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A Hybrid Fuzzy SWARA-VIKOR Model for Sustainable Wastewater Treatment Technology Selection in the Steel Industry

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Sustainability prioritization, Water scarcity, Resource management Climate resilience, Water conservation.

Abstract

This study proposed an integrated decision-making framework that systematically incorporated specific industrial characteristics with fundamental sustainability considerations. The framework introduced a structured, analytical approach based on a dual methodology, combining SWARA (Step-wise Weight Assessment Ratio Analysis) and VIKOR (Višekriterijumsko kompromisno rangiranje) within a fuzzy logic framework. This integrated approach leveraged the strengths of each technique, offering a robust, multi-dimensional model to support precise and reliable decision-making in complex, sustainability-oriented contexts. The fuzzy SWARA method was used to determine the criteria and sub-criteria weights, followed by fuzzy VIKOR to rank decision alternatives. Five wastewater treatment technologies for the steel industry were identified and prioritized based on sustainability principles. These included CASPF (Conventional Activated Sludge with Mold Flow), MBR (Membrane Bio-Reactor), SBR (Sequencing Batch Reactors), AS (Activated Sludge), and UASB (Up-flow Anaerobic Sludge Blanket). The study demonstrated that this integrated approach yields more reliable and informed decisions in complex evaluations. Findings revealed that experts largely favor SBR technology as the most sustainable option.

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Introduction

Effective water pollution control is essential for sustainable water management, especially in countries with water scarcity like Iran, where low rainfall and growing population, agriculture, and industry intensify water stress. Iran faces an increasing threat to its aquatic systems due to high effluent levels. (Fetanat et al., 2021a; Mahjouri et al., 2017). The steel industry, a key sector globally and in Iran, contributes significantly to this challenge due to its extensive use across various industries. Steel demand is expected to increase by 1.5 times by 2050 to meet the needs of a growing global population (Zhou et al., 2023). Currently, Iran ranks 14th in global steel production and leads in the Middle East. The steel industry, however, is a major water consumer, using significant volumes for cooling, waste transport, and dust control. This leads to large volumes of wastewater containing a mix of dissolved and chemical pollutants, necessitating varied treatment approaches for pollutant removal. Effective treatments must address solids, oils, greases, organic compounds, and toxic substances (Ali et al., 2022; Zhou et al., 2023). Selecting appropriate wastewater treatment technology (WTT) is essential for sustainability, which entails balancing economic, technical, environmental, and social factors (Singh et al., 2023; Wang et al., 2022). Key criteria for technology selection include acceptability, manageability, and affordability. Since the 1990s, sustainability indicators (SIs) have become vital in evaluating progress toward sustainable development (Chowdhury and Viraraghavan, 2021). This study introduced a structured, mathematical approach to assess SIs and identify sustainable WTTs for the steel industry in Iranian Ghadir, Ardakan.

Wastewater treatment plants were essential for sustainable water management, particularly in evaluating suitable treatment technologies (WTTs) using sustainability indicators (SIs) (Garrido-Baserba et al., 2014; Balkema et al., 2002). SIs address local and regional priorities and help assess if a technology fits specific decision-making contexts (Kalbar et al., 2012a). Environmental, social-cultural, and economic criteria evaluate a solution’s effectiveness, while practical criteria assess feasibility (Balkema et al., 2002). Selecting sustainable WTTs using SIs is challenging for policymakers due to trade-offs between social, economic, environmental, and technical impacts and differing stakeholder perspectives (Kalbar et al., 2012b; Huang et al., 2011). MCDM methods support this process by balancing these aspects and integrating diverse criteria and stakeholder input, which is vital in complex decision-making (Figueira et al., 2004; Bottero et al., 2011). In the Conventional Activated Sludge with Mold Flow (CASPF) technology, sludge is introduced into wastewater, optimizing conditions for the growth of aerobic microorganisms. This method involves directing a significant portion of settled sludge back into a designated pond, enhancing the aeration process and treatment efficiency (Bertanza et al., 2017).

MBR technology also relies on activated sludge but separates sludge using specialized filters. Unlike traditional filtration methods, MBR technology eliminates the need for sedimentation ponds by utilizing membranes capable of filtering particles as small as 0.1 to 0.4 micrometers. However, the system tends to be costlier due to the high expense of these membranes (Pardey et al., 2017). In SBR technology, sedimentation and aeration are used together and in combination. SBR technology has several periods and lasts several days. It takes 3 hours to fill the source and 2 hours to aerate the diffusers and jet aerators. Finally, half an hour should be allowed for the sludge to settle and half an hour for the discharged wastewater to be discharged (Aziz et al., 2020). Activated Sludge technology is the most common process of aerobic purification in which solid and liquid are separated and in the solid phase the least moisture and in the liquid phase the least possible particles remain (Nowrouzi et al., 2021). In UASB technology granular sludge layers are used for wastewater treatment. In this way, wastewater passes through these layers and a reaction is created between the organic matter in the wastewater and the microorganisms in the sludge layer. During this reaction, biogas is produced. These gases are removed from the upper part of the tank and with them, the pollutants are removed (Fetanat et al., 2021a).

Selecting criteria in many studies often stems from literature reviews, but local factors make it critical to include input from regional experts. By gathering both comprehensive literature insights and expert perspectives, decision-making accuracy in MCDM procedures improves. MCDM methods like SWARA and VIKOR, under fuzzy set theory, are effective for assessing multi-criteria decisions, accommodating both measurable and intangible factors simultaneously, and clarifying decision-maker preferences and rankings (Ghenai et al., 2020; Opricovic and Tzeng, 2007).

However, selecting WTTs in sustainable contexts often faces obstacles, including ambiguous data and reliance on local conditions (Mahjouri et al., 2017). Fuzzy set theory, created to handle vagueness (Zadeh, 1965), offers a way to model uncertainty similar to human reasoning, helping manage real-world inaccuracies in decision-making (Ren and Ren, 2018). By providing a flexible structure, fuzzy set theory helps address issues of precision and supports decisions in complex situations (Cheng and Lin, 2002).

Recent studies have continued to highlight the importance of fuzzy MCDM (multi-criteria decision-making) techniques in selecting optimal wastewater treatment technologies (WWTT) based on criteria like economic, environmental, and technical factors. For example, research by Attri et al. (2022) used a combined fuzzy approach for WWTT selection, considering sustainability aspects, where the Sequencing Batch Reactor (SBR) emerged as a top choice. Additionally, fuzzy AHP combined with TOPSIS has been employed for technology comparison in various settings, emphasizing the role of scenario-based assessments and sustainability in decision-making (Zhang and Ju, 2021; Nuhu et al., 2020). These studies support the broader application of fuzzy methods like SWARA-VIKOR in refining WWTT selections across different industrial contexts

This research aimed to develop a hybrid model using two MCDM methods, SWARA and VIKOR, within a fuzzy framework (Fuzzy SWARA-VIKOR) to address a complex decision-making scenario involving a comprehensive set of sustainability indicators (SIs). The proposed MCDM approach assisted in selecting a sustainable wastewater treatment technology (WTT) from several alternatives, including Conventional Activated Sludge with Mold Flow (CASPF), Membrane Bio-Reactor (MBR), Sequencing Batch Reactors (SBR), Activated Sludge (AS), and Up-flow Anaerobic Sludge Blanket (UASB), tailored for wastewater management in the steel industry of Ghadir, Ardakan, Iran. Evaluation criteria are based on sustainability principles, and three experts were engaged in selecting the most suitable technology. The findings intended to support sustainable wastewater management and promote green growth in the sector.

Material and Methods

Methodology

This research aimed to identify a sustainable wastewater treatment technology for the steel industry in Ardakan, Iran, using Multi-Criteria Decision-Making (MCDM) methods. The fuzzy-based SWARA and VIKOR models were employed to help decision-makers select the most suitable technology, promoting sustainability and green goals in wastewater management. The methodology consists of ten stages, which were outlined in the research, with an overview provided in Figure 1.

