}2 > \phi^{+}1$ and $\phi^{-}2 < \phi^{-}1$).

Phase II: Decision on technology

ABC has carried out a technical study that compared various water treatment methods and decided that the most suitable WWT technology for its needs is the use of an ion exchanger (alternatives in phase II are based on this technology). Ion exchangers can help purify the water from cyanides and heavy metals.

There are two alternatives for ion exchangers, with different methods. For alternative A3, the wastewater generated by the CN and alkali baths and the wastewater coming from the Cr and acidic baths is combined and then sent to the ion-cathode exchanger. Then they are sent to the ion-anode exchanger without paying attention to ions' signs of the wastewater. For alternative A4, the wastewater that comes from the CN and alkali baths is sent to the ion-anode exchanger. At the same time, the wastewater that comes from the Cr and acidic baths is separately directed to the ion-cathode exchanger. With this method, wastewater streams having different signs are not mixed.

These two alternatives are compared based on facility management, economic, volumetric capacity, and water quality criteria (Arroyo and Molinos-Senante 2018; Chen et al. 2018; Garrone et al. 2018; Gherghel et al. 2020). Here, *facility management* implies those processes that make the system easier to manage and maintain (Sawaf and Karaca 2018). *Economic* feature is represented by the net present value (NPV) of the considered investment. *Volumetric capacity* is the total amount of daily wastewater that can be treated and recycled with the associated system. The last criterion, *water quality*, stands for the threshold limits for the chemicals, heavy metals, and other contaminants dissolved in the discharged water. A detailed model of phase II is presented in Fig. 3.

Assessment data submitted by the experts is shown in Table 5. It also lists the results of the assessment, which concludes that the alternative A4 should be chosen as it has a higher score of importance weight.

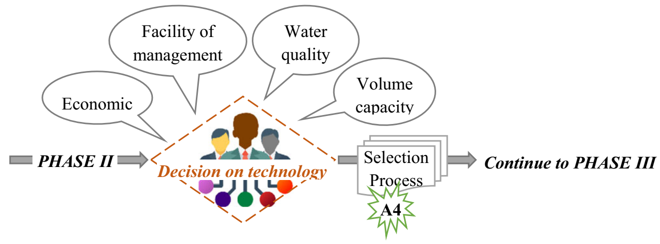
Phase III: Decision on system type

In this phase, based on the market research of ABC Company, the alternatives in question are either implementing a modular (A5) or a central (A6) system. While A6 is a standard ion exchange system, A5 has mobile modular ion exchange units. The central system includes a holding tank, pre-filtration with bag filters followed by cartridges, and two ion exchange tanks. The modular system uses the same cation exchange resin as

Table 4 Data of the first phase

	Evaluations							Results	
	C11 (TL)	C12 (TL)	C13 (TL)	C14 (TL)	C15	C21	C22	ϕ+	ϕ-
A1	Approx. 100	Approx. 100	Approx. 700	Approx. 10	L	FL	G	(0, 0, 0)	(0.44, 0.87, 1.48)
A2	Approx. 700	Approx. 900	Approx. 700	Approx. 70	VG	FG	L	(0.44, 0.87, 1.48)	(0, 0, 0)

Fig. 3 Overview of phase II



the system in the mine that treats the major metal source. These alternatives are compared based on economic (C1), technical (C2), and administrative (C3) characteristics of the alternative (Molinos-Senante et al. 2015; Arroyo and Molinos-Senante 2018; Sawaf and Karaca 2018; Zhang et al. 2020a). C1 includes capital, personnel, operational, and maintenance costs. C2 includes applicability and performance. C3 includes reliability and sustainability. A detailed model of phase III is presented in Fig. 4.

The evaluations submitted by the experts of ABC Company Istanbul are shown in Table 6. Table 7 gives the results obtained. Accordingly, the central system (A6) should be preferred over the modular alternative as it has a higher evaluation weight for each of the criteria.

Phase IV: Decision on technology supporting company

The candidate technology providers are also determined by the experts of ABC Company (as A7, A8, and A9) and evaluated based on six criteria (Kalbar et al. 2012; Molinos-Senante et al. 2015; Chen et al. 2018; Garrone et al. 2018; Zhang et al. 2020a) supported by our literature survey (Fig. 5).

