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Performance evaluation of textile wastewater treatment techniques using sustainability index: An integrated fuzzy approach of assessment

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ABSTRACT

The Textile Wastewater Treatment Technique (TWWTT) plays a prominent role in reducing effluent contaminants and thus keeping the environment cleaner. To select appropriate technology, evaluating the unified performance of TWWTTs towards social, technical, economic, and environmental sustainability parameters is of utmost importance. Though there are TWWTTs available, no ready framework exists that can help decision-makers choose the appropriate technology based on their requirement. The study proposes a novel and systematic decision-making framework and a comprehensive mathematical model for judiciously selecting the TWWTT. It integrates fuzzy Delphi and hybrid Fuzzy Analytical Hierarchy Process (FAHP) approach of Multi-Criteria Decision Making (MCDM). A total of 38 sub-indicators of sustainability are identified from past studies and expert opinions. Fuzzy Delphi is applied to identify the essential sub-indicators of sustainability, and hybrid FAHP is used to rank the sustainability dimensions, key sub-indicators, and alternatives. Twenty-eight sub-indicators are rounded down from the initial 38. The results from hybrid FAHP indicate that the technical dimension of sustainability is of paramount importance while selecting the TWWTTs followed by the economic dimension. The key sub-indicators for the selection of TWWTTs that scored higher than the others in technical, economic, social, and environmental aspects respectively are as under (i) color removal efficiency, COD removal efficiency, and quantity of sludge generation; (ii) cost of construction, operation, and maintenance; (iii) awareness within textile industries, public safety; (iv) effluent suitability for reuse and space requirements. The five TWWTTs, namely, Activated Sludge Process (ASP), Membrane Biological Reactor (MBR), Electrochemical Coagulation (EC), Mixed Bed Bio Reactor (MBBR), and the Rotating Biological Contactors (RBC), are compared using the estimated entropy weights also called as sustainability indices. MBR has scored the highest sustainability index value, and ASP has the least value. MBR, EC and MBBR have higher sustainability indices proving them better sustainable alternatives than ASP and RBC. The MBR permeate quality is good enough to be reused in the textile industry without any further treatment. This will reduce the effluent quantity and groundwater demand leading to cleaner production of textile. The study will help the decision-makers in the overall assessment of the sustainability of TWWTTs prior to selection.

1. Introduction

Rapid urbanization and population growth have led to increased demand for manufactured goods, textile, pharmaceuticals, infrastructure and non-renewable resources. Industries worldwide generate a tremendous amount of solid and liquid waste, resulting in an inevitable tradeoff between industrial development and environmental perseverance. The treatment and management of industrial wastes have become challenging for the human community (Dasgupta et al., 2015). The textile industry has an undeniable contribution in satisfying basic human needs and is also one of the largest environmental polluters (Yaseen and Scholz, 2019).

The textile industry is a prominent consumer of water, dyes and chemicals during various stages of textile processing, such as dyeing, mercerizing, scouring, finishing and cleaning. Subsequently, this industry generates a significant amount of chemically contaminated water, which is unsuitable for further usage (Holkar et al., 2016). This can be assessed by the fact that the textile industry, on average, uses between 230 and 270 t of water for producing 1 t of finished textile fabric (Keskin et al., 2021). The effluent from the textile industry is rich

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in complex chemicals, acids, bases, dyes, heavy metals and inorganic salts (Karthik and Rathinamoorthy, 2015). According to US Environmental Protection Agency (USEPA), textile waste is defined as a dispersible hazardous toxic waste that is high in volume and difficult to treat (Foo and Hameed, 2010). Among the various contaminants present in the effluent, dyes are the primary and recalcitrant pollutants that are toxic and carcinogenic in nature (Zhou et al., 2019). The discharge of raw effluent into the freshwater bodies or in sewer lines adversely affects the dissolved oxygen, inhibits the biological treatment process, increases turbidity and is aesthetically unpleasant, affecting the overall water quality of the river and surrounding environment (Singh et al., 2019; Srinivas and Singh, 2018). It imparts toxicity to both biotic as well as abiotic components of the environment, comprising air, soil, water, terrestrial and aquatic life (Behera et al., 2021).

The textile industry poses one of the greatest dangers to the environment due to its water intensiveness resulting in depletion of freshwater as well as groundwater. The increased scarcity of water resources and the decline in water quality with the increasing water demand in industries has obliged the researchers to assess the aptness of various TWWTTs for proper disposal and reuse of effluent. Numerous methods exist for treating textile wastewater. These are categorized as physical, chemical, biological and hybrid processes (Behera et al., 2021). Most of these processes vary in terms of their fundamental working principle and are compared based on their performance, the cost involved and the merits/demerits associated with them. Apart from this, the development of the textile wastewater treatment unit requires extensive infrastructure, consumes a considerable amount of energy during its operational life, harms the ecosystem's hydrology and contributes to carbon footprint (Sawaf and Karaca, 2018). The treatment of effluents reduces the contamination level and makes it safe for reuse and disposal but has the inherent limitation of producing hazardous sludge and its expensive disposal. Consequently, the selection of a sustainable TWWTT is a multidimensional and challenging task where decision-makers face multiple conflicts. It can be concluded that the selection of appropriate TWWTT is an MCDM problem.

The sustainability concept here means the performance of TWWTTs should be balanced by the environmental, economic and societal dimensions (Muga and Mihelcic, 2008; Singh and Dhadse, 2021). Some studies have considered technical and management aspects of sustainability. The related articles suggest divergent use of sustainability in the studies. Padilla-Rivera et al. (2016) and Tsalidis et al. (2020) have focused only on the social aspects of sustainability of Wastewater Treatment (WWT) alternatives. Muga and Mihelcic (2008) have evaluated the performance of WWT using the social, environmental and economic dimensions. Yang et al. (2020) compared the technical, economic and environmental perspective of TWWTTs. Garrido-Baserba et al. (2014) has considered the environmental criteria while selecting the WWTT. Pretel et al. (2016) studied the economic and environmental aspects of sustainability. The performance evaluation of the sustainability aspects can be done by incorporating the judgement of different experts in the field of wastewater treatment (Srinivas and Singh, 2018). The suggestions and opinions of experts need to be put together using a mathematical model. This will help the decision-makers to come up with a single, functional and efficient decision. The MCDM mathematical methods have been used widely in studies. Ouyang et al. (2015) have considered the environmental, ecological, management and technical aspects to assess the performance of natural WWT facilities using a unified approach of the multidimensional scaling and fuzzy analytical process. Zheng et al. (2016) established a scenario-based framework to compare the socio-economic dimensions of sustainability of different WWT facilities using multi-criteria decision analysis. Ren and Liang (2017) have used the intuitionistic fuzzy set theory for measuring the sustainability of WWT processes. Lizot et al. (2021) integrated the AHP and ELECTRE II methods to prioritize the WWT system. Omran et al. (2021) evaluated the sustainability of WWT techniques for the urban regions of Iraq using the weighted sum model of multi-criteria decision analysis.

Though all these studies are focused on wastewater treatment, scant attention has been paid towards evaluating the sustainability of TWWTTs. Kumar et al. (2016) optimized the process parameters for the bio-treatment of textile wastewater using the Fuzzy Inference System (FIS). Dogdu et al. (2017) monitored the performance of vertical flow wetlands in treating the real textile effluent using fuzzy logic. Periyasamy et al. (2018) reviewed and discussed the various sustainable TWWTTs considering the primary, secondary and tertiary treatment levels. Sawaf and Karaca (2018) investigated the difference in stakeholders' opinions towards the sustainability of common WTT used for the textile industry in Turkey using the Analytical Hierarchical Process (AHP), Simple Additive Weighing (SAW) approach. An ample number of studies have applied the AHP approach to drive the score for different criteria or alternatives of WWT processes. The summary of related research articles is presented in Table 1. Limited studies have focused on the prioritization of textile effluent treatment techniques.

The research gaps identified based on the literature review are: (1) Most articles have investigated the sustainability of WWT techniques, and the same results cannot be applied to textile wastewater treatment processes. The discarded textile effluent contains dyes, salts and other pollutants and hence the efficiency of the treatment process changes, influencing their sustainability; (2) In most articles, a few aspects of sustainability are considered without any suitable framework; (3) No study has comprehensively identified the sub-criteria for the sustainability dimensions of TWWTTs; (4) There is a need for developing a decision-making framework and a mathematical model for a unified performance assessment of the sustainability of different TWWTTs. The model should incorporate the fuzziness associated with the stakeholders from various backgrounds.