The flowchart stages for selecting the appropriate sustainable wastewater treatment technology are as follows:

1. Stage 1: An expert team was invited to discuss the issue.

The expert team in this study likely

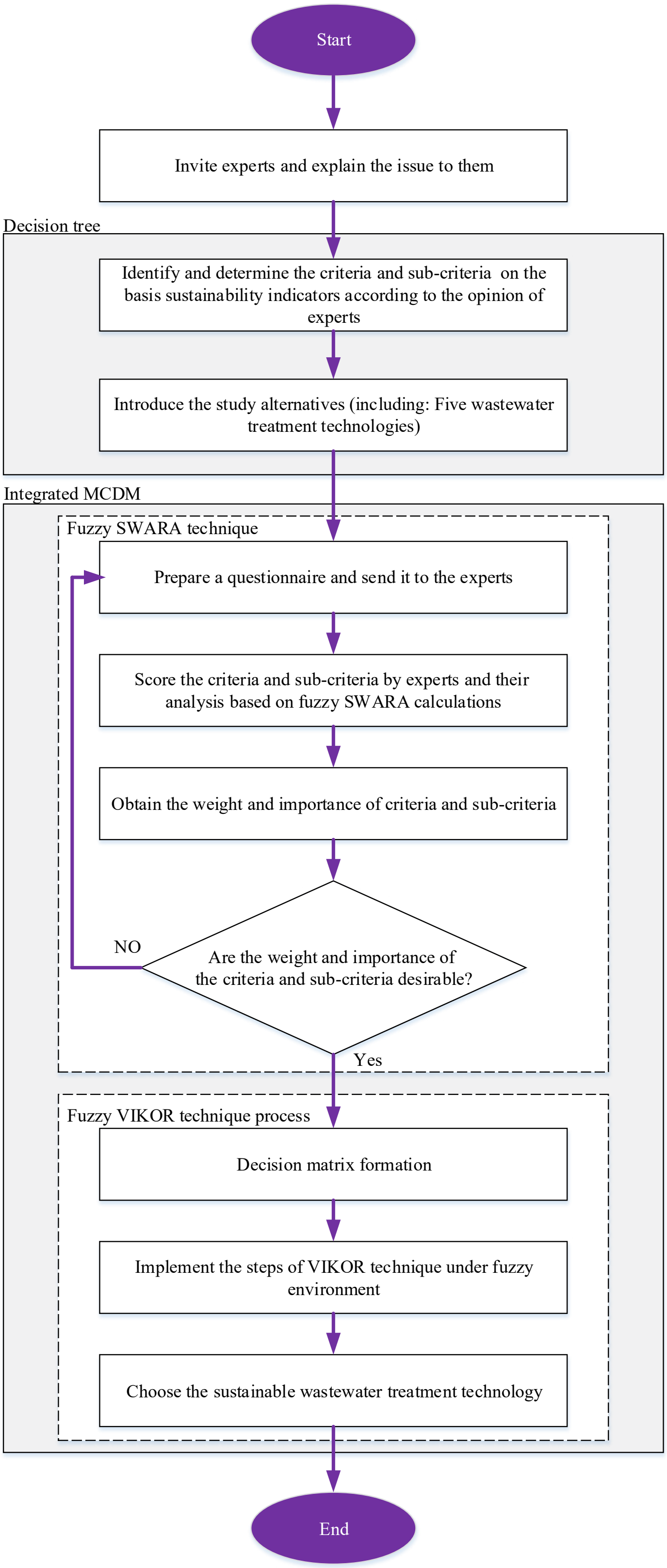

Fig.1. The flowchart of the study approach.

consists of professionals with knowledge and experience in wastewater treatment, environmental management, and sustainability, particularly as they relate to the steel industry. These experts may include environmental engineers, sustainability analysts, and industry consultants who were familiar with the economic, technical, and environmental aspects of wastewater treatment technologies (WTT). The team would contribute insights on criteria for WTT selection, assess the relevance of sustainability indicators, and help guide the application of the fuzzy SWARA-VIKOR model in evaluating the WTT options.

2. Stage 2: A framework of assessment criteria and sub-criteria based on sustainability pillars was identified, using expert opinions and relevant literature.
3. Stage 3: Five wastewater treatment technologies (CASPF, MBR, SBR, Activated Sludge Process, and UASB) were defined as alternatives.
4. Stage 4: A questionnaire was prepared and distributed to experts.
5. Stage 5: Experts evaluate and score the criteria and sub-criteria using fuzzy SWARA calculations.
6. Stage 6: The weights of the criteria and sub-criteria were determined.
7. Stage 7: If the weights were satisfactory, the process continues; if not, the process returns to Stage 2.
8. Stage 8: A decision matrix was formed for the fuzzy VIKOR method, evaluating alternatives based on sub-criteria.
9. Stage 9: The VIKOR method was applied under a fuzzy environment.
10. Stage 10: The most appropriate and sustainable wastewater treatment technology was selected.

Designed decision tree of the research

The designed decision tree for solving the problem of the research consists of four levels, these levels were defined as follows:

Level 1) Objective: Select the appropriate and sustainable WTT;

Level 2) Criteria: Technical (C1), environmental (C2), economic (C3), and social (C4);

Level 3) Sub-criteria: Reliability (SC1), complexity (SC2), efficiency (SC3), odor generation (SC4), sound impact (SC5), insects and other parasites generation (SC6), amount of sludge generation (SC7), Occupational health and safety (SC8), land requirements (SC9), construction costs (SC10), operating and maintenance costs (SC11), waste disposal costs (SC12), social acceptability (SC13) and employment (SC14).

Level 4) Alternatives: CASPF technology (A1), MBR technology (A2), SBR technology (A3), Activated Sludge technology (A4), and UASB technology (A5).

The indicators of sustainability as the framework for assessment criteria

Criteria for assessing the considered alternatives were given in Table 1. Sustainability typically encompasses achieving economic prosperity, social responsibility, and environmental stewardship (Fetanat et al., 2021a). Consequently, sustainability assessment criteria generally align with three core pillars: environmental, social, and economic factors. However, in evaluating sustainability for wastewater treatment and energy production from wastewater, a fourth technical pillar was also considered (Mahjouri et al., 2017). This study aimed to determine a sustainable wastewater treatment technology (WTT) by developing a framework of criteria and sub-criteria across these four pillars, informed by expert insights and prior research. The criteria framework used for evaluating the technologies is outlined in Table 1.

Table 1. The framework of defined criteria and sub-criteria for evaluation

Criteria	Sub-Criteria
C_1: Technical	SC_1: Reliability SC_2: Complexity SC_3: Efficiency
C_2: Environmental	SC_4: Odor generation SC_5: Noise impact SC_6: Insects and other parasites generation SC_7: Amount of sludge generation SC_8: Occupational health and safety
C_3: Economic	SC_9: Land requirements SC_{10}: Construction costs SC_{11}: Operation and maintenance costs SC_{12}: Waste disposal costs
C_4: Social	SC_{13}: Social acceptability SC_{14}: Employment

Alternatives

Based on literature references and expert team input, five wastewater treatment technologies have been identified as potential alternatives for addressing the issue. These technologies were as follows:

- **CASPF technology (A1):** The primary features of CASPF technology include the following (Aziz et al., 2020; Bertanza et al., 2017): Its use is very common in the treatment of various types of waste water;
- The base process of many types of activated sludge processes;
- Capable of converting into many kinds of activated sludge processes including step feeding, selector design, and anoxic/aerobic processes.

Despite its advantages, CASPF technology is generally not recommended for use in many industries due to several limitations:

1. The design requirements for mold flow

aeration in CASPF are more complex and challenging than those of other processes.

2. Balancing the injected oxygen levels with the oxygen demand is difficult to achieve consistently.
3. The management and operational aspects of this process are more complicated compared to alternative technologies.

Figure 2 is demonstrated the schematic of the CASPF process.