- Initial cost of the investment—C1: This criterion refers to the initial investment cost proposed by the companies.
- References—C2: This criterion stands for the proven experience of companies to ensure their capability, such as having recently constructed similar plants for other clients.
- Popularity—C3: This represents the image, public acceptance, and recognition of this firm in the market.
- Quality—C4: This is the offered service quality of that company.
- Experience with the company—C5: This criterion checks whether ABC Istanbul has received acceptable services from this company in the past.
- After-sales services—C6: This criterion is about the characteristics and the quality of the after-sales services.

The evaluation data of the experts for this stage is given in Table 8. Table 9 shows the obtained results, indicating that the most suitable company is A8 with the highest coefficient of closeness.

Results and discussion

Managerial implications

The findings of this study provide clues for both administrators and researchers. WWT selection will not only have implications for the environmental footprint for many companies; it also leads to cost savings and other benefits. Each phase of the proposed framework can be adapted individually or wholly, according to the needs of the firms. The final adaptation can be made according to the different criteria. Although the obtained results are specific to the case study of this article, the proposed analytical decision methods can also be used to decide on the best alternatives for other types of WWT. Besides being an individual support tool, this proposed framework can also be used for supporting the decisions of the senior management by offering a structured input for WWT selection. According to Ozturk (2018), Turkey is a candidate member of the European Union, and the harmonization process of the EU acquis has been initiated with the environmental protection laws. Therefore, Turkey is aligning its national laws, and regulations with the European Union environmental legislation. New industry installations will be subjected to stricter environmental requirements, and existing conventional WWT facilities will be upgraded for compliance in the future. ABC Company also aims to revise its treatment processes accordingly. The selection of an appropriate treatment process is an important issue before the design and implementation of treatment plants.

Table 5 Data for the second phase

	Evaluations				Results
Technology	C1 (Fuzzy NPV-TL)	C2	C3	C4	Fuzzy appropriate index
A3	(−238.94, −321.28, −402.80)	FL	M	M	(0.040, 0.115, 0.230)
A4	(−227.79, −264.31, −299.05)	FG	M	M	(0.063, 0.133, 0.240)

Fig. 4 Overview of phase III

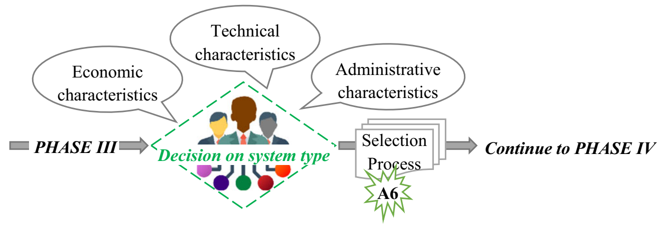


Table 10 presents the results of the case application in this study. According to the case company, WWT enables companies to reduce their water consumption by up to 90%. It can allow to recycle and reuse the treated effluent in the manufacturing processes, thereby reducing freshwater consumption and related operational costs (Gholipour et al. 2020). Another point is that the use of such a WWT system also makes the process become discontinuous, lessening the frequency of monitoring (C5 in the first phase). To summarize the first phase of the case study, economic criteria are more important than environmental criteria.

Ion exchangers (the evaluated alternative in the second phase) prevent sludge formation, which is composed of metals and other chemicals so that there is no more toxic waste to discharge. The second phase shows that ion exchangers, which do not mix wastewater streams with different signs, are more desired. When the question is about selecting the most suitable system type for ion exchangers, the third phase indicates that implementing a central system is better than a modular system according to economic, technical, and administrative characteristics. Finally, the fourth phase selects the most suitable technology provider company that will construct the WWT system. The results of the case study support the literature about using adsorption mechanism via ion exchange. The literature has extensively explored various treatment methods, such as chemical oxidation and biological treatment, for removing metal complexes from industrial effluents. Ion exchange methods have so far been one of the most widely accepted technologies, thanks to their low cost, short equilibrium time, ease of implementation, and reusability (Vidal et al. 2012; Chen et al. 2021). ABC Company also agrees with these benefits. When the results of this case study are presented to the expert group, it is observed that they agree with the experts' judgments. Several observations were made by the case company showing that the selected alternatives in the decision phases were appropriate and correct and that this analytical method gave good results. ABC Company also stated that the standard ion exchange system (central system) can remove metals from the source effectively enough to treat the entire mine discharge and meet water quality standards. Even though this WWT system has increased the firm's capital and operational expenditures, the termination of high discharge fees and transportation and disposal costs have brought further gains to the company. The environmental impacts of wastewater and the efficient use of resources provide additional benefits.