In accordance with the identified research gaps, the main contributions of the study are: (1) developing a hierarchal evaluation system for this decision-making problem; (2) identification of sub-criteria in the context of TWWTTs which may positively or negatively impact the sustainability dimensions; (3) developing a novel decision framework using the hybrid MCDM method established on fuzzy set theory for aiding the decision-makers in prioritizing the textile effluent treatment techniques. To achieve these objectives, a fuzzy Delphi and hybrid FAHP approach are used in this study. The Fuzzy Delphi Method (FDM) is used to select the critical sub-criteria for maximizing the sustainability of TWWTTs. Hybrid FAHP is used to rank the different TWWTTs and to determine the sustainability indices.

The study is structured as follows: Introduction being section 1, the related literature is reviewed to identify the criteria and sub-criteria for measuring the sustainability score of TWWTTs in section 2. The research methodology for explaining the FDM and hybrid FAHP methods is presented in section 3, followed by a case study in Section 4. The results and discussion are presented in section 5 and conclusions in section 6.

2. Selection of sustainability criteria and sub-criteria

The sustainability criteria and sub-criteria are gleaned through the literature review in this section. The three main aspects of sustainability are economy, environment and society used in the Triple Bottom Line (TBL) approach (Nozari et al., 2021). Apart from these, the sub-criteria in the technical and managerial aspects considerably influence the overall sustainability of the technology considered (Ouyang et al., 2015). The four aspects of sustainability, economic, social, environmental, and technical, are considered in this study, whereas some of the managerial sub-criteria are included in the economic and the technical aspects. The set of sub-criteria to evaluate the sustainability of WWT processes are first listed by Muga and Mihelcic (2008). For the textile industries, Sawaf and Karaca (2018) have comprehensively listed the set of sub-criteria. Table 2 summarizes the sustainable sub-indicators based on the past literature and inputs from the focus groups. These 38 sub-criteria are classified into four categories.

Table 1
Literature review summary.

Contribution	Sustainability dimensions				Methodology	Reference
	Economic	Social	Environmental	Technical		
Selection of WWT technologies	✓	✓	✓			Muga and Mihelcic (2008)
Selection of natural WWT alternatives	✓		✓	✓	AHP, Multidimensional scaling	Ouyang et al. (2015)
Addressing the social dimension of sustainability of WWT technologies.		✓			Basic requirement scale	Padilla-Rivera et al. (2016)
Framework for the planning of wastewater infrastructure under uncertainty	✓	✓	✓		Stochastic multi-criteria acceptability analysis, Monte Carlo simulations	Zheng et al. (2016)
Sustainability measurement of WWT processes	✓	✓	✓	✓	Intuitionistic fuzzy set theory	Ren and Liang (2017)
Selection of WWT facilities	✓	✓	✓	✓	AHP, ELECTRE II	Lizot et al. (2021)
Sustainability assessment of WWT facilities for urban areas of Iraq	✓	✓	✓	✓	Weighted sum model	Omran et al. (2021)
Bio-treatment process for real textile industry effluent- process parameter modelling and optimization				✓	Fuzzy inference system, Mamdani's method	Kumar et al. (2016)
Monitored the performance of vertical flow constructed wetlands for textile industry effluent				✓	Fuzzy logic	Dogdu et al. (2017)
Comparison of different stakeholder opinions towards the sustainability of TWWTTs	✓	✓	✓	✓	AHP, SAW, CP, TOPSIS	Sawaf and Karaca (2018)

Table 2
Sustainability indicators, sub-criteria classification.

Sustainable indicators	Sub-criteria	Source
Technical	Energy consumption, Maintenance frequency, Hydraulic retention time, BOD removal efficiency, COD removal efficiency, TSS removal efficiency, Color removal efficiency, Turbidity removal efficiency, NH_3 removal efficiency, Odor removal, Sludge generation, Durability, Flexibility, Reliability, Complexity, Construction ease, Upgradability ease, Accessibility ease.	(Lizot et al., 2021; Omran et al., 2021; Sawaf and Karaca, 2018; Ouyang et al., 2015; Dogdu et al., 2017)
Economic	Technology cost, Construction cost, Operation and maintenance cost, Capacity up-gradation cost, Use of locally available material.	(Lizot et al., 2021; Omran et al., 2021; Ouyang et al., 2015; Ren and Liang, 2017; Sawaf and Karaca, 2018)
Environmental	Space requirement, Soil contamination, Effect on the surrounding environment, Odor problem, Poor aesthetics, Footprint requirement, Implications on flora and fauna, Effluent suitability for reuse.	(Lizot et al., 2021; Omran et al., 2021; Ouyang et al., 2015; Ren and Liang, 2017; Sawaf and Karaca, 2018; Singh and Dhadse, 2021)
Social	Public safety, Employee health, Community participation, Awareness within industries, Acoustic/visual comfort, Hiring local services.	(Omran et al., 2021; Padilla-Rivera et al., 2016; Sawaf and Karaca, 2018; Lizot et al., 2021; Ren and Liang, 2017)

3. Methodology

An extensive literature review helped identify the gaps in the existing studies and decide upon the sustainability indicators and sub-criteria. The prominent sub-indicators had to be selected from this list, and the fuzzy Delphi approach of MCDM is used accordingly. Further, the ranking of such selected criteria and sub-criteria for a TWWTT is carried out using a hybrid fuzzy AHP approach, and these TWWTTs are ranked based on their sustainability indices. The expert opinions required for the analysis is collected through a questionnaire survey. Fig. 1 depicts the overall framework of the proposed research.

3.1. Fuzzy-Delphi method (FDM)

The concept of FDM was established by Ishikawa (1993) and it integrates the concept of the conventional Delphi method with fuzzy set theory. The traditional Delphi method is an expensive and time-consuming exercise as the experts are required to give their feedback until the desired consistency in opinion is achieved. It is also challenging to get a unanimous opinion of the experts. In the Delphi method, the expert opinion is collected in crisp numbers. These numbers do not incorporate the vagueness of human judgement. The FDM overcomes these demerits as experts are made to share their opinions in the form of a three-point membership function using Triangular Fuzzy Number (TFN) and are not required to review their judgements (Nozari et al., 2021; Zhao et al., 2019).

Due to these advantages, researchers have used the FDM in different studies to select the key variables from the available variables (Chen et al., 2018; Tsai et al., 2020; Zhao et al., 2019). In this study, the FDM has been used to select the crucial sub-indicators. Based on the FDM proposed by T. H. Hsu and Yang (2000), the procedure is discretized into three main steps such as (i) data collection, (ii) conversion of expert opinion into TFN using Table 3, (iii) calculation of fuzzified weights followed by the defuzzification of the fuzzy scores. The detailed procedure of the FDM is given in Appendix A. After calculating the de-fuzzified score, the threshold value for selecting critical sub-criteria is set. The key sub-criteria are finalized for the next phase of the study.

3.2. Hybrid Fuzzy Analytical Hierarchy Process (FAHP)

Analytical Hierarchy Process (AHP) is the MCDM approach introduced by Thomas L. Saaty in 1980. The technique can use both qualitative and quantitative variables and determine the relative significance of each alternative over the other for the given set of criteria (Thomas and Doherty, 1980). In the AHP, the pairwise comparison matrices of alternatives and criteria are prepared using the crisp values called as Saaty scale (Saaty, 2004). The crisp scale may not correspond to the real world due to the ambiguity, imprecision and vagueness of human judgement (Mangla et al., 2015). To overcome these drawbacks of uncertainty, the proposed methodology incorporates the objective-based approach of Fuzzy Analytical Hierarchical Process (FAHP). In FAHP, the crisp values of Saaty's scale are converted into fuzzy numbers using the chosen membership function (Anqi and Mohammed, 2021; Vyas