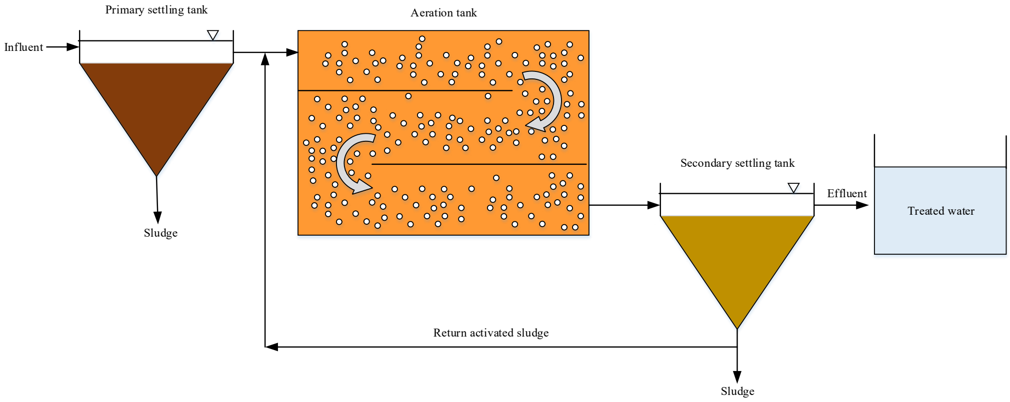

Fig. 2. The CASPF process (Aziz et al., 2020; Bertanza et al., 2017).

MBR technology (A2):

The main properties of MBR technology were as follows (Bertanza et al., 2017):

- Ability to remove all suspended solids;
- The ratio of food to microorganisms;
- Apply high loading rates;
- Production of low excess sludge;
- Relatively little space is required;
- Possibility of automation and less labor force;
- No need for an initial pool;
- High-quality outlet water.

Despite all the advantages of MBR technology in wastewater treatment, its use and implementation were faced with problems and limitations, which can include issues such (Pardey et al., 2017; Santos et al., 2020)directions and trends in academic research as well as commercial developments require further analysis. This paper aims to critically characterize and review worldwide academic research efforts in the area of MBRs as well as focus attention to commercial MBR applications. Various research papers published in peer-reviewed international journals were used as the database for the analysis provided in this paper. After a surge of MBR publications, research appears to have reached a plateau in the last 7 years using both submerged and external MBR units. Although much of the pioneering research occurred in Japan, France and the UK, countries such as South Korea, China and Germany have significantly contributed to the research pool in the last 5 years. The primary research focus has been on water filtration MBRs with limited growth in extractive and gas diffusion MBRs which still hold un-tapped potential. Fundamental aspects studied in academic research predominantly involve issues related to fouling, microbial characterization and optimizing operational performance. Zenon occupies the majority of the MBR market in America, whereas Kubota and Mitsubishi-Rayon has a larger number of installations in other parts of the world. Due to more stringent regulations and water reuse strategies, it is expected that a significant increase in MBR plant capacity and widening of application areas will occur in the future. Potential application areas include nitrate removal in drinking water treatment, removal of endocrine disrupting compounds from water and wastewater streams; enhancing bio-fuels production via membrane assisted fermentation and gas extraction and purification MBRs. Treatment technology for water recycling encompasses a vast number of options. Membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are included in a number of prominent schemes world-wide, e.g. for artificial groundwater recharge, indirect potable reuse as well as for industrial process water production. Membrane bioreactors (MBRs:

1. The need for high initial investment,
2. High cost of membrane replacement,
3. Higher energy consumption than common activated sludge methods,
4. Membrane clogging, and
5. Flow reduction.

The MBR technology schematic is indicated in Figure 3.

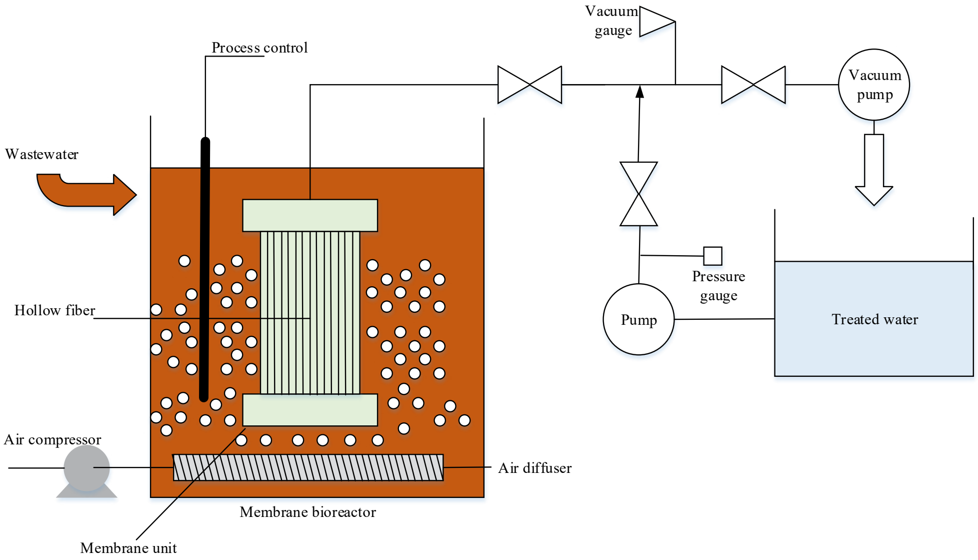

Fig. 3. The MBR technology (Pardey et al., 2017)

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- **SBR technology (A3):** The main features of SBR technology include the following items (Aziz et al., 2020; Kim et al., 2019):

➢ Decrease in initial investment;
➢ Reduction of excreted sludge volume;
➢ Do not wash activated sludge during peak flow times;
➢ Reduced energy consumption compared to activated sludge systems;
➢ High resistance to hydraulic and organic shocks;
➢ Achieve very high efficiency;
➢ Perform all purification operations in one reactor;
➢ No need to return the sludge;

- ➢ Easy to develop and increase its capacity;
- ➢ No need a final clarifier and return sludge pumping.

This technology can have very good efficiency in industries, especially steel, and it can be used as a suitable and sustainable option in wastewater treatment and the reuse of its effluent.

Figure 4 shows the schematic scheme of the SBR technology.

primary treatment, secondary treatment, and tertiary treatment or polishing. In secondary treatment, dissolved oil and other organic pollutants may be consumed biologically by microorganisms. Biological treatment of complex chemicals in the petroleum industry wastewaters is specially challenging due to the inhibition and/or toxicity of these compounds when they serve as microbial substrates. Processes such as sequencing batch reactor (SBR.

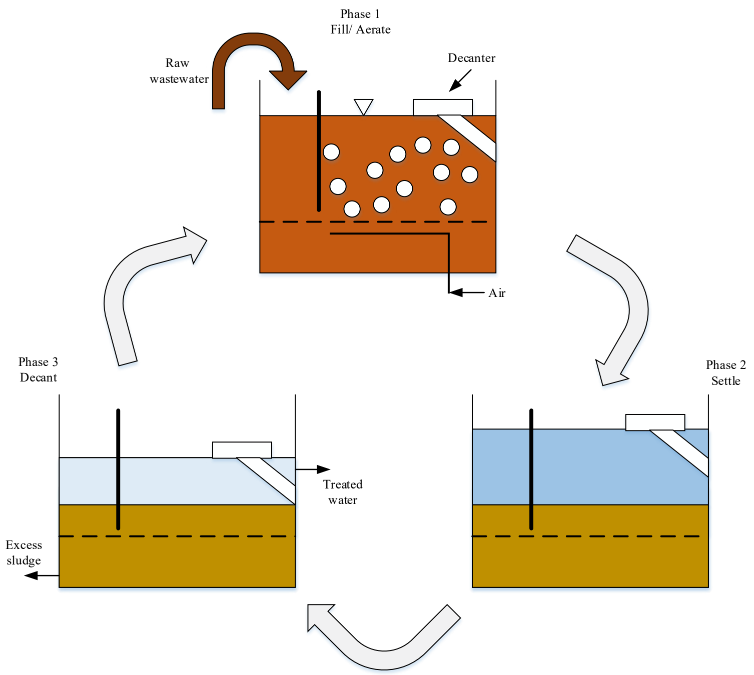

Fig. 4. The SBR technology (Jafarinejad, 2017)

- **Activated Sludge technology (A4):** The advantages of this technology were as follows (Nowrouzi et al., 2021; Pranoto et al., 2019)coal mining operations generally involve a huge number of workers. This\u00a0condition causes its own challenges in managing environmental impacts that\u00a0potentially generated from human activities. One of them is domestic wastewater.\u00a0Domestic waste water is waste water that comes from activities of daily living of\u00a0humans related to water usage. In mining operations, domestic wastewater is\u00a0generated from office and residential areas. Because of the potential impact on the\u00a0environment, domestic wastewater must be treated before flowing to natural water\u00a0bodies. Since the beginning of mining operations in 1990s, PT Kaltim Prima Coal has\u00a0been building and operating Domestic Wastewater Treatment Plant (IPALD:

- High efficiency and efficiency in the removal of organic matter;
- Affordability in terms of economic costs;
- The use in different situations with different temperatures and PH.