In real-world cases, decisions should be supported by multiple criteria and logical methods. In this paper, ABC Company's expert group reaches similar or the same results in the case study without this application framework and methods. However, when problems are supported with real analytical techniques, the results become more tangible, convincing, and reliable. Regarding the advantages and appropriateness of the proposed method for the problems to be solved, the criteria used in the framework are considered to be independent. AHP is selected especially for parts where linguistic evaluations can be performed between independent criteria. Several studies also emphasize the condition of the AHP method as the independency of the criteria from each other (Büyüközkan and Çifçi 2012; Kazuva et al. 2020; Uliasz-Misiak et al. 2021).

WWT problems are frequently handled with MCDM methodologies, as Table 1 shows. Here, AHP acts as a value measurement model by decomposing a decision problem into its hierarchical components and prioritizing a set of weighted criteria. In phases I and III, this method also supported the translation of the subjective decision-maker opinions into measurable numeric relations. Also, in phase I, PROMETHEE as an outranking method simultaneously dealt with qualitative and quantitative criteria for the decision of investment. This method compared the alternatives pairwise for each criterion, finding the strength of preferring "to invest" over "not to invest." In phase II, as the economic criterion is represented by the net present value (NPV) of the considered investment, cash flow analysis is used to define the cash position of ABC Company. According to Kahraman et al. (2002), experts' knowledge about discounting cash flows consists of many uncertainties rather than randomness in an ambiguous economic decision environment. Cash amounts and interest rates are usually predicted using educated guesses based on expected values or other statistical techniques to obtain them. Fuzzy numbers can handle the difficulties in

Table 6 Evaluations of the third phase

C1	A5	A6	C2	A5	A6	C3	A5	A6
A5	1		A5	1		A5	1	
A6	FG	1	A6	VG	1	A6	VG	1

Table 7 Results of the third phase

Weight	C1	C2	C3
A5	(0.117, 0.125, 0.135)	(0.095, 0.100, 0.106)	(0.095, 0.100, 0.106)
A6	(0.810, 0.875, 0.935)	(0.849, 0.900, 0.949)	(0.849, 0.900, 0.949)

estimating these parameters. Finally, in phase IV, TOPSIS as a simple and effective MCDM model, measured how well the technology supporting company alternatives meet the desired criteria goals. Also, when fuzzy logic is integrated into these methods, the decision tool becomes more flexible and works more similar to human reasoning by handling the problems with imprecise data.

The use of fuzzy sets introduces robustness in decision-making processes by facilitating the comparison in the traditional weighting methods by addressing the uncertainty associated with human judgments. The literature also supports the features of fuzzy logic when integrated into decision-making methods such as removing bias from decision criteria and increasing the reliability of evaluation results (Büyüközkan and Çifçi 2011; Ali et al. 2021; Tang et al. 2021; Wang and Yang 2021). According to Ali et al. (2021), uncertainty is better addressed by using fuzzy numbers instead of crisp values under the assumption that this is a good solution that decision-makers can provide. Also, the fuzzification of the rating approach provides a way to better deal with decision-makers' uncertainty regarding the boundaries of their preferences. As a result, a hybrid analytic framework is built to strengthen the decision-making process.

Comparative analysis

Another crucial point is the evaluation approach's feasibility. The proposed hybrid approach consists of different multi-attribute evaluation and decision methods. Especially in the fuzzy AHP steps of the study, criteria priorities can be changed when other fusion methods are applied. This difference can lead to diverse evaluation results. Therefore, a comparative analysis is applied.

For MCDM problems, different aggregation methods are employed in the literature. After research on these methods, it is decided to perform a comparative analysis to confirm the feasibility of the fuzzy AHP prioritization step. In this study, the logarithmic least-squares method (LSM) (Eq. 6) is used to obtain the final weights. To make a comparison, the Ordered Weighted Aggregation (OWA) operator (Yager 1988) is applied, which also handles aggregation and prioritization issues. Readers are referred to that article for more detailed information. A sample comparison is performed for the third phase of the proposed evaluation framework, and the changes in the ranking are controlled. The outcomes of the analysis are displayed in Fig. 6.

