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ORIGINAL PAPER

Selection of Greywater Reuse Options Using Multi-criteria Decision-making Techniques

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Abstract
On-site reuse of treated greywater for non-potable purposes such as toilet flushing, garden irrigation and car washing is one of the alternatives to meet the increasing water demand and to reduce the load on sewage treatment plants. However, no studies have been reported on selecting the most appropriate reuse option among the different reuse options available. In the present study, multi-criteria decision-making (MCDM) methods TOPSIS, VIKOR, ELECTRE and PROMETHEE were used to rank the greywater reuse alternatives. The main criteria considered included acceptability, adaptability and the risk involved with the reuse option along with technical and economic considerations. Alternative uses considered in the study were household reuse, public reuse, industrial reuse, groundwater recharge and agricultural reuse. Based on expert opinion, the weightage of criteria and relative importance of each alternative to criteria were determined using the defuzzification method. Kendall's coefficients of concordance and Spearman's rank correlation coefficients were used to compare the ranks, while sensitivity analysis was performed to find the least impacted results. Results show that domestic reuse is the best alternative for greywater reuse, followed by public reuse. Kendall's concordance value suggests more than partial agreement between the ranks obtained by different MCDM techniques. Sensitivity analysis showed that technical consideration was the most sensitive criterion.

Keywords ELECTRE · Greywater reuse · MCDM · PROMETHEE · TOPSIS · VIKOR

Abbreviations

AHP	Analytic hierarchy process
ELECTRE	ELimination and Choice Expressing REality
MCDM	Multi-criteria decision-making
NIS	Negative ideal solution
PIS	Positive ideal solution
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	VIekriterijumsko KOmpromisno Rangiranje

Symbols

A	Decision matrix
m	Alternative
n	Criteria
i	Row
j	Column
x_{ij}	Intersection of alternative and criteria
r_{ij}	Normalized decision matrix
v_{ij}	Weighted normalized decision matrix
$A+$	Best alternative
A-	Worst alternative
J	Beneficial attribute
J'	Non-beneficial attribute
S_i^+	Distances from the largest alternative i to the best
S_i^-	Distances from the largest alternative i to the worst
C_i^*	Relative closeness
$f+$	Best alternative
f-	Worst alternative
Si	Utility
Ri	Regret
Wj	Weights of criteria
Qi	VIKOR index
ϑ	Weight of the maximum group utility
1-ϑ	Weight of an individual regret
C_{ab}	Concordance

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D_{ab}	Discordance
c	Concordance interval matrix
d	Discordance interval matrix
c_a	Net superior value
d_a	Net inferior value
$d_{j(ab)}$	Difference between alternatives
P_i	Positive non-decreasing preference function
$\varphi+$	Leaving flow
φ-	Entering flow
φ	Net outflow
Z	Concordance value
S_i	Sum of ranks of the same alternative in different methods
k	Count of alternatives
r_s	Spearman's rank correlation coefficient
D_i	Difference between the two ranks of each observation

Introduction

Due to increased demand for freshwater all over the world, efforts are being made to conserve the water resources. This has led to increased attention to wastewater reuse. Reuse of greywater is promoted worldwide, but greywater reuse without treatment is detrimental since this could lead to health-related issues [1, 2]. Water from hand basin, bathroom, kitchen, floor cleaning and laundry contribute to greywater [3]. Multiple studies reported that greywater contributes about 50–80% of the total wastewater generated in a household while the degree of treatment required for greywater to be used for non-potable purposes is significantly less compared to that for wastewater [4, 5]. The reuse of greywater for toilet flushing and garden irrigation could reduce the total domestic water consumption by up to 50% [6]. Treated greywater can be reused for multiple purposes as shown in Fig. 1.

Water reuse is prioritized for domestic reuse, agriculture reuse, power generation, agricultural reuse, industrial reuse and commercial reuse based on the integrity of the ecosystem [7]. Treated greywater/wastewater was reused for a whole range of applications around the world for non-potable uses such as household reuse [8], public reuse [9], industrial reuse [7], groundwater recharge [10] and agricultural reuse [11].

Acceptability, adaptability, technical and economic considerations along with the risk involved in particular reuse options are important criteria needed to be considered while selecting an appropriate reuse option. Since multiple greywater reuse alternatives are available, it is difficult to select the most preferred reuse alternative considering