Disadvantages that limit the use of this technology in the industry were as follows:

1. The need for relatively high electrical and mechanical equipment,
2. Increased imports and valuation compared to other types of wastewater treatment processes,
3. More need for specialized personnel and skilled personnel for maintenance than most purification systems, and
4. High costs of wastewater treatment plants owing to higher energy use during the years of operation.

The activated sludge system schematic is indicated in Figure 5.

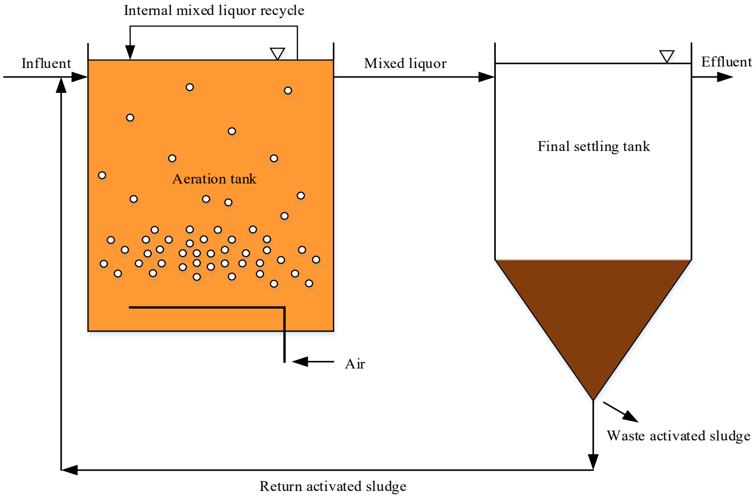

Fig. 5 The activated sludge system.

- **UASB technology (A5):** Important features of this technology are as follows (Adhikari and Lohani, 2019):
  - The space required to create UASB technology is not large. Since the load on the UASB system is 10 times higher than the aerobic system, the space required for the UASB system is one-tenth of the space that the aerobic system needs for the treatment of the same volume of wastewater.
  - In the UASB system, usable energy is produced in the form of biogas, 75% of which is methane gas. This gas is

applied in industrial heating systems or as a source for wastewater heating.

- The UASB system can be used to treat wastewater with very high pollution intensity and concentration between 1500 and 50 thousand mg of COD per liter.
- About 95% of the COD produced in this system is converted to biogas and the remaining 5% is converted to new cells or sludge. The amount of sludge produced in this system is about 10% of sludge that is produced by the same volume of wastewater but aerobically. Reducing sludge production also reduces its disposal cost significantly.

Due to its valuable features, this technology is an appropriate option for the production of wastewater into energy, and the energy produced by it can be used for other parts. Implementing this technology for wastewater treatment helps to navigate the wastewater management sector toward the aims of green growth and sustainability (Adhikari and Lohani, 2019; Cruz-Salomón et al., 2017; Fetanat et al., 2021a).

Figure 6 illustrates the schematic scheme of the UASB technology.

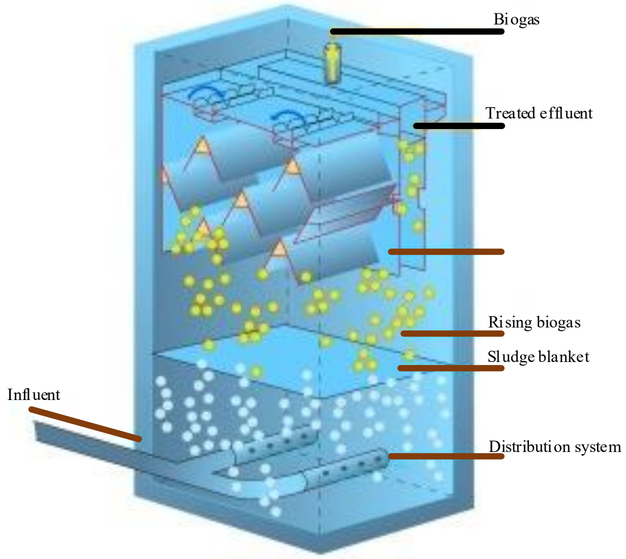

Fig. 6. The UASB technology (Fetanat et al., 2021a).

Integrated decision-making methodology

In the current work, an integrated decision-making model based on MCDM methods was applied. The model was the fuzzy-based SWARA and VIKOR for applying and implementing WTT in the steel industry of Iranian Ghadir in Ardakan city. The SWARA technique was utilized for weighting the criteria and the VIKOR technique was employed for prioritizing alternatives. Figure 7 shows a hybrid algorithm schematic related to the proposed model based on hierarchy.

the role of waste management sector shifts from being a regulator to being a facilitator. Instead of just regulating waste flows, the sector tries to encourage businesses to address all aspects of circular economy sustainability in a more efficient manner. The sustainability assessment in the sector lacks a hybrid method to aggregate the sustainability dimensions of circular economy strategies into a single summary indicator. This process is a multiple-criteria decision-making problem that requires the integration of circular economy strategies to form the sustainability indices. In order to make the right choices here, this study proposes a fuzzy three-phase group multiple-criteria decision-making approach. This approach integrates fuzzy analytic network process (fuzzy ANP.

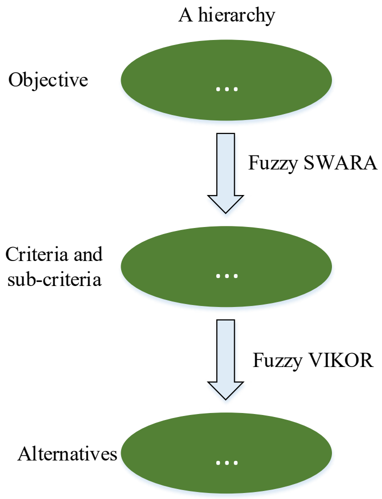

Fig. 7. Hybrid algorithm of decision-making (Fetanat et al., 2021b)

Fuzzy approach

The fuzzy approach, first introduced in 1965 (Zadeh, 1965), offers a mathematical and systematic method for decision-making in complex systems requiring sophisticated modeling. By using linguistic terms and expert knowledge, it facilitates decision-making when precise data were unavailable or hard to quantify. Ambiguous terms were converted into mathematical scales through fuzzy logic, enabling clearer assessments despite incomplete or inaccessible data. This approach is especially beneficial in real-world scenarios where direct, measurable data were limited. Consequently, fuzzy logic has gained prominence for addressing uncertainty in decision-making processes (Chou and Chang, 2008; Lin and Wu, 2008).The TFN (triangular fuzzy number) $\tilde{N}$ was as three numbers (*l*, *m*, *u*), and the function of membership $\mu^{\tilde{N}}(x)$ was expressed by the formula (1): (1)

$$\mu^{\tilde{N}}(x)=\begin{cases} 0 & x<l \\ (x-l)/(m-l) & l\le x\le m \\ (u-x)/(u-m) & m\le x\le u \\ 0 & x>u \end{cases}$$

where *l*, *m,* and *u* were real numbers in the range $l\le m\le u$. Figure 8 shows a TFN diagram.

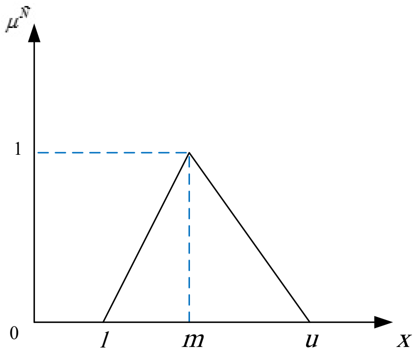

Fig. 8. A TFN (Fetanat et al., 2019).