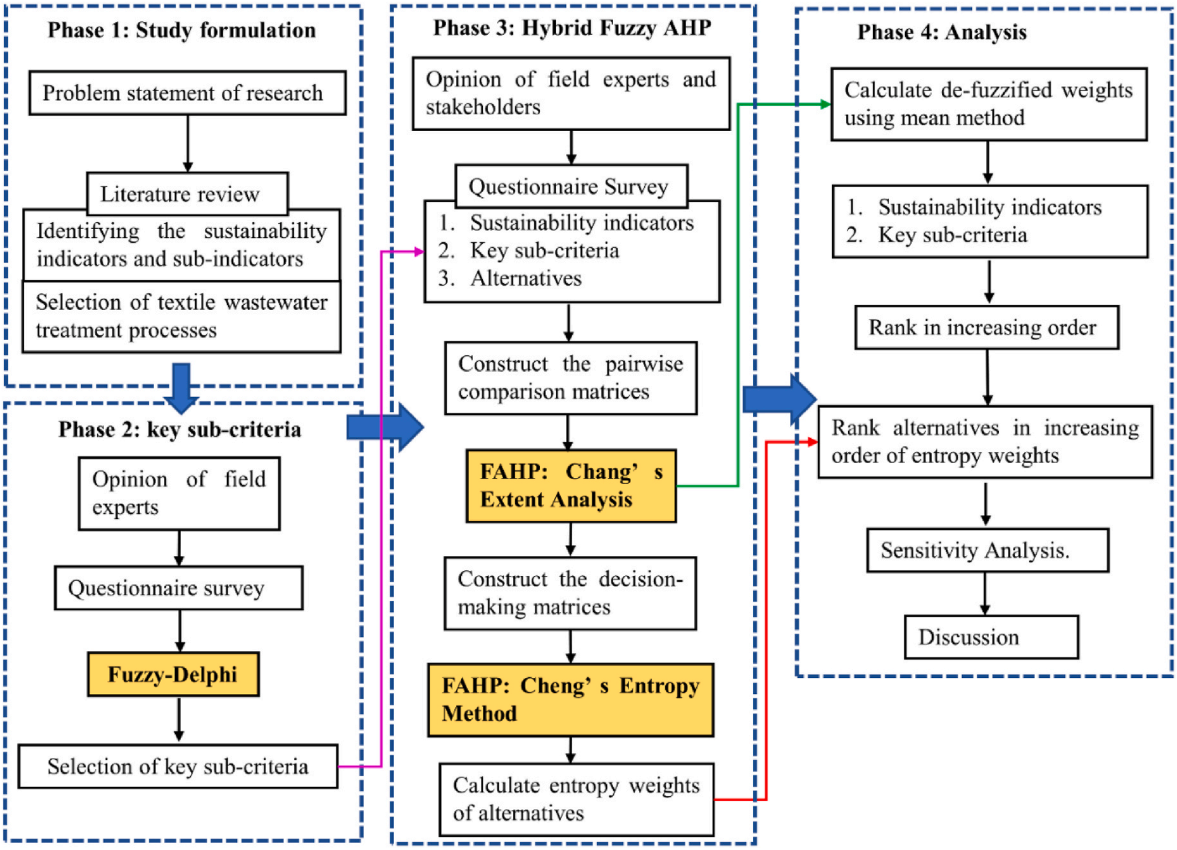

Fig. 1. A framework of the proposed methodology.

Table 3
The fuzzy conversion scale for FDM.

Score	Fuzzy triangular number
1	(0, 0, 0.1)
2	(0, 0.1, 0.3)
3	(0.1, 0.3, 0.5)
4	(0.3, 0.5, 0.7)
5	(0.5, 0.7, 0.9)
6	(0.7, 0.9, 1.0)
7	(0.9, 1.0, 1.0)

et al., 2019). The FAHP organizes and analyses the complex decision problem in an elementary form and comes up with the best possible solution (Mangla et al., 2017). The FAHP approach by Chang (1996) is used for the estimation of decision matrices, and the Entropy-based FAHP by Cheng (1997) is applied for the final ranking of alternatives. The steps involved in the study for ranking the alternatives are given below.

3.2.1. *Step A: data collection and construction of pairwise comparison matrices*

I. Based on the hierarchical structure of the study, expert opinion is gathered using the questionnaire in three steps for developing the pairwise judgement matrices as: (1) for criteria; (2) for each criterion comparing key sub-criteria; (3) for each sub-criterion comparing the alternatives.

II. The response collected from the experts is in the form of crisp numbers. These crisp numbers are converted into symmetric TFN before aggregation of responses using the scale given in Table 4. The responses are combined into single pairwise assessment matrices using the mean method.

3.2.2. ***Step B:*** *computation* ***of weights***

In this study, we utilize the FAHP synthetic extent analysis method proposed by Chang (1996) for estimating the weights of sustainable indicators, sub-indicators and for developing the decision matrices of the alternatives. For better understanding, the mathematical background of Chang's extent analysis is presented below.

Let, A = {$a_1, a_2, a_3, \ldots a_n$} is the set of objects; and U = {$u_1, u_2, u_3, \ldots u_m$} is the set of goals. According to the synthetic extent analysis of Chang, the extent of an object concerning each of the goals can be quantified, resulting in m extent analysis values for each object (Chang, 1996; Srdjevic and Medeiros, 2008). All u_i^j $(i = 1 \ldots\ldots\ldots n,\ j = 1 \ldots\ldots\ldots m)$ are the TFN representing the performance of the object a_i for each goal u_j. The fuzzy extent value of an object can be computed using Eq. (1)

$$S_i = \sum_{j=1}^{m} u_i^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} u_i^j\right]^{-1} \tag{1}$$

where, $\sum_{j=1}^{m} u_i^j = \left(\sum_{j=1}^{m} p_i, \sum_{j=1}^{m} q_i, \sum_{j=1}^{m} r_i\right)$, $and \left[\sum_{i=1}^{n}\sum_{j=1}^{m} u_i^j\right]^{-1} = \left[\frac{1}{\sum_{i=1}^{n} r_i}, \frac{1}{\sum_{i=1}^{n} q_i}, \frac{1}{\sum_{i=1}^{n} p_i}\right]$

where, S_i is the normalized fuzzy number, and the medium values are considered unity and i = 1 … n (n = number of criteria).

The fuzzy pairwise comparison matrices for the M number of sustainability indicators are constructed and the weights w_j are estimated using Eq. (1). Similarly, for the given sustainability M_j, which has k_j sub-criteria, weights are calculated. The final weights for the sub-criterion are estimated by multiplying the weights with the respective sustainability indicator's weight. The total aggregated weights X are as follows.

$$X = \left(\widetilde{X}_1, \widetilde{X}_2, \ldots\ldots\ldots\ldots \widetilde{X}_K\right) \tag{2}$$

The de-fuzzified score for sustainable indicator and each sub-criterion is calculated using the mean method. The decision matrix for the N alternatives compared for each K sub-criteria is estimated using Eq. (1).

3.2.3. Step C: final assessment

For the final assessment and ranking of alternatives, several methods such as dominance method, total integral value, the α-cut with interval synthesis and the entropy method have been used by the researchers (Cheng, 1997; Hsu et al., 2010; Mahpour, 2018; Srdjevic and Medeiros, 2008). In this study, Cheng's entropy method of FAHP is used to rank the alternatives. The α-cut performance matrix, $\widetilde{Z}_\alpha$ is determined with the assistance of Eq. (3). Here, α defines the confidence level and the λ is an index of the optimism of the decision experts (Vyas et al., 2019).

$$\widetilde{Z}_\alpha = \begin{bmatrix} \left[z^\alpha_{11p}, z^\alpha_{11q}\right] & \cdots & \left[z^\alpha_{1np}, z^\alpha_{1nq}\right] \\ \vdots & \ddots & \vdots \\ \left[z^\alpha_{n1p}, t^\alpha_{n1q}\right] & \cdots & \left[z^\alpha_{nnp}, z^\alpha_{nnq}\right] \end{bmatrix} \tag{3}$$

where, $z^\alpha_{ijp} = X^\alpha_i y^\alpha_{ijp}$, $z^\alpha_{ijq} = X^\alpha_i y^\alpha_{ijq}$, for $0<\alpha < 1$ and for all i, j. The precise judgment matrix $\widehat{Z}$ is estimated as shown in Eq. (4).

$$\widehat{Z} = \begin{bmatrix} \widehat{z}^\alpha_{11} & \widehat{z}^\alpha_{12} & \cdots & \widehat{z}^\alpha_{1n} \\ \widehat{z}^\alpha_{21} & \widehat{z}^\alpha_{22} & \cdots & \widehat{z}^\alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widehat{z}^\alpha_{n1} & \widehat{z}^\alpha_{n2} & \cdots & \widehat{z}^\alpha_{nn} \end{bmatrix} \quad where \quad \widehat{z}^\alpha_{ij} = (1-\lambda) z^\alpha_{ijp} + \lambda z^\alpha_{ijq} \ \forall \lambda \in [0,1] \tag{4}$$

The relative frequency matrix Eq. (5) of the precise judgment matrix, is calculated and the entropy values are estimated using Eq. (6). This is followed by the calculation of entropy weights using Eq. (7), where E_i is the i^{th} entropy value. It is worth mentioning that the estimated entropy weights are also called sustainability scores or the sustainability indices in the study.

$$\begin{bmatrix} \frac{z_{11}}{p_1} & \frac{z_{12}}{p_1} & \cdots & \frac{z_{1n}}{p_1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{z_{n1}}{p_n} & \frac{z_{n2}}{p_n} & \cdots & \frac{z_{nn}}{p_n} \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{5}$$

where, $p_k = \sum_{j=1}^{n} z_{kj}$

$$E_n = -\sum_{j=1}^{n} (r_{nj}) \log_2 (r_{nj}) \tag{6}$$

$$E_i = \frac{E_j}{\sum_{j=1}^{n} E_j} \tag{7}$$

4. Case study

The study is focused on the textile industry cluster situated in the Balotra region of Barmer district of Rajasthan state, India. About 400 textile industries in the cluster have an allocated discharge capacity of effluent as 15.33 MLD. These industrial units are of textile processing dealing with dyeing, mercerizing, printing and finishing. The textile effluent from these industrial clusters is collected in the CETP and the Activated Sludge Process (ASP) is used for its treatment. Due to the presence of excessive chemicals in industrial effluents such as caustics soda, dyes and other metallic salts, the ASP is not sufficient to remove all these impurities and make it suitable for its reuse in the industry. There is a need for up-gradation of the treatment process. Concerning these issues, the alternatives for the study are the following five TWWTTs, Activated Sludge Process (ASP), Rotating Biological Contactor (RBC), Membrane Bioreactor (MBR), Electrochemical Coagulation (EC) and Moving Bed Biofilm Reactor (MBBR). The ASP and RBC are conventional treatment techniques, while MBR, MBBR and EC are non-conventional techniques.