According to the results, two methods provided equivalent alternative rankings (A6 > A5) with different weights. Although these weighting operators supply different weight scales, the results indicate A6 as the best alternative. The result of LSM can be seen in Table 7 with the middle values of fuzzy results. Here, the results of the OWA operator act in a similar way. It shows that both of these methods are consistent and valid for weighting purposes in decision-making. Based on this comparative analysis, it can also be concluded that these methods give different weights and do have an impact on the results. Even if the ranking did not change, the effects of varying weighting methods can be seen more clearly as the ranking changes with different evaluations, which includes similar criteria weights.

Fig. 5 Overview of phase IV

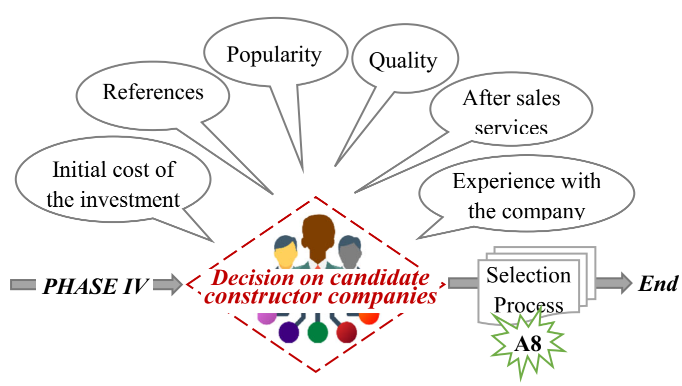


Table 8 Evaluations of the fourth phase

Company	C1 (1000 €)	C2	C3	C4	C5	C6
A7	Approximately 120	G	MG	G	VL	FG
A8	Approximately 140	VG	VG	VG	L	FG
A9	Approximately 100	FG	MG	FG	L	VG

Conclusion

This paper introduced an integrated fuzzy MCDM evaluation model as a solution alternative for the WWT investment problem. Its usability is validated on a case study with ABC Company, Istanbul. Real-life multi-criteria problems are usually solved with uncertain and imprecise inputs. The fuzzy set theory can be an adequate tool to handle such situations. Once the relevant evaluation criteria are properly identified, the proposed four-phase evaluation framework is deployed step by step by combining different MCDM algorithms. The framework allows experts to express their preferences in a more systematic and accountable selection process.

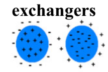
Evaluation criteria are determined at every phase of the study, based on a literature review and expert opinions. Then, critical decisions are made, such as "to invest or not to invest" and "to select the most suitable technology, system type, or candidate constructor company." This study contributes to the state of the art by proposing a new evaluation framework that includes different stages of the decision model including quantitative and qualitative data. Moreover, it is the first publication that handles all of the possible strategic decision-making stages for a WWT investment process, integrating AHP, PROMETHEE, cash flow analysis, and TOPSIS techniques in a fuzzy environment with group decision-making. This guides researchers and business managers to better understand the process of WWT investment problem and thus helps select WWT system strategies. A case study is provided to validate the presented approach.

The proposed integrated method can also be useful to form other suitable decision-making processes for other purposes. To the knowledge of the authors, this paper is the first study that deals with four phases of a WWT system investment and selection using a combined decision-making methodology. The study also has its limitations. The case study showed that the evaluation framework is reasonable and easily applicable

Table 9 Results of the fourth phase

The distance to PIS	The distance to NIS	CC
S_{A7}^{+} = (0.050, 0.082, 0.145)	S_{A7}^{-} = (0.022, 0.029, 0.045)	C_{A7}^{*} = (0.116, 0.261, 0.625)
S_{A8}^{+} = (0.035, 0.012, 0.068)	S_{A8}^{-} = (0.052, 0.082, 0.144)	C_{A8}^{*} = (0.245, 0.872, 1.655)
S_{A9}^{+} = (0.049, 0.063, 0.089)	S_{A9}^{-} = (0.036, 0.056, 0.111)	C_{A9}^{*} = (0.180, 0.470, 1.300)