Linguistic scales can be shown using fuzzy scales. Table 2 presents the scales based on a fuzzy approach equivalent to linguistic scales.

Table 2. The Linguistic and fuzzy scales of the study.

Linguistic scales	Abbreviation	TFN
None	N	(0, 0, 0.1)
Very low	VL	(0, 0.1, 0.2)
Low	L	(0.1, 0.2, 0.3)
Fairly low	FL	(0.2, 0.3, 0.4)
More or less low	MLL	(0.3, 0.4, 0.5)
Medium	M	(0.4, 0.5, 0.6)
More or less good	MLG	(0.5, 0.6, 0.7)
Fairly good	FG	(0.6, 0.7, 0.8)
Good	G	(0.7, 0.8, 0.9)
Very good	VG	(0.8, 0.9, 1)
Excellent	E	(0.9, 1, 1)

Fuzzy SWARA technique

The SWARA technique, a time-efficient MCDM method, exceled in capturing expert insights regarding the relative importance of criteria to determine their weights. It is particularly useful in complex or unconventional environments where it manages vague and imprecise data through fuzzy logic. The fuzzy approach stands out for its ability to assess criteria on a relative, flexible scale, accommodating both numerical and linguistic variables. Consequently, fuzzy-based SWARA was employed here to calculate weights for defined criteria and sub-criteria. The steps to implement this technique were outlined by Agarwal et al. (2020) and Prajapati et al. (2019).

1. The selected criteria or sub-criteria for the decision-making process were classified in a descending order, based on the team of experts. Because the making decisions on the real subject were riddled with uncertainties, the linguistic scales used for proposing expects more independence. The linguistic scales given through a TFN were employed. The fuzzy assessment scales showed in Table 2.
2. This step started with the second criteria or sub-criteria, where the experts determined a linguistic scale for each criterion or sub-criteria *j* on the basis of the relative significance of the former (*j*-1) criteria or sub-criteria, for each criterion or sub-criteria based upon Table 2. This proportion was termed the comparative importance of average value, $\hat{b}_j$ (Keršulienė et al., 2010).
3. The coefficient $\hat{p}_j$ was computed as follows:

$$\hat{p}_j = \begin{cases} 1 & j = 1, \\ \hat{b}_j + 1 & j > 1, \end{cases} \qquad (5)$$

The recalculated fuzzy weight $\hat{z}_j$ was calculated by the following formula:

$$\hat{z}_j = \begin{cases} 1 & j = 1, \\ \dfrac{\hat{z}_{(j-1)}}{\hat{p}_j} & j > 1, \end{cases} \qquad (2)$$

4. The relative criteria and sub-criteria weights were computed by the following formula.

$$\hat{k}_j = \frac{\hat{z}_j}{\sum_{p=1}^{n} \hat{z}_p} \qquad (3)$$

where, $\hat{k}_j$ denoted the relative fuzzy weight of the *j*th criteria or sub-criteria, and *n* shows the number of criteria or sub-criteria.

5. Defuzzification of the obtained weight of the *j*th criteria or sub-criteria was ulfilled by the center-of-area method which was the most employed (Turskis et al., 2019).

$$k_j = \frac{1}{3}\hat{k}_j = \frac{1}{3}(\hat{k}_{j\alpha} + \hat{k}_{j\beta} + \hat{k}_{j\gamma}) \qquad (4)$$

where, the k_j showed defuzzified relative fuzzy weight of the *j*th criteria or sub-criteria.

Fuzzy VIKOR technique

The VIKOR technique, specifically developed for multi-criteria optimization within complex systems, demonstrated superior decision-making capabilities due to its use of the *v* index and emphasis on achieving collective agreement. This has positioned VIKOR as a preferred choice in recent research for addressing challenges involving conflicting criteria and sub-criteria (Chang, 2010; Opricovic and Tzeng, 2007). The method was structured to rank and select options based on their closeness to an ideal solution, which was particularly valuable in complex decision-making contexts. The relative significance of each alternative, with respect to the weighted sub-criteria, was determined by applying fuzzy scales, as outlined in Table 2.

Decision-making matrix formation

In this matrix, scoring alternatives based on sub-criteria completed according to the fuzzy scales. Figure 9 shows the schematic of the decision-making matrix of the study under the fuzzy scales.

$$\tilde{f} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_{m_{alt}} \end{array} \begin{array}{c} \begin{array}{cccc} SC_1 & SC_2 & & SC_{n_{sub}} \end{array} \\ \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n_{sub}} \\ \tilde{r}_{12} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n_{sub}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m_{alt}1} & \tilde{r}_{m_{alt}2} & \cdots & \tilde{r}_{m_{alt}n_{sub}} \end{bmatrix} \end{array} \qquad (6)$$

Fig. 9. The decision-making matrix under the fuzzy scales.

here, the alternatives included $A_i,\ i=1,\ 2,\ \ldots,m_{alt}$, the sub-criteria define as $SC_j,\ j=1,\ 2,\ \ldots,\ n_{sub}$.

The arithmetic means approach was used to collect the responses of the expert team and to calculate triangular fuzzy numbers (TFNs). Using the method of Yager, fuzzy scales were taken out of the fuzzy mode and fuzzy numbers that were the result of the opinions of the expert team were summed up. The formula of the Yager method is as follows:

$$\tilde{N}_{i,j} = \int_0^1 \frac{1}{2}\left(\left(\tilde{N}_{i,j}\right)_\alpha^l + \left(\tilde{N}_{i,j}\right)_\alpha^u\right) \qquad (8)$$

$$d\alpha = \frac{l_{i,j} + 2m_{i,j} + u_{i,j}}{4} \qquad (9)$$

In the following, implementing the computational process of the fuzzy VIKOR technique was introduced.

Computational steps of fuzzy VIKOR technique

The calculation steps of this technique were under Figure 10(Chang, 2010). The following were the steps for calculating the fuzzy VIKOR technique for prioritizing the considered alternatives and choosing the most appropriate alternative according to the m_{alt} alternatives and n_{sub} sub-criteria (Chang, 2010; Sayadi et al., 2009).

Step 1. Decision-making matrix normalization:

Normalizing the decision matrix of the research was calculated by employing the formula (7).

$$f_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m_{alt}} r_{ij}^2}} \qquad (7)$$

Step 2. The ideal (positive) and anti-ideal

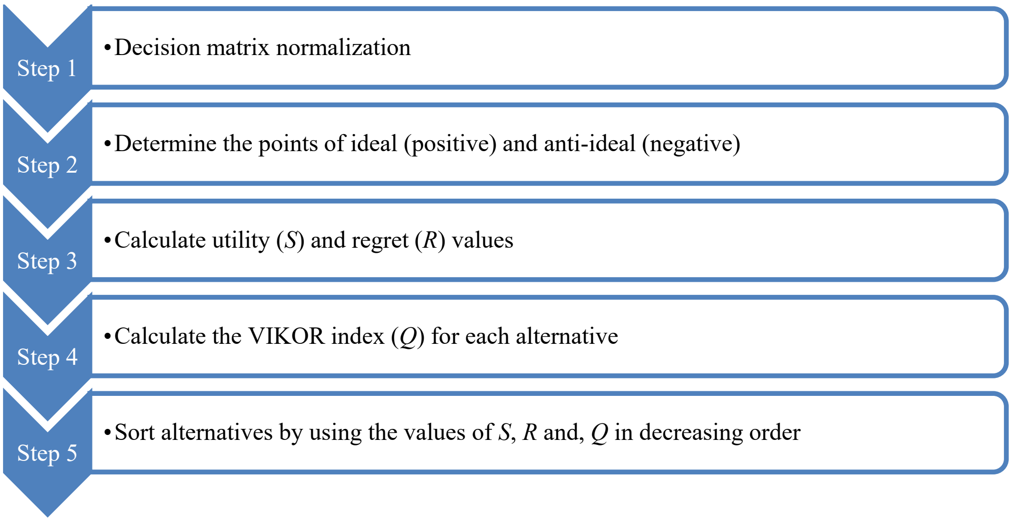

Fig 10. Steps of fuzzy VIKOR method.