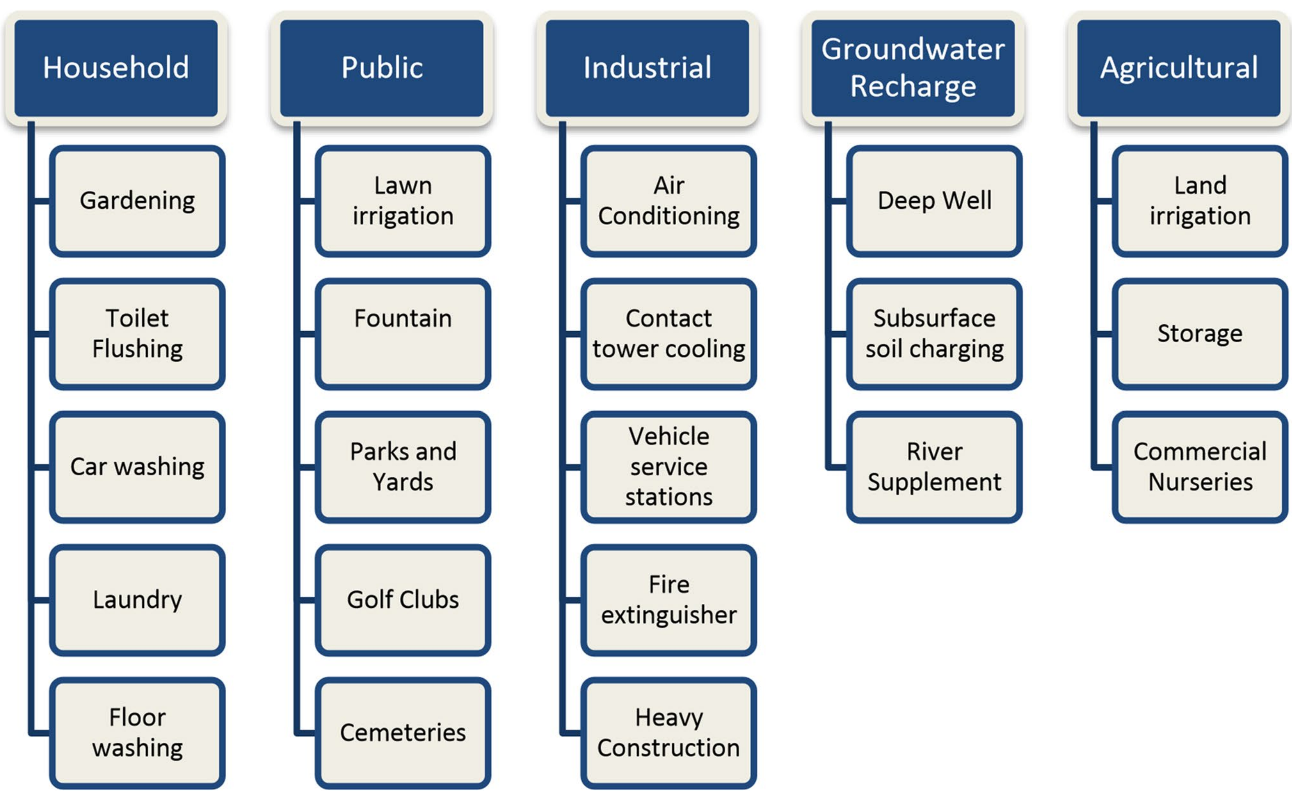

Fig. 1 Treated greywater reuse options [7–13]

different criteria hence, to determine the most preferred reuse option multi-criteria decision making (MCDM) methods can be used. MCDM methods are the composition of the set of multiple criteria, a set of alternatives and their comparison in some manner [14]. Mathematical simulation is used to evaluate and compare the conflicting alternatives in MCDM. The incidence and impact of biases from decision-makers are reduced by employing MCDM. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIekriterijumsko KOmpromisno Rangiranje (VIKOR), ELimination and Choice Expressing REality (ELECTRE) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) are most frequently used MCDM techniques available for selecting the best option from the alternatives [15].

Yahya et al. [16] used the TOPSIS method to select the most appropriate wastewater treatment technology and reported that the activated sludge method was the best compared to nano-filtration, membrane bioreactor, trickling filter, waste stabilization pond and constructed wetlands. Dursun [17] reported that an aerated lagoon was the best wastewater treatment alternative compared to the activated sludge process, sequential batch reactor and constructed wetlands based on the ranking by VIKOR method. Ghorbani Mooselu et al. [18] used the ELECTRE method to allocate treated wastewater to different districts considering different criteria. Coban et al. [19] evaluated the feasibility of eight different solid waste disposal scenarios and seven criteria using the PROMETHEE method in Turkey and recycling and landfilling were selected to be the most prominent alternatives.

MCDM techniques have been used for water supply allocation and reservoir operation [20], monitoring network design [21], wastewater treatment alternatives [16, 17, 22], water quality [23], allocation of treated wastewater [18], wastewater disinfection technique [24, 25] and wastewater reuse alternatives [10, 26]. However, no studies have been reported on the selection of greywater reuse alternatives. Reuse of the treated greywater for domestic, public, industrial, agricultural reuse and groundwater recharge are among the most preferred and suitable alternatives and the same are used in the present study [10].

In the present study, the most preferred option for greywater reuse among domestic reuse, public reuse, industrial reuse, agricultural reuse and groundwater recharge was chosen. The criteria used included acceptability, adaptability and risks involved for a particular reuse option along with technical and economic considerations. The opinion of experts was elicited through a survey questionnaire. The solution was determined using different MCDM techniques namely TOPSIS, VIKOR, ELECTRE and PROMETHEE. Spearman's rank correlation coefficient and Kendall's coefficient of concordance were used to compare the ranking of greywater reuse alternatives. Besides, a sensitivity analysis was done on the results obtained.

Methods

Figure 2 presents the methodology adopted in this study for selecting the most preferred alternative using different MCDM techniques. The process began with the selection of criteria and alternatives associated with the problem. Based on selected criteria and alternatives a questionnaire was prepared for expert opinion. Based on the responses received from experts, weightage was determined and a decision matrix was formulated for each of the alternatives. From the weightage, different alternatives were ranked and compared using Kendall's coefficient of concordance and Spearman's rank correlation coefficient. Sensitivity analysis was performed to choose the least impacted option.

Selection of Criteria and Alternatives

Quantitative and qualitative factors selected to discriminate the alternatives is termed as criteria. Criteria or attribute is very crucial to the MCDM technique as they play an important role in the decision-making process [27]. Figure 3 presents different criteria and alternatives considered for greywater reuse. Alternatives are compared against selected criteria to meet the optimal selection [28]. Each of the criteria had sub-criteria for better understanding. In the present study, there were 5 main criteria and 16 sub-criteria.

Acceptability and adaptability are qualitative criteria while technical, economic and risks are the quantitative criteria. Acceptability criterion as the term indicates deals with factors affecting the people to accept greywater reuse for different uses. Perceptions towards wastewater use, disgust factor, neighbourhood acceptance, awareness of the scope of water reuse and public acceptance of recycled