4.1. Screening of essential sustainability sub-criteria by FDM

In this study, the FDM is used to identify the essential sub-criteria useful for evaluating the performance of TWWTTs. Initially, 38 sub-criteria in four sustainability dimensions were identified, as shown in Table 2. In the next step, a questionnaire survey was designed to collect the opinion of experts. The expert's selection is based on their knowledge, professional skills, background and practical experience. For this study, five experts with different backgrounds, two academicians, an engineer working in CETP, a resident and an expert member of the Central Pollution Control Board (CPCB), India, have been selected. Ocampo et al. (2018) has stated in their research work that there is no relation between the quality of decision and the number of experts.

The data collected is in the form of crisp numbers having their linguistic definitions further converted to fuzzy scale using Table 3. Once the response of the experts is gathered, the fuzzy scores are calculated as given in Appendix A. The typical threshold value of 0.6 for selecting the critical sub-indicator was set with the consultation of experts and from the literature (Shen et al., 2010). The sub-indicators with a score equivalent to the threshold value or above are chosen for the study's next phase. The estimated fuzzy weights, along with the de-fuzzified score, are presented in Table 5. The de-fuzzified score is shared among the experts and allowed to include any additional sub-criteria. The additions were not suggested. The twenty-eight sub-indicators (colored as grey) are chosen for the next phase of the analysis.

4.2. Hybrid fuzzy AHP for ranking of alternatives

To begin with, a hierarchical model is developed by including only 28 key sub-criteria, finalized after FDM as shown in Fig. 2. The four levels of the established hierarchical diagram are as follows: (1) the goal of the study, (2) sustainability indicators, (3) sustainability sub-criteria and (4) the TWWTTs. After developing the hierarchy model, the pairwise assessment matrices are developed with the assistance of a group of 3 experts. The expert response is collected using the questionnaire survey in the form of a crisp number. The crisp numbers are converted into TFN using Table 3. With the help of Eq. (1), the fuzzy extent values are estimated for the sustainability indicators, sub-criteria and alternatives. The calculations for fuzzy synthetic extent values for sustainability dimension environment (E) are given below.

$$\begin{aligned} \mathrm{E} &= (4.656,\ 6.0865,\ 8.65) \otimes (0.0215,\ 0.0274,\ 0.0332) \\ &= (0.10047,\ 0.16730,\ 0.28742) \end{aligned}$$

The complete result for all the sustainability aspects is shown in Table 6.

Similarly, the fuzzified pairwise comparison matrix of the sub-criteria falling under each sustainable indicator is constructed with expert opinions. The fuzzy synthetic extent analysis values are

Table 4
The fuzzy conversion scale used for FAHP.

Crisp values	TFN
1	(1, 1, 2)
2	(1, 2, 3)
3	(2, 3, 4)
4	(3, 4, 5)
5	(4, 5, 6)
6	(5, 6, 7)
7	(6, 7, 8)
8	(7, 8, 9)
9	(8, 9, 9)

Table 5
Fuzzy Delphi analysis to finalize the sustainable sub-indicators.

Sustainable indicators	Sustainable sub-indicators	Fuzzy weight	De-fuzzified Score
Technical (T)	Energy consumption (T1)	(0.5, 0.89, 1)	0.798
	Maintenance frequency (T12)	(0.3, 0.73, 1)	0.676
	Hydraulic Retention time	(0.1, 0.37, 0.7)	0.389
	BOD removal efficiency	(0.5, 0.77, 1)	0.758
	COD removal efficiency	(0.5, 0.89, 1)	0.798
	TSS removal efficiency	(0.5, 0.86, 1)	0.785
	Color removal efficiency	(0.5, 0.87, 1)	0.791
	Turbidity removal efficiency	(0.3, 0.65, 0.9)	0.618
	NH_3	(0.1, 0.52, 0.9)	0.505
	Odor removal	(0.1, 0.49, 1)	0.53
	Sludge generation	(0.5, 0.86, 1)	0.785
	Durability	(0.5, 0.7, 0.9)	0.7
	Reliability	(0.3, 0.57, 0.9)	0.591
	Flexibility	(0.3, 0.69, 1)	0.663
	Complexity	(0.5, 0.81, 1)	0.769
	Construction ease	(0.1, 0.48, 0.9)	0.494
	Upgradability ease	(0.3, 0.69, 1)	0.663
	Accessibility ease	(0.1, 0.41, 0.7)	0.403
Social	Public safety	(0.3, 0.69, 1)	0.663
	Employee health	(0.5, 0.81, 1)	0.771
	Community participation	(0.1, 0.58, 1)	0.560
	Awareness to industries	(0.3, 0.66, 1)	0.652
	Acoustic/visual to workers	(0.3, 0.69, 1)	0.662
	Hiring local services	(0.3, 0.69, 1)	0.663
Economic	Use of locally available material.	(0.1, 0.48, 0.9)	0.494
	Construction costs	(0.5, 0.75, 1)	0.751
	Operation/maintenance costs	(0.3, 0.78, 1)	0.692
	Capacity up-gradation	(0.5, 0.89, 1)	0.798
	Technology cost	(0.3, 0.78, 1)	0.692
Environmental	Space requirement	(0.3, 0.74, 1)	0.68
	Soil contamination	(0.1, 0.52, 0.9)	0.505
	Surface water contamination	(0.5, 0.83, 1)	0.777
	Effect on surrounding environment	(0.5, 0.81, 1)	0.771
	Footprint requirements	(0.3, 0.69, 1)	0.663
	Implications on flora and fauna	(0.1, 0.58, 1)	0.56
	Poor aesthetics	(0.5, 0.81, 1)	0.771
	Odor problems	(0.3, 0.69, 1)	0.663
	Effluent suitability for reuse	(0.3, 0.74, 1)	0.68

calculated for each sub-criterion. The complete result and ranking of sustainability indicators, sub-criteria are given in Table 7.

With the help of expert opinions, the pairwise comparison matrix of alternatives for each sub-criterion is constructed. The fuzzy extent values for constructing the decision matrices of the alternatives are estimated using Eq. (1). To estimate the final ranking of the alternatives, the entropy weights are calculated as given in the research methodology section. Firstly, the lower and upper bounds $[z_l^{\alpha}\ ,\ z_u^{\alpha}]$ are estimated from the fuzzy triplets of the alternative and sub-criterion decision matrix. All the elements of the total fuzzy judgment matrix $\widetilde{Z}_{\alpha\,=\,0.8}$ are determined, followed by the calculation of the precise judgement matrix $\widehat{Z}$ as shown in Table A of Appendix B. Lastly, the entropy weights are estimated using Eq. (7). The obtained entropy weights are also called the sustainability score or sustainability indices of alternatives and serve as a good estimator for prioritizing the TWWTT. The alternative with a higher sustainability score should be given higher priority and will be ranked accordingly.

5. Results and discussion

5.1. *Sustainability indicators ranking using the FAHP approach*

The ranking of sustainability indicators is as follows: T > EC > E > S and is shown in Fig. 3. It can be concluded that the 'technical sustainability indicator (T)' got the maximum score value in the priority ranking, thus indicating the higher influence of the technical aspect over other aspects while selecting the treatment technique. The technical dimension consists of the operational and performance sub-criteria of the treatment technique. The technical functionality of TWWTTs is emphasized as the vital sustainability dimension due to the following reasons: (1) the physical and chemical properties of different textile industrial effluent varies and hence, the efficiency of the treatment processes differs (2) the contaminant removal efficiency of the treatment process decides its reusability for different purposes such as irrigation or industrial usage, (3) some of the treatment techniques are being imported and require skilled labor for its regular maintenance or during sudden breakdown resulting in relatively long recovery time. The increasing shift towards the reuse of treated effluent instead of disposing it back into the environment is also one of the major concerns of the stakeholders while selecting any treatment process (Akhoundi and Nazif, 2018).