(negative) points determination:

here, the values related to the best f_j^* and the worst f_j^- of each column belonging to the decision-making matrix were determined. The formulas of these two were presented as follows:

$$f_j^* = Max\left\{f_{ij}\right\} \qquad f_j^- = Min\left\{f_{ij}\right\} \qquad (12)$$
$$\forall i = 1,\ldots,m_{alt} \qquad \forall j = 1,\ldots,n_{sub}$$

Step 3. The values calculation of utility (*S*) and regret (*R*) for each alternative:

In this step, the desired value (utility) and the undesirable value (regret) were calculated. The *S* and *R* formulas were given as follows:

$$S_i = \sum_{j=1}^{n} w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_i^-)} \qquad (13)$$

$$R_i = Max\left[w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)}\right] \qquad (14)$$

Step 4. The calculation of the VIKOR index (*Q*) for each alternative.

This index was calculated by using the formula (10):

$$Q_i = v\left[\frac{S_i - S^*}{S^- - S^*}\right] + (1-v)\left[\frac{R_i - R^*}{R^- - R^*}\right] \qquad (10)$$

In the above formula:

$$S^- = Max S_i \qquad R^- = Max R_i$$
$$S^* = Min\ S_i \qquad R^* = Min\ R_i$$

v: The maximum weight was the group utility, which was considered equal to 0.5.

Step 5. The alternatives sort by using the *S*, *R*, and, *Q* values in decreasing order.

The obtained values of *S*, *R*, and *Q* were arranged in three prioritization lists in decreasing order. Therefore, the alternative with having the smallest value of *Q* was chosen as the optimal alternative, if the two following conditions were satisfied.

Condition 1. If alternatives A1 and A2 had the first and second rank among m_{alt} alternatives, formula (11) must be established:

$$Q(A_2) - Q(A_1) > \frac{1}{(m_{alt} - 1)} \qquad (11)$$

Condition 2. Alternative A1 must be the best alternative in at least one of the lists of *R* and *S* (Chang, 2010; Opricovic and Tzeng, 2007; Yücenur and Senol, 2021)it has some problems when solving MCDM problems .This study discussed existing problems in the traditional VIKOR method. The objective of this study was to develop a modified VIKOR method to avoid numerical difficulties in solving problems by the traditional VIKOR method .Several synthetic experiments were designed and assessed to verify the improvement of solution efficiency of the modified VIKOR method in MCA\ .u00a9 2009 Springer Science+Business Media B.V» ,«.author« » }] :dropping-particle» ,«» : «family: « »Chang» ,«given» : «Chia Ling» ,«non-dropping-particle» ,«» : «parse-names« :false» ,suffix» ,[{ «» : «container-title» : «Environmental Monitoring and Assessment» ,«id» : «ITEM» ,«1-issue« » ,«1-4» :issued» } : «date-parts] : « » ,{ [[«2010»]page,«339-344» : « »title» : «A modified VIKOR method for multiple criteria analysis» ,«type: « »article-journal» ,«volume,{ «168» : « »uris»] : «http//:www.mendeley.com/documents?/uuid7=f7eb11c2-dcc474-c-b649-3c9ad30d0f61» } ,{ [«id» : «ITEM-» ,«2itemData» } : «DOI/10.1016» : «j.ejor» ,«2006.01.020.ISSN,«03772217» : « »abstract» : «The VIKOR method was developed to solve MCDM problems with conflicting and noncommensurable) different units.

Results and Discussion

The results from the SWARA and VIKOR techniques, conducted within a fuzzy framework, were presented here. This hybrid fuzzy-based SWARA-VIKOR model had been applied to address the selection of a sustainable wastewater treatment technology (WTT) for the steel industry in Iranian Ghadir, located in Ardakan, Iran. By employing this model, five WTT alternatives were evaluated based on 14 defined sustainability indicators (SIs).

The calculations result of the proposed hybrid model

The numerical values of the proposed integrated model were given as follows:

Computing the criteria weights and sub-criteria employing the technique of fuzzy SWARA

The present part showed the findings of the SWARA method under the fuzzy environment to weigh the determined criteria. After a brainstorming meeting, the expert team ordered all the criteria or sub-criteria in decreasing arrangement regarding their importance. The relative importance of the average value, , of each criterion or sub-criteria was assessed by the experts ‘group utilizing fuzzy scales presented in Table 2. The formula (2) was employed for the computation of the fuzzy coefficient,

$\hat{p}_j$. Next, formulas (3) and (4) calculate the recalculated fuzzy weight, $\hat{z}_j$, and the relative fuzzy weight, k_j, of criterion or sub-criteria, respectively (see Tables 3 and 4). Defuzzification of the relative fuzzy weight, k_j, of each criteria or sub-criteria was performed utilizing the center-of-area method by using the formula (5).

The findings of this technique were given as follows:

Table 3. Findings of fuzzy SWARA to weight criteria.

Criteria	$\hat{b}_j$			$\hat{p}_j$			$\hat{z}_j$			$\hat{k}_j$			k_j
C_3	-	-	-	1	1	1	1	1	1	0.9487	0.9751	1.0080	0.6043
C_1	0.80	0.83	0.87	1.80	1.83	1.87	0.5556	0.5464	0.5348	0.3707	0.3695	0.3669	0.2282
C_2	0.77	0.80	0.83	1.77	1.80	1.83	0.3139	0.3036	0.2922	0.1804	0.1763	0.1719	0.1090
C_4	0.70	0.73	0.77	1.70	1.73	1.77	0.1846	0.1755	0.1651	0.0988	0.0949	0.0904	0.0585

Table 4. Findings of fuzzy SWARA to weight sub-criteria.

Sub-criteria	$\hat{b}_j$			$\hat{p}_j$			$\hat{z}_j$			$\hat{k}_j$			k_j
SC_{10}				1	1	1	1	1	1	0.6881	0.7323	0.7809	0.5208
SC_{11}	0.80	0.83	0.87	1.80	1.83	1.87	0.5556	0.5464	0.5348	0.2928	0.3004	0.3063	0.2128
SC_{12}	0.77	0.8	0.83	1.77	1.80	1.83	0.3139	0.3036	0.2922	0.1467	0.1472	0.1470	0.1043
SC_9	0.70	0.73	0.77	1.70	1.73	1.77	0.1846	0.1755	0.1651	0.0814	0.0801	0.0780	0.0567
SC_3	0.53	0.57	0.63	1.53	1.57	1.63	0.1207	0.1118	0.1013	0.0517	0.0496	0.0465	0.0350
SC_8	0.50	0.53	0.57	1.50	1.53	1.57	0.0804	0.0731	0.0645	0.0339	0.0319	0.0291	0.0224
SC_1	0.43	0.5	0.53	1.43	1.50	1.53	0.0563	0.0487	0.0422	0.0235	0.0210	0.0188	0.0150
SC_7	0.37	0.43	0.50	1.37	1.43	1.50	0.0411	0.0341	0.0281	0.0170	0.0146	0.0125	0.0104
SC_{14}	0.43	0.5	0.53	1.43	1.50	1.53	0.0287	0.0227	0.0184	0.0118	0.0097	0.0081	0.0070
SC_4	0.33	0.37	0.43	1.33	1.37	1.43	0.0216	0.0166	0.0128	0.0089	0.0071	0.0057	0.0051
SC_2	0.33	0.37	0.53	1.33	1.37	1.53	0.0162	0.0121	0.0084	0.0067	0.0051	0.0037	0.0037
SC_{13}	0.20	0.33	0.43	1.20	1.33	1.43	0.0135	0.0091	0.0059	0.0055	0.0039	0.0026	0.0028
SC_6	0.20	0.33	0.47	1.20	1.33	1.47	0.0113	0.0068	0.0040	0.0046	0.0029	0.0018	0.0022
SC_5	0.20	0.33	0.37	1.20	1.33	1.37	0.0094	0.0051	0.0029	0.0038	0.0022	0.0013	0.0017

Tables 3 and 4 displayed the calculated weights for the study's criteria and sub-criteria. In these tables, criteria (in Table 3) and sub-criteria (in Table 4) were first organized in descending order, based on expert opinions. The criteria and sub-criteria were then scored using linguistic variables from Table 2, which were converted into triangular fuzzy numbers (TFNs). Applying the Yager method, these TFNs were then reduced to single values. As a result, each criterion and sub-criterion had three scores, except for the last column, which listed the normalized weights calculated for assessment. The value in column $\hat{k}_j$ and k_j were derived using the center-to-area method, and results were normalized in the last column.