Table 10 Summary for the proposed WWT Framework's Application

WWT Problems	Aspects	Results	Decisions
Decision on **investment**	Economic (Water costs, Electricity costs, Discharge costs, Chemicals costs, Monitoring frequency) Environment (Environmental impact, Safeguarding)	A2 > A1	**To invest** 
Decision on **technology**	Economic Water quality Facility of management Volume Capacity	A4 > A3	**Ion exchangers** 
Decision on **system type**	Economic (Capital costs, Personnel costs, Operational costs, Maintenance costs) Technical (Applicability, Performance) Administrative (Reliability, Sustainability)	A6 > A5	**Central System** 
Decision on **company**	The initial cost of the investment References Popularity Quality Experience with the company After-sales services	A8 > A9 > A7	**Company Y** 

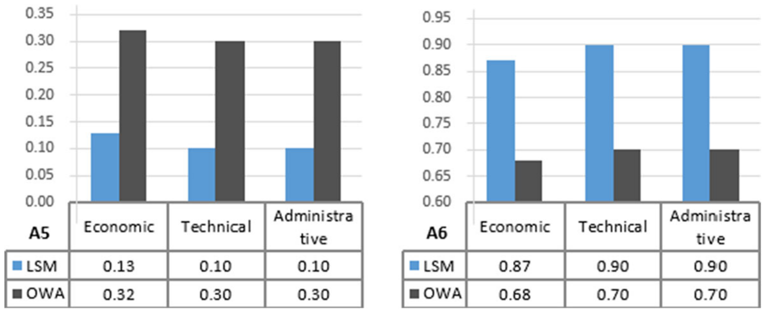


Fig. 6 Results of the comparative analysis for phase III

to the strategic decisions about WWT. With the judgment of experts in this case study, it is considered that the criteria of the framework are sufficient, and the methodology is reliable. Nevertheless, for future work, evaluation criteria and the framework can be enriched. Another perspective can be the application of different MCDM approaches and fuzzy extensions for comparison purposes.

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Availability of data and materials All data generated or analyzed during this study are included in the article.

Author contribution GB contributed to the conceptualization, methodology, resources, investigation, writing (review and editing), project administration, and funding acquisition. GT contributed to the conceptualization, methodology, formal analysis, investigation, and writing of the original draft. All authors have read and approved the final manuscript.

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References

Ali SKA, Parvin F, Al-Ansari N, Pham QB, Ahmad A, Raj MS, Anh DT, Ba LH, Thai VN (2021) Sanitary landfill site selection by integrating AHP and FTOPSIS with GIS: a case study of Memari Municipality, India. Environ Sci Pollut Res 28:7528–7550

Arroyo P, Molinos-Senante M (2018) Selecting appropriate wastewater treatment technologies using a choosing-by-advantages approach. Sci Total Environ 625:819–827

Aydiner C, Sen U, Koseoglu-Imer DY, Can Dogan E (2016) Hierarchical prioritization of innovative treatment systems for sustainable dairy wastewater management. J Clean Prod 112:4605–4617

Büyüközkan G, Çifçi G (2011) A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information. Comput Ind 62(2):64–174

Büyüközkan G, Çifçi G (2012) Evaluation of the green supply chain management practices: a fuzzy ANP approach. Prod. Plan. Control 23(6):405–418

Büyüközkan G, Gocer F, Karabulut Y (2019) A new group decision making approach with IF AHP and IF VIKOR for selecting hazardous waste carriers. Measurement 134:66–82

Castillo A, Cheali P, Gómez V, Comas J, Poch M, Sin G (2016) An integrated knowledge-based and optimization tool for the sustainable selection of wastewater treatment process concepts. Environ Modell Softw 84:177–192

Chan FTS, Chan MH, Tank NKH (2000) Evaluation methodologies for technology selection. J Mater Process Tech 107:330–337

Chen CT (2000) Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Set Syst 114:1–9

Chen X, Xu Z, Yao L, Ma N (2018) Processing technology selection for municipal sewage treatment based on a multi-objective decision model under uncertainty. Int J Env Res Pub He 15(3):448

Chen M, Li S, Jin C, Shao M, Huang Z, Xie X (2021) Removal of metal-cyanide complexes and recovery of Pt(II) and Pd(II) from wastewater using an alkali–tolerant metal-organic resin. J Hazard Mater 406: 124315