The second-highest ranked indicator is economical, as the selected treatment technique should be beneficial for the industrial sector, society and profitable for the government. In India, most of the small-scale textile industries do not have a separate treatment plant due to the high cost of industrial effluent treatment technologies and rely on government-run CETP. The uneconomical treatment facility would also be a burden for the government and may require repetitive funds. The increasing number of industries with time also demands the increase in capacity of the treatment facility and hence, the treatment plant may need capacity up-gradation (Behera et al., 2021).

Environmental criterion is ranked the third most important indicator. The development of any industrial effluent treatment technique has an adverse impact on the surrounding environment and disturbs the ecosystem. The treatment sites also act as a breeding ground for many insects and mosquitoes. The treatment plants have environmental

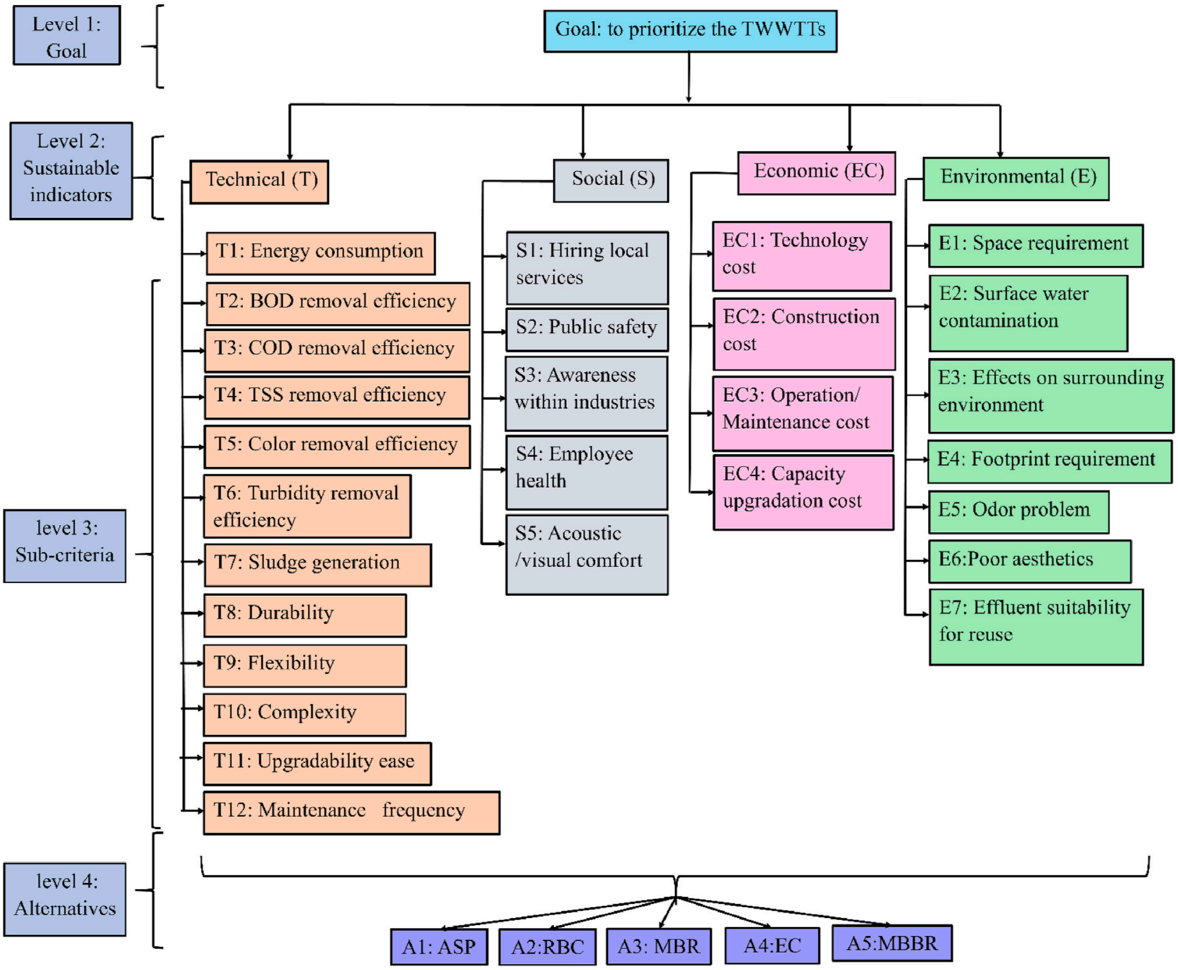

Fig. 2. The hierarchical structure of the study.

Table 6
The fuzzy evaluation matrix of sustainability indicators.

Sustainability indicators	E	S	EC	T	Weights
E	(1,1,2)	(3, 4, 5)	(0.225, 0.306 0.511)	(0.431, 0.781, 1.138)	0.185
S	(0.205, 0.261, 0.361)	(1, 1, 2)	(0.189, 0.233, 0.306)	(0.122, 0.129, 0.15)	0.057
EC	(3,4,5)	(3.333 4.333 5.333)	(1,1,2)	(0.148, 0.169, 0.206)	0.28
T	(3.444, 4.166, 5)	(7, 8, 8.333)	(5,6,7)	(1,1,2)	0.541

Table 7
Weights of the sustainability indicators and key sub-criteria of TWWTTs.

Sustainability indicators	Weights	Rank	Sub-criteria	Weights	Rank
T	0.541	1	T1	0.0189	7
			T2	0.0214	6
			T3	0.0431	2
			T4	0.0319	4
			T5	0.0453	1
			T6	0.0249	5
			T7	0.0388	3
			T8	0.0159	9
			T9	0.0174	8
			T10	0.0059	12
			T11	0.0092	10
			T12	0.0073	11
S	0.057	4	S1	0.0192	3
			S2	0.0194	2
			S3	0.0196	1
			S4	0.0079	4
			S5	0.0022	5
EC	0.28	2	EC1	0.0322	3
			EC2	0.0943	2
			EC3	0.1791	1
			EC4	0.0175	4
E	0.185	3	E1	0.0431	2
			E2	0.026	5
			E3	0.0323	3
			E4	0.0299	4
			E5	0.0081	6
			E6	0.0069	7
			E7	0.0734	1

benefits as they mitigate the contaminants from effluents and produce the sludge used as fertilizer by composting or as a building material (Holkar et al., 2016). However, this sludge is chemically hazardous and requires to be disposed of safely without contaminating the environment. It is essential to adhere to the environmental standards and regulations prescribed by the CPCB of India for selecting the treatment technique.

The social indicator is the lowest scorer among all the sustainability aspects. The social impact assessment of TWWTTs means considering all the issues related to TWWTTs that impact the different groups of people associated with them. The three different groups mainly concerned are the employees, community, society and the industrial administration.

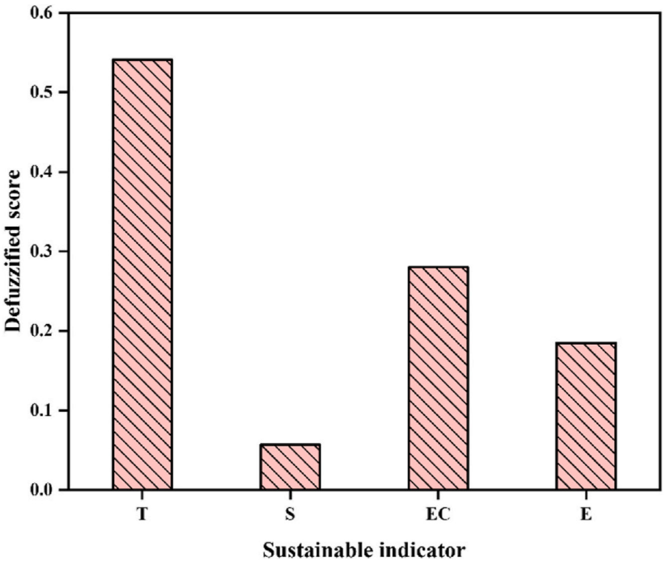

Fig. 3. Comparison of the score for sustainability indicators.

The variables associated with the community are employment generation and public safety. The treatment unit should have acoustic and visual comfort. There should be no or less risk of occupational disease to the employees (Padilla-Rivera et al., 2016). These are the few variables of social aspects of the TWWTTs.