Determining the most critical criteria for selecting a sustainable WTT could be complex, but the proposed integration of the fuzzy SWARA-VIKOR methods with sustainability indicators (SIs) offered a systematic and thorough framework. Through the fuzzy SWARA approach, criteria weights were precisely obtained to guide the selection of a sustainable WTT for the Iranian Ghadir steel industry in Ardakan, Iran.

In Table 3, among four criteria, economic criterion (C_3), with a value of 0.2661 had the highest rank among other criteria, followed by the technical criterion (C_1), with a weight of 0.2538. Then the environmental criteria (C2), and social criteria (C4), with weights of 0.2446 and 0.2355, respectively, were in the next ranks.

Table 4 illustrated the weights of the sub-criteria defined for all four technical, environmental, economic, and social criteria. Among these, economic sub-criteria including construction costs (SC_{10}), with a value (0.5208), operation and maintenance costs (SC_{11}), with weight (0.2128), and sludge disposal costs (SC_{12}), with a value (0.1043) were the foremost sub-criteria that overshadows the choice of appropriate and sustainable WTT. Because the factors of cost management systems or financial planning had an effective effect on industrial actions and the establishment of technologies in the industry. It is required to assign adequate financial resources to implement suitable and sustainable technologies like WTT for upgrading sustainable wastewater management in diverse industries like the steel industry. Among technical sub-criteria, efficiency (SC_3) and reliability (SC_1) were the two most significant sub-criteria of technical, having weights with the values of 0.0350 and 0.0150, respectively. Because these sub-criteria were related to the important sectors of the avoidance of wasting materials, energy, capital, and time doing work and robustness to the failure in the wastewater treatment equipment of industries. Occupational health and safety (SC_8), amount of sludge generation (SC_7), and odor generation (SC_4) were the highest importance among environmental sub-criteria, having weights with values of (0.0224), (0.0104), and (0.0051), respectively. Owing to they affect the health of individuals. Social acceptability (SC_{14}), was the most significant sub-criteria among social sub-criteria, having a weight value of 0.0070. It was taken into consideration as a very important criterion in the use of wastewater treatment systems. Therefore, these were the topmost of the importance in implementing an appropriate and sustainable WTT for the steel industry of Iranian Ghadir in Ardakan city, Iran.

Finally, this prioritization of criteria and sub-criteria corresponds to the real situation in the steel industry chain in Iran that most economic and technical criteria were effective in selecting, transferring, and implementing technology, especially in sustainable wastewater management of these industries.

The prioritization of candidate alternatives employing the method of fuzzy VIKOR

In the present part, after obtaining the criteria and sub-criteria weights, the prioritization of the candidate alternatives and selection of the most sustainable alternative was obtained by using the VIKOR method under the fuzzy environment. Five alternatives were evaluated (A_1, A_2, A_3, A_4, and A_5). The experts or decision-makers (DMs) assess each alternative utilizing a fuzzy assessment scale and construct the decision-making matrix (DMM) of fuzzy VIKOR (see Tables 5 and 6). Next, formula (7) was employed to calculate the normalized values of the DMM (see Table 7). Then, the best f_j^* and the worst f_j^- values of each column of the decision-making matrix were determined by the formula (8) (see Table 8). Formulas (9), (10), and (11) were used for obtaining the values of *S*, *R*, and *Q*, respectively. The alternatives were sorted by using the values of *S*, *R,* and, *Q* indices in decreasing order and alternatives were ranked according to these indices (see Tables 9, 10, and 11). Therefore, the option with having the smallest value of *Q* was determined as the most sustainable alternative, if the two conditions of the VIKOR technique were satisfied.

The findings of this technique were shown as follows:

Table 5. Linguistic importance of the five candidate alternatives concerning the sub-criteria by the three DMs.

DMs	Alter	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
DM_1	A_1	L	M	VL	L	L	G	M	L	L	VL	VL	VL	L	L
	A_2	G	G	FG	VL	VL	L	MLL	G	L	MLL	M	MLL	L	L
	A_3	VG	VG	MLG	L	VL	M	VG	MLL	G	L	MLG	FG	M	MLL
	A_4	VL	VL	MLL	L	M	VL	M	VG	MLL	VL	L	VL	VL	M
	A_5	MLG	MLL	G	FG	L	VL	G	MLG	MLL	M	MLL	VL	MLL	VL
DM_2	A_1	MLL	MLL	M	MLL	MLG	MLG	MLL	MLG	MLL	M	M	L	MLL	MLG
	A_2	MLG	MLG	G	M	L	MLL	MLG	MLG	MLG	M	MLL	M	MLG	MLL
	A_3	VG	G	G	MLG	M	MLL	G	MLG	G	MLL	G	G	MLL	MLG
	A_4	L	M	MLG	MLL	M	MLL	M	MLL	MLG	L	MLL	M	M	MLL
	A_5	G	MLG	MLG	G	MLG	L	MLG	G	M	MLL	M	L	M	M
DM_3	A_1	M	MLG	MLL	M	M	M	MLG	M	M	MLL	MLL	FL	M	M
	A_2	M	M	VG	MLL	FL	M	FG	M	M	FG	MLG	FG	M	M
	A_3	G	G	VG	M	MLL	MLG	G	FG	M	M	VG	VG	MLG	FG
	A_4	FL	FG	M	MLG	MLL	MLG	FG	MLG	FG	FL	M	MLL	MLL	MLG
	A_5	VG	FG	M	VG	M	FL	M	VG	FG	MLG	FG	FL	FG	MLL

The linguistic values of this table were converted to triangular fuzzy and then, using the Yager method, they were taken out of the TFNs and converted into single values as given the following table.

Table 6. Single values of the five alternatives relative to the defined sub-criteria of the research.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A_1	0.43	0.5	0.33	0.37	0.43	0.63	0.5	0.43	0.37	0.33	0.33	0.2	0.37	0.43
A_2	0.63	0.63	0.8	0.33	0.2	0.37	0.57	0.63	0.43	0.53	0.5	0.53	0.43	0.37
A_3	0.87	0.83	0.77	0.43	0.33	0.5	0.83	0.57	0.7	0.37	0.77	0.8	0.5	0.57
A_4	0.2	0.53	0.43	0.5	0.33	0.5	0.53	0.5	0.57	0.2	0.37	0.33	0.33	0.5
A_5	0.77	0.57	0.63	0.8	0.43	0.2	0.63	0.57	0.53	0.5	0.43	0.2	0.53	0.33

Then, the normalized values of the Table 6 were given in Table 7. It is shown as follows:

Table 7. Normalized values of the alternatives relative to the defined sub-criteria of the research.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A_1	0.1483	0.1634	0.1115	0.1523	0.2500	0.2864	0.1634	0.1593	0.1423	0.1710	0.1375	0.0971	0.1713	0.1955
A_2	0.2172	0.2059	0.2703	0.1358	0.1163	0.1682	0.1863	0.2333	0.1654	0.2746	0.2083	0.2573	0.1991	0.1682
A_3	0.3000	0.2712	0.2601	0.1770	0.1919	0.2273	0.2712	0.2111	0.2692	0.1917	0.3208	0.3883	0.2315	0.2591
A_4	0.0690	0.1732	0.1453	0.2058	0.1919	0.2273	0.1732	0.1852	0.2192	0.1036	0.1542	0.1602	0.1528	0.2273
A_5	0.2655	0.1863	0.2128	0.3292	0.2500	0.0909	0.2059	0.2111	0.2038	0.2591	0.1792	0.0971	0.2454	0.1500