Collivignarelli MC, Carnevale Miino M, Caccamo FM, Baldi M (2020) Evaluation of foaming potential for water treatment: limits and developments. Environ Sci Pollut Res 27:27952–27960

Cossio C, McConville JR, Mattsson A, Mercado A, Norrman J (2020) EVAS - a practical tool to assess the sustainability of small wastewater treatment systems in low and lower-middle-income countries. Sci Total Environ 746(1):140938

Dursun M (2016) Evaluation of wastewater treatment alternatives using fuzzy VIKOR method. J Adv Manag Sci 4(4):333–336

Eskandari M, Homaee M, Falamaki A (2016) Landfill site selection for municipal solid wastes in mountainous areas with landslide susceptibility. Environ Sci Pollut Res 23:12423–12434

Garrone P, Grilli L, Groppi A, Marzano R (2018) Barriers and drivers in the adoption of advanced wastewater treatment technologies: a comparative analysis of Italian utilities. J Clean Prod 171:69–78

Gherghel A, Teodosiu C, Notarnicola M, De Gisi S (2020) Sustainable design of large wastewater treatment plants considering multi-criteria decision analysis and stakeholders' involvement. J Environ Manage 261:110158

Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. Chemosphere 247:125966

Gómez T, Gémar G, Molinos-Senante M, Sala-Garrido R, Caballero R (2018) Measuring the eco-efficiency of wastewater treatment plants under data uncertainty. J Environ Manage 226:484–492

Goumas M, Lygerou V (2000) An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects. Eur J Oper Res 123:606–613

Kahraman C, Ruan D, Tolga E (2002) Capital budgeting techniques using discounted fuzzy versus probabilistic cash flows. Inf Sci 142(1–4):57–76

Kalbar PP, Karmakar S, Asolekar SR (2012) Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. J Environ Manage 113:158–169

Kalbar PP, Karmakar S, Asolekar SR (2013) The influence of expert opinions on the selection of wastewater treatment alternatives: a group decision-making approach. J Environ Manage 128:844–851

Kalbar PP, Karmakar S, Asolekar SR (2016) Life cycle-based decision support tool for selection of wastewater treatment alternatives. J Clean Prod 117:64–72

Kamble SJ, Singh A, Kharat MG (2017) A hybrid life cycle assessment based fuzzy multi-criteria decision making approach for evaluation and selection of an appropriate municipal wastewater treatment technology. Euro-Mediterr J Environ Integr:2–9

Kazuva E, Zhang J, Tong Z, Liu XP, Memon S, Mhache E (2020) GIS- and MCD-based suitability assessment for optimized location of solid waste landfills in Dar es Salaam, Tanzania. Environ Sci Pollut Res:1–20

Khoshand A, Rahimi K, Ehteshami M, Gharaei S (2019) Fuzzy AHP approach for prioritizing electronic waste management options: a case study of Tehran, Iran. Environ Sci Pollut Res 26:9649–9660

Liu Z, Tam NFY, Kuo DTF, Wu Q, du Y, Shi Y, Kong D, Zhang Y, Li H, Hu X (2020) Removal, seasonal variation, and environmental impact of parabens in a municipal wastewater treatment facility in Guangzhou, China. Environ Sci Pollut Res 27:28006–28015

Lizot M, Goffi AS, Thesari SS et al (2020) Multi-criteria methodology for selection of wastewater treatment systems with economic, social, technical and environmental aspects. Environ Dev Sustain:1–25

Lockström M, Schadel J, Harrison N, Mose R, Malhotra MK (2010) Antecedents to supplier integration in the automotive, industry: a multiple-case study of foreign subsidiaries in China. J Oper Manag 28(3):240–256

Mahjouri M, Ishak MB, Torabian A, Abd Manaf L, Halimoon N, Ghoddusi J (2017a) Optimal selection of iron and steel wastewater treatment technology using integrated multi-criteria decision-making techniques and fuzzy logic. Process Saf Environ 107:54–68

Mahjouri M, Ishak MB, Torabian A, Abd Manaf L, Halimoon N (2017b) The application of a hybrid model for identifying and ranking indicators for assessing the sustainability of wastewater treatment systems. Sustain Prod Consump 10:21–37

Molinos-Senante M, Gómez T, Caballero R, Hernández-Sancho F, Sala-Garrido R (2015) Assessment of wastewater treatment alternatives for small communities: an analytic network process approach. Sci Total Environ 532:676–687