5.2. *Sub-criteria and the alternative ranking using FAHP*

5.2.1. *Technical sustainability indicator*

The technical criterion is relevant to the operational and performance aspects of TWWTTs. This sustainability dimension has the first position in the priority ranking. The treatment techniques have the benefits of treating textile wastewater, but their operation and performance vary based on their working principle and the type of effluent to be treated. The 12 sub-criteria have been considered and are ranked accordingly. The ranking of these sub-criteria is as follows: T5 > T3 > T7 > T4 > T6 > T2 > T1 > T9 > T8 > T11 > T12 > T10. The color removal efficiency, COD removal efficiency followed by the amount of sludge generated are the three important governing attributes for the selection of the TWWTTs and the same can be observed in Fig. 4 (a). The color and COD removal efficiency are areas of primary focus for most textile industry effluent treatment processes (Ayed et al., 2021; Donkadokula et al., 2020). The storage of chemically active sludge from the TWWT plants is difficult and can easily be carried away by the wind and water during storms or rains and hence, it has been ranked as the third most significant sub-criteria. The operational variables such as durability (T8), flexibility (T9), complexity (T10), upgradability (11) and the maintenance frequency (T12) secured lower ranks.

The scores of TWWTTs for the technical indicator are given in Fig. 4 (b). The ranking of TWWTTS for the technical dimension are as follows: MBR > RBC > MBBR > EC > ASP. The MBR treatment technique is noticeably identified as the best scorer, followed by RBC and MBBR. The MBR process reduces 80–99% of COD and 83.7–98.5% of color at 525 nm (Jegatheesan et al., 2016). The color removal efficiency of ASP is 37–55% (Nawaz and Ahsan, 2014), RBC is 85% (Sawaf and Karaca, 2018), EC is 92–100% (Zazou et al., 2019) and MBBR is 61%. The COD removal efficiency of ASP is 45% (Nawaz and Ahsan, 2014), 86% for MBBR (Siddique et al., 2017), RBC is 95.5% and EC is 90% (Sawaf and Karaca, 2018). The low score of ASP is due to poor COD, color and TSS removal efficiency. The MBR technology produces less sludge and can adapt to more pollution concentration as compared to EC and other biological treatment processes (Keskin et al., 2021). The MBR is efficient in removing both the azo dyes and aromatic amines (Sahinkaya et al., 2017). The overall performance of MBR in relevance to the technical aspect is better than the other treatment techniques.

5.2.2. *Economic sustainability indicator*

The economic dimension holds the second-highest score. This dimension is associated with all types of costs that may help in analyzing the cost-effectiveness of the TWWTTs. The technology cost (EC1), construction cost (EC2), operation and maintenance cost (EC3) and capacity up-gradation cost (EC4) are the sub-criteria of the economic dimension. The ranking of economic sub-criteria is as follows: EC3 > EC2 > EC1 > EC4 as shown in Fig. 5 (a). The high construction, operation and maintenance costs will exert extra economic pressure on the system (Jafarinejad, 2017). The operation and maintenance of some imported treatment technologies require skilled operators, thus increasing their costs. A very high construction cost for any treatment technology will not be preferred as it requires substantial initial investment (Sawaf and Karaca, 2018).

The treatment techniques' scores for the economic criterion are summarized in Fig. 5 (b). The ranking of TWWTTs is as follows: MBBR > EC > RBC > MBR > ASP. The fact that MBBR uses the biofilm attached to thousands of tiny plastic media to decompose the waste present in the effluent makes it economically viable than the other treatment techniques. The cost of plastic media used in MBBR is low, and the backwashing or cleaning of membranes is not required, which reduces both operational and maintenance costs. The construction cost for MBBR is also low as only one tank is required which uses relatively lesser space (Francis and Sosamony, 2016). The operational cost of EC is relatively high due to the requirement of chemicals and high energy consumption. This not only increases the overall treatment cost but the quantity of unconsumed waste products adds to an increase in secondary pollutant sludge (Dasgupta et al., 2015). The RBC has operational problems of mechanical failures of shaft, media support structure and the bearings.

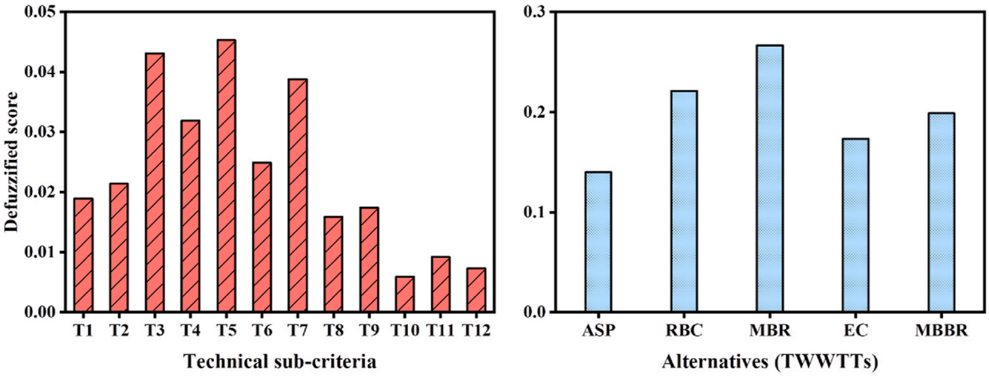

Fig. 4. The de-fuzzified scores for (a) technical sub-indicator, (b) alternatives for the technical indicator.

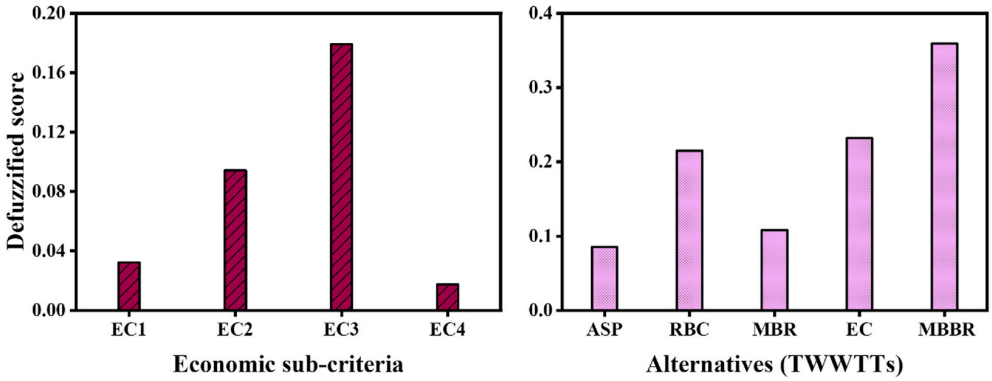

Fig. 5. The de-fuzzified score of (a) economical sub-indicators, (b) alternatives for an economic sustainability indicator.

This increases the operation and maintenance cost (Cortez et al., 2008). The main limitation of MBR is the high maintenance cost due to the fouling of the membrane and requires a chemical cleaning, which eventually decreases the membrane life span. This results in a frequent change of membrane resulting in high operational cost. The ASP has high construction costs and medium operation and maintenance costs (Behera et al., 2021).

5.2.3. *Environmental sustainability indicator*

The environmental dimension has obtained the third position in the ranking of sustainability indicators, as shown in Fig. 3. The experts' perspectives towards the environmental sub-criteria are summarized in Fig. 6 (a). The ranking of these sub-criteria is as follows: E7 > E1 > E3 > E4 > E2 > E5 > E6. The effluent suitability for reuse (E7) has the highest score. The selection of a TWWTT whose effluent is highly suitable for reuse is preferred as it will reduce the freshwater demand of the industries, saving the natural resources (Sawaf and Karaca, 2018). The space required (E1) by the TWWTTs and its effect on the surrounding environment (E3) holds the second and third rank. The larger space requirement for the infrastructure will affect the nearby ecosystem and will have a nested impact on the economic aspect of sustainability.

The experts' opinions regarding the environmental dimension of TWWTTs are as shown in Fig. 6 (b). The ranking of the textile effluent treatment techniques from the environmental aspect of sustainability is as follows: MBR > MBBR > RBC > EC > ASP. The MBR followed by MBBR is identified as the most environment-friendly technique by the decision-makers. The effluent suitability for reuse is the best in MBR, and the space requirement is moderate as compared to MBBR (Jegatheesan et al., 2016; Yang et al., 2020). The treated water from MBR can directly be reused in dyeing, finishing and sizing units of the textile industry without significantly decreasing the quality of the fabric produced (Cinperi et al., 2019). The effluent from the other treatment techniques requires further treatment prior to its reuse (Keskin et al., 2021). The RBC, EC and ASP are the least preferred due to the poor effluent suitability for reuse and higher space requirements (Behera et al., 2021).