The obtained results for f_j^* and f_j^- is shown as follows:

Table 8. The obtained results for f_j^* and f_j^-.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
Sub-criteria weight	0.5208	0.2128	0.1043	0.0567	0.0350	0.0224	0.0150	0.0104	0.0070	0.0051	0.0037	0.0028	0.0022	0.0017
A_1	0.1483	0.1634	0.1115	0.1523	0.2500	0.2864	0.1634	0.1593	0.1423	0.1710	0.1375	0.0971	0.1713	0.1955
A_2	0.2172	0.2059	0.2703	0.1358	0.1163	0.1682	0.1863	0.2333	0.1654	0.2746	0.2083	0.2573	0.1991	0.1682
A_3	0.3000	0.2712	0.2601	0.1770	0.1919	0.2273	0.2712	0.2111	0.2692	0.1917	0.3208	0.3883	0.2315	0.2591
A_4	0.0690	0.1732	0.1453	0.2058	0.1919	0.2273	0.1732	0.1852	0.2192	0.1036	0.1542	0.1602	0.1528	0.2273
A_5	0.2655	0.1863	0.2128	0.3292	0.2500	0.0909	0.2059	0.2111	0.2038	0.2591	0.1792	0.0971	0.2454	0.1500
f_j^*	0.5208	0.2712	0.2703	0.3292	0.2500	0.2864	0.2712	0.2333	0.2692	0.2746	0.3208	0.3883	0.2454	0.2591
f_j^-	0.0690	0.1634	0.1115	0.1358	0.1163	0.0909	0.1634	0.1593	0.1423	0.1036	0.1375	0.0971	0.1528	0.1500

The values obtained for the indices of *S*, *R*, and *Q* were shown as follows:

Table 9. Obtained results of S, R and Q for the five alternatives.

Alternatives	*S*	*R*	*Q*
A_1	0.8432	0.4294	0.7854
A_2	0.6077	0.3499	0.4249
A_3	0.3337	0.2545	0.0000
A_4	0.8911	0.0975	1.0000
A_5	0.5458	0.0986	0.2649

The alternatives were sorted by using the values of *S*, *R*, and, *Q* indices in decreasing order as illustrated the following table:

Table 10. Sorted values of S, R, and Q.

Alternatives	Sorted values of *S*	Alternatives	Sorted values of *R*	Alternatives	Sorted values of *Q*
A_4	0.8911	A_1	0.4294	A_4	1.0000
A_1	0.8432	A_2	0.3499	A_1	0.7854
A_2	0.6077	A_3	0.2545	A_2	0.4249
A_5	0.5458	A_5	0.0986	A_5	0.2649
A_3	0.3337	A_4	0.0975	A_3	0.0000

The alternatives were ranked according to these indices as given in the following table:

Table 11. Alternatives ranking by S, R, and Q.

	Alternatives ranking		
	S	*R*	*Q*
1	A_3	A_1	A_3
2	A_5	A_2	A_5
3	A_2	A_3	A_2
4	A_1	A_5	A_1
5	A_4	A_4	A_4

Two conditions of the VIKOR technique were as follows:

Condition 1:

$$Q(A_5)-Q(A_3)>\frac{1}{(5-1)} \quad \rightarrow \quad 0.2649-0>\frac{1}{4}$$

Condition 2:

The third alternative (A_3) in *S* and *R* was also the best.

Therefore, the alternative with having the smallest value of *Q* was determined as the most sustainable alternative, if the two conditions of the VIKOR technique were satisfied. To this, since the lowest value based on the *Q* index was assigned to the third alternative (A_3) and the two conditions were also met, thus this alternative was selected as the most appropriate alternative. It was SBR technology. This technology had its characteristics and was a cheap system to treat low and high volumes of wastewater. In addition, a valuable advantage of SBR technology was that do not require a clarifier. Hence, it saves money and was affordability for the steel industry of Iranian Ghadir in Ardakan city, Iran. Based on the results, the fifth alternative (A_5) ranks second. It was UASB technology. The unique capabilities of this technology have attracted much attentions in recent years to generate energy from the wastewater treatment process. For industry, such as steel was the most suitable alternative if it seeks to produce energy with wastewater treatment. The study (Fetanat et al., 2021a) assessed several technologies for energy production from wastewater treatment, and the results showed that UASB technology was among the technologies evaluated as the most appropriate and sustainable alternative.

This study aligns with previous research in sustainable wastewater treatment technology (WTT) selection, particularly studies that emphasize a balance between economic, technical, and environmental criteria. For example:

1. **Economic Priorities:** Research by Fetanat et al. (2021) and Aziz et al. (2020) has similarly highlighted economic factors—specifically Construction costs and Operation and maintenance costs—as crucial considerations in WTT choice, especially in developing regions where budget constraints were significant.

2. **Technical Aspects:** The importance of technical criteria like Efficiency and Reliability was echoed in studies by Mahjouri et al. (2017) and Chang (2010), where these indicators were emphasized as central to achieving optimal treatment performance and ensuring system resilience. These studies also prioritize technologies with stable, reliable outputs for wastewater treatment.
3. **Environmental Considerations:** Environmental factors, particularly those concerning occupational health, sludge management, and odor control, were stressed in prior research, such as by Bertanza et al. (2017) and Pardey et al. (2017), which underscore the need for safer, more environmentally sound WTT systems. In these studies, MBR technology sometimes ranks higher due to its filtration capabilities, although its costs were a limiting factor.
4. **Methodological Approach:** While past studies, including those by Opricovic and Tzeng (2007) and Chou and Chang (2008), often apply VIKOR alone or use fuzzy MCDM methods like AHP or TOPSIS, this study's hybrid fuzzy SWARA-VIKOR approach was unique. The combined model offers refined weighting and prioritization, allowing for nuanced decision-making that considers economic, technical, and environmental criteria simultaneously.
5. **Technology Rankings:** Similar to this study, other research often ranks SBR as a top choice for industrial WTT due to its adaptability and effectiveness, particularly in studies with industrial application contexts (Ren and Ren, 2018). However, in studies prioritizing environmental sustainability, MBR was sometimes rated higher, despite its higher costs, for its advanced particle filtration capability (Lin and Wu, 2008).

Recent research emphasizes a strong need for sustainable wastewater treatment in the steel industry. Studies like Purkait et al. (2023) focus on various advanced techniques such as ozonation and electrocoagulation for steel industry wastewater remediation, underscoring the importance of both economic and environmental considerations. This approach complements the findings of this study, which used hybrid MCDM models to prioritize technologies based on criteria such as cost, efficiency, and environmental impact. Additionally, both studies highlight the complexity of wastewater treatment in steel plants and the critical role of sustainable solutions in the industry's wastewater management strategies. In summary, this research builds on a foundation established by similar studies, adding value with a novel hybrid MCDM model that balances conflicting criteria more effectively for WTT selection in complex industrial settings. This structured framework provides a practical tool for policymakers aiming for sustainable development in the industrial wastewater sector, particularly within regions with resource constraints.

Conclusion

This study seeks to identify key sustainability indicators and select the most suitable wastewater treatment technology (WTT) for the Iranian Ghadir steel industry in Ardakan, using a comprehensive model to address complex decision-making conditions. Given the technical challenges and rising costs of WTT, a systematic approach was crucial. The research proposes a hybrid model combining SWARA and VIKOR techniques with fuzzy logic to effectively compare multiple conflicting criteria. Results indicate that Construction costs and Operation and maintenance costs were the most influential economic indicators, while Efficiency and Reliability were central to technical performance. In terms of environmental impact, Occupational health and safety, Amount of sludge generation, and Odor generation rank highly, with Noise impact being least influential.

The Sequencing Batch Reactor (SBR) emerged as the most sustainable WTT option, followed by UASB, highlighting the value of fuzzy SWARA in defining criteria based on sustainability principles and fuzzy VIKOR in ranking alternatives. This was the first application of the model in Iran's steel industry, offering policymakers a structured framework for sustainable decision-making in wastewater management. The authors anticipate that this model will guide the industry toward sustainability goals and facilitate future technological advancements for sustainable industrial systems.

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