Ozturk E (2018) Applying analytical decision methods for determination of the best treatment alternative to remove emerging micropollutants from drinking water and wastewater: triclosan example. Environ Sci Pollut Res 25:30517–30546

Promentilla MAB, Janairo JIB, Yu DEC, Pausta CMJ, Beltran AB, Huelgas-Orbecido AP, Tapia JFD, Aviso KB, Tan RR (2018) A stochastic fuzzy multi-criteria decision-making model for optimal selection of clean technologies. J Clean Prod 183:1289–1299

Ren J, Liang H (2017) Multi-criteria group decision-making based sustainability measurement of wastewater treatment processes. Environ Impact Assess Rev 65:91–99

Saaty TL (1980) The Analytical Hierarchy Process. McGraw-Hill, New York

Sadr SMK, Saroj DP, Kouchaki S, Ilemobade AA, Ouki SK (2015) A group decision-making tool for the application of membrane technologies in different water reuse scenarios. J Environ Manage 156:97–108

Sawaf MBAL, Karaca F (2018) Different stakeholders' opinions toward the sustainability of common textile wastewater treatment technologies in Turkey: a case study Istanbul province. Sustain Cities Soc 42:194–205

Tang C, Xu D, Chen N (2021) Sustainability prioritization of sewage sludge to energy scenarios with hybrid-data consideration: a fuzzy decision-making framework based on full consistency method and fusion ranking model. Environ Sci Pollut Res 28:5548–5565

Triantafyllidis CP, Koppelaar RHEM, Wang X, van Dam KH, Shah N (2018) An integrated optimisation platform for sustainable resource and infrastructure planning. Environ Modell Softw 101:146–168

Tuzkaya UR, Önüt S (2008) A fuzzy analytic network process based approach to transportation-model selection between Turkey and Germany: a case study. Inform Sciences 178:3133–3146

Tuzkaya G, Ozgen A, Ozgen D, Tuzkaya UR (2009) Environmental performance evaluation of suppliers: a hybrid fuzzy multi-criteria decision approach. Int J Environ Sci Te 6:477–490

Uliasz-Misiak B, Lewandowska-Śmierzchalska J, Matuła R (2021) Criteria for selecting sites for integrated CO2 storage and geothermal energy recovery. J Clean Prod 285:124822

Vidal L, Riekkola ML, Canals A (2012) Ionic liquid-modified materials for solid-phase extraction and separation: a review. Anal Chim Acta 715:19–41

Wang Y, Yang Y (2021) Analyzing the green innovation practices based on sustainability performance indicators: a Chinese manufacturing industry case. Environ Sci Pollut Res 28:1181–1203

Wei C, Wei J, Kong Q, Fan D, Qiu G, Feng C, Li F, Preis S, Wei C (2020) Selection of optimum biological treatment for coking wastewater using analytic hierarchy process. Sci Total Environ 742:140400

Yager RR (1988) On ordered weighted averaging aggregation operators in multicriteria decision-making. IEEE T Syst Man Cy 18(1):183–190

Yao L, Xu Z, Lv C, Hashim M (2020) Incomplete interval type-2 fuzzy preference relations based on a multi-criteria group decision-making model for the evaluation of wastewater treatment technologies. Measurement 151:107137

Zadeh LA (1965) Fuzzy sets. Inf Control 8:338–353

Zeng G, Jiang R, Huang G, Xu M, Li J (2007) Optimization of wastewater treatment alternative selection by hierarchy grey relational analysis. J Environ Manage 82(2):250–259

Zhang F, Ju Y, Dong P, Wang A, Santibanes Gonzalez EDR (2020a) Multi-period evaluation and selection of rural wastewater treatment technologies: a case study. Environ Sci Pollut Res 27:45897–45910

Zhang H, Li W, Miao P, Sun B, Kong F (2020b) Risk grade assessment of sudden water pollution based on analytic hierarchy process and fuzzy comprehensive evaluation. Environ Sci Pollut Res 27:469–481

Zhou Z, Dou Y, Zhang X, Zhao D, Tan Y (2018) A group decision-making model for wastewater treatment plans selection based on intuitionistic fuzzy sets. J Environ Eng Landsc 26(4):251–260