5.2.4. *Social sustainability indicator*

The social dimension has scored the fourth rank. In the social dimension, the ranking of sub-criteria is as follows: S3 > S2 > S1 > S4 > S5. Fig. 7 (a) summarizes the score of different sub-criteria that makes into the social dimension. The sub-criteria 'awareness within the industry' is ranked first. It is extremely important to create awareness among different textile processing units about the proper disposal of untreated effluent and encourage them to follow the rules and regulations. The awareness of TWWTT within industries will help understand the worries and benefits of the treatment technologies. The public safety from the operation of the treatment unit is ranked second and the hiring of local services that would benefit the community is ranked third. The TWWTTs should operate safely, causing no harmful impacts on the community. The TWWTTs release hazardous gases and generate contaminated sludge, thus causing danger of any occupational disease affecting the employee's health. The acoustic comfort in the treatment unit is also an essential sub-criterion.

The scores of a treatment technique for the sustainability's social dimension are illustrated in Fig. 7 (b) and are ranked as follows: RBC > MBR > ASP > EC > MBBR. RBC and MBR treatment technologies are the first and second preferences of the experts. Sawaf and Karaca (2018) have also observed similar results in which the decision-makers and industry managers have preferred the MBR and RBC in the priority ranking. Compared to other treatment techniques, MBBR and EC have performed poorly due to their limited social characteristics.

5.3. *Overall ranking of alternatives*

The different TWWTTs are ranked based on their entropy weights.

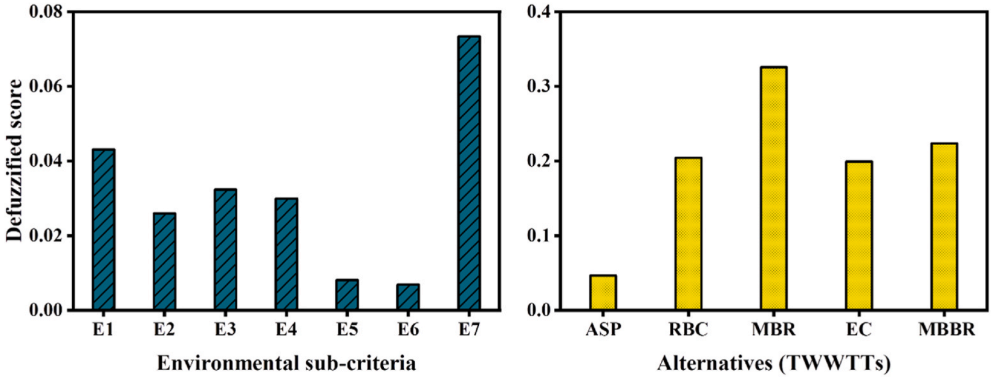

Fig. 6. The de-fuzzified score of (a) environmental sub-criteria, (b) alternatives for environmental sustainability indicator.

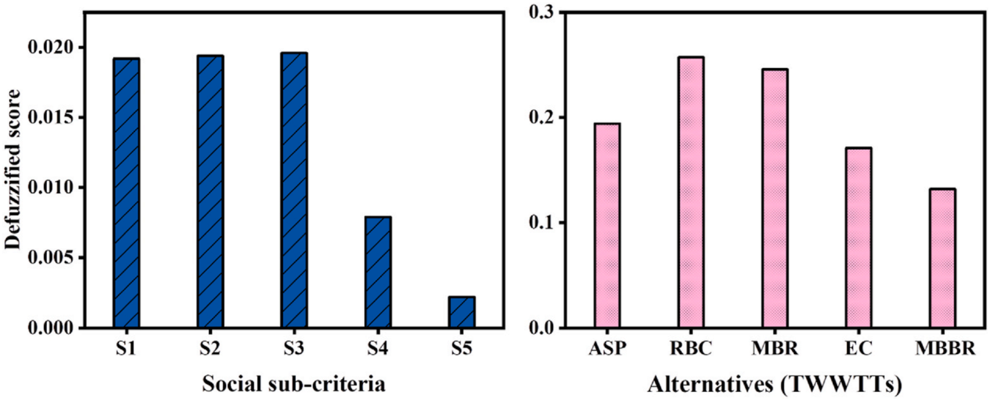

Fig. 7. The de-fuzzified score of (a) social sub-criteria, (b) alternatives for social sustainability indicator.

Table 8
Fuzzy entropy weights for the ranking of alternatives.

	α = 0.8						α = 0.95					
TWWTs	λ = 0.25	rank	λ = 0.5	rank	λ = 0.75	rank	λ = 0.25	rank	λ = 0.5	rank	λ = 0.75	rank
A1: ASP	0.1893	5	0.1893	5	0.1893	5	0.1888	5	0.1887	5	0.1886	5
A2: RBC	0.1942	4	0.1939	4	0.1937	4	0.1943	4	0.1939	4	0.1936	4
A3: MBR	0.2181	1	0.2189	1	0.2196	1	0.2183	1	0.2191	1	0.2198	1
A4: EC	0.2029	2	0.2031	2	0.2032	2	0.2030	2	0.2028	2	0.2027	2
A5: MBBR	0.1955	3	0.1948	3	0.1942	3	0.1957	3	0.1954	3	0.1952	3

Table 8 shows the entropy weights calculated for all the alternatives for the different levels of confidence (α) and at a different level of optimism (λ) of decision-makers. The entropy weights obtained are good estimators of overall sustainability TWWTTs. The effluent treatment techniques with higher entropy values have better-unified performance for all the aspects of sustainability. The final ranking of the alternatives is as follows: MBR > EC > MBBR > RBC > ASP. The MBR has technical and environmental benefits, such as high COD (95–97.4%), color removal efficiency (97-80%) and high permeate quality which makes it the first choice of decision-makers (Luong et al., 2016; Yigit et al., 2009). This is also apparent from the highest entropy weights of the MBR and its subsequent first rank. The EC followed by MBBR have scored the second and third rank. The higher ranking of MBR than EC and MBBR is because it combines two treatment processes i.e., biological treatment and membrane filtration (ultrafiltration or nanofiltration). The EC and MBBR are single treatment processes and are less effective on a technical aspect. The RBC and ASP are ranked fourth and fifth as these techniques are biological treatment processes and are less preferred for treating chemically contaminated effluents. Thus, by making interpretations from the estimated entropy weights, the decision-makers can adopt suitable sustainable TWWTTs.

5.4. Sensitivity analysis

The sensitivity analysis is required in the MCDM problem to counter the vagueness and the imprecision associated with the data collection process. It also demonstrates the robustness and feasibility of the model with change in time. In this study, the sensitivity analysis has been performed by calculating the entropy weights for the two different levels of confidence (α = 0.8 and 0.95) for the three different types of decision-makers pessimistic (λ = 0.25), nominal (λ = 0.50) and the optimistic (λ = 0.75). Table 8 shows the entropy weights for all the alternatives. The results show that the ranking obtained for each level of optimism and confidence is the same. For the higher value of λ, the MBR(A3) and EC (A4)'s entropy weights are increasing, RBC(A2) and MBBR(A5) are decreasing while for ASP(A1) is almost constant. From Table 8, it is also evitable that there is no variation in rank with change in the optimism degree and confidence level, proving that the developed model is robust.

6. Conclusion

The present research aims to develop a novel methodology for evaluating the sustainability of different TWWTTs. Discussions presented in this work precisely explain the challenges faced while planning for any TWWTTs due to the multitude of governing factors, some of which are often ignored. It is almost imperative in such a dynamic world to develop a mathematical model for comprehensively assessing the sustainability parameters prior to the selection of TWWTTs. In this study, 38 sub-indicators were initially chosen which were rounded down to 28 with the help of fuzzy Delphi and further ranked using hybrid FAHP. The alternatives (TWWTTs) were also ranked based on their sustainability indices.

The indicators in the context of the sustainability of TWWTTs are ranked sequentially as follows: technical, economic, environmental and social indicators. The sub-indicators with higher scores from each category are the color removal efficiency, COD removal efficiency, the quantity of sludge generated from the treatment units, the effluent suitability for reuse, operation/maintenance cost, awareness within industries and hiring of local services. The ASP and RBC have low indices values showing poor sustainability. This is due to the poor integrated performance in COD and color removal efficiency, poor treated effluent quality requiring further treatment prior to reuse, low social acceptance and economically infeasible. The poor sustainability indicates its lesser contribution to the cleaner production of fabric. Therefore, the selection of appropriate technology will help the industries not only in advancing the quest for a cleaner environment but will also support the industries for efficient products at an economical cost. The MBR, EC and MBBR have higher sustainability scores and are the competitive alternatives showing better overall performance. It is important to note that MBR technology is recommended as it integrates the biological treatment process with membrane filtration, demonstrating high contaminants removal efficiency. The high effluent quality of the permeate from MBR makes it suitable for reuse in the textile industry with no negative impact on finished fabric quality. The high social acceptance of the MBR technique by the industries will reduce the uncontrolled and illegal practices of waste disposal. The reuse of recycled water in different textile processes will ultimately contribute to cleaner production by decreasing the textile effluent quantity and reducing the requirement for groundwater. The result of sensitivity analysis indicates no rank reversal and thus the model is robust.

A case study was introduced in the paper to comprehensively explain and demonstrate the framework's applicability and the methodology developed. The study integrates the practical and analytical approaches, which increases its applicability and significance. However, the framework developed applies to other problems also due to its high flexibility. The methodology provides a broad scope to decision-makers as one can customize (add or delete) the alternatives according to the problem and the data availability. Therefore, the proposed methodology is highly beneficial for planning and decision-making problems. The limitation of the study is that the methodology is that the target group is all from the same region. The selection of these techniques may have economic, social, environmental, and technical constraints that may impact the study's outcome. The paper is expected to be a remarkable contribution to encouraging clean and sustainable practices for treating the textile industry effluent. The study is also a preliminary attempt to serve as the stepping stone for future studies.

CRediT authorship contribution statement

Somya Agarwal: Conceptualization, Methodology, Investigation, Data Collection, Data Interpretation, Analysis, Original draft preparation, Writing, and Editing. . **Ajit Pratap Singh:** Conceptualization, Methodology, Data Collection, Data Interpretation, Investigation, and Analysis, Validation, Visualization, Writing – original draft, review and editing, Supervision, Correspondence.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130384.

Appendix: A

Fuzzy Delphi Technique

Step A: Data collection.

In this first step of the study, the sustainability sub-criteria are identified from the extant literature and the expert opinion. Later, the list is circulated among the chosen experts from different backgrounds so that the analyst can capture both the subjective and the objective aspects of the experts' judgement.

Step B: Conversion of expert opinion into TFN.

The experts' judgement was collected from the questionnaire using the linguistic scale for which the fuzzy score is associated and is given in Table 3 of section 3.1.

Let G_{ij} is the fuzzy score corresponding to the linguistic scale given for the ith sub-criterion of 'm' sub-criteria and by the jth expert of 'n' experts. Then the score can be represented using Eq. (A1).

$$G_{ij} = \left(a_{ij,}\ b_{ij,}\ c_{ij}\right)\ where,\ \ i = 1, 2, 3\ldots\ldots m; j = 1, 2, 3\ldots\ldots n \tag{A1}$$

The ith sub-criterion overall fuzzy weight, considering the 'n' experts' scores, can be computed using Eq. (A2). The lower bound and the upper bound are the minimum and maximum value among the $a^{n}_{i\,j=1}$ and $c^{n}_{i\,j=1}$ respectively. The middle bound is estimated by geometric mean of all the b_{ij} for each sub-criterion for n experts.

$$G_i = \left[\min\left(a_{ij}\right),\quad \left(\prod_{j=1}^{n} b_{ij}\right)^{1/n},\quad \max\left(c_{ij}\right)\right] \tag{A2}$$

Step-C: Defuzzification of fuzzy score.

The de-fuzzified weight of each sub-criterion is estimated using the mean method given in Eq. (A3).

$$G_i^d = \left[\frac{\min\left(a_{ij}\right) + \left(\prod_{j=1}^{n} b_{ij}\right)^{1/n} + \max\left(c_{ij}\right)}{3}\right] \tag{A3}$$

Appendix B

The final assessment and the ranking of alternatives are carried out using Cheng's Entropy method of FAHP. The calculated fuzzy synthetic extent analysis of alternatives for each criterion is used to find the α-cut performance matrix at the confidence level (α=0.8) and the optimism index (λ = 0.5). This matrix is also called as the total fuzzy judgement matrix and is shown in Table A.

Table A
The total fuzzy judgement matrix for $\alpha = 0.8,\ \lambda = 0.5$ of alternatives and the sub-indicators.

	T1	T2	T3	T4	T5
A1: ASP	[0.0025,0.0027]	[0.004,0.0043]	[0.004,0.0043]	[0.0008,0.0009]	[0.0023,0.0025]
A2: RBC	[0.0044,0.0048]	[0.0033,0.0036]	[0.0164,0.0174]	[0.0057,0.006]	[0.008,0.0084]
A3: MBR	[0.0018,0.002]	[0.0092,0.0099]	[0.0123,0.0131]	[0.0132,0.014]	[0.0086,0.0091]
A4: EC	[0.0004,0.0005]	[0.0023,0.0024]	[0.0076,0.0082]	[0.006,0.0064]	[0.0188,0.0198]
A5: MBBR	[0.0051,0.0054]	[0.0016,0.0018]	[0.0013,0.0014]	[0.005,0.0054]	[0.0062,0.0065]
	T6	T7	T8	T9	T10
A1: ASP	[0.0017,0.0018]	[0.001,0.0011]	[0.0013,0.0014]	[0.0026,0.0028]	[0.0015,0.0017]
A2: RBC	[0.0041,0.0044]	[0.0139,0.0148]	[0.0031,0.0034]	[0.0006,0.0006]	[0.0008,0.0009]
A3: MBR	[0.0087,0.0092]	[0.0064,0.0068]	[0.0055,0.006]	[0.0023,0.0025]	[0.0007,0.0008]
A4: EC	[0.0089,0.0094]	[0.0127,0.0134]	[0.0005,0.0005]	[0.0022,0.0024]	[0.0003,0.0004]
A5: MBBR	[0.0006,0.0007]	[0.0034,0.0037]	[0.0045,0.0048]	[0.0088,0.0094]	[0.0018,0.002]
	T11	T12	S1	S2	S3
A1: ASP	[0.0013,0.0014]	[0.0019,0.0021]	[0.003,0.0037]	[0.0019,0.0023]	[0.0011,0.0013]
A2: RBC	[0.0012,0.0013]	[0.0023,0.0025]	[0.003,0.0036]	[0.0044,0.0053]	[0.0005,0.0006]
A3: MBR	[0.0042,0.0045]	[0.0004,0.0004]	[0.0025,0.003]	[0.0037,0.0045]	[0.0037,0.0045]
A4: EC	[0.0003,0.0004]	[0.0008,0.0009]	[0.0022,0.0027]	[0.0013,0.0016]	[0.0034,0.0041]
A5: MBBR	[0.0014,0.0015]	[0.0011,0.0012]	[0.0015,0.0019]	[0.0009,0.0011]	[0.0035,0.0042]
	S4	S5	E1	E2	E3
A1: ASP	[0.0014,0.0017]	[0.0002,0.0002]	[0.0008,0.0009]	[0.0005,0.0005]	[0.0009,0.001]
A2: RBC	[0.0015,0.0018]	[0.0004,0.0005]	[0.0052,0.006]	[0.0024,0.0028]	[0.0071,0.0084]
A3: MBR	[0.0003,0.0004]	[0.0004,0.0005]	[0.0022,0.0026]	[0.0083,0.0095]	[0.0064,0.0076]
A4: EC	[0.001,0.0012]	[0.0001,0.0001]	[0.0089,0.0102]	[0.002,0.0023]	[0.0025,0.003]
A5: MBBR	[0.0005,0.0006]	[0.00004,0.0001]	[0.0145,0.0165]	[0.0054,0.0062]	[0.0059,0.007]
	E4	E5	E6	E7	EC1
A1: ASP	[0.0011,0.0013]	[0.0003,0.0004]	[0.0002,0.0003]	[0.0014,0.0016]	[0.0012,0.0014]
A2: RBC	[0.0055,0.0064]	[0.001,0.0012]	[0.001,0.0012]	[0.0067,0.0048]	[0.0042,0.0049]
A3: MBR	[0.0099,0.0114]	[0.0021,0.0025]	[0.0008,0.0009]	[0.0266,0.0221]	[0.0006,0.0007]
A4: EC	[0.0009,0.0011]	[0.0014,0.0017]	[0.002,0.0024]	[0.0051,0.004]	[0.0073,0.0086]
A5: MBBR	[0.0041,0.0048]	[0.0002,0.0002]	[0.0002,0.0002]	[0.0162,0.0131]	[0.0082,0.0096]
	EC2	EC3	EC4		
A1: ASP	[0.0039,0.0046]	[0.0278,0.0313]	[0.0003,0.0003]		
A2: RBC	[0.0129,0.0148]	[0.0578,0.0646]	[0.001,0.0012]		
A3: MBR	[0.0022,0.0026]	[0.0114,0.013]	[0.0029,0.0035]		
A4: EC	[0.0272,0.0311]	[0.0035,0.004]	[0.0019,0.0023]		
A5: MBBR	[0.0256,0.0291]	[0.0458,0.0513]	[0.0043,0.0051]		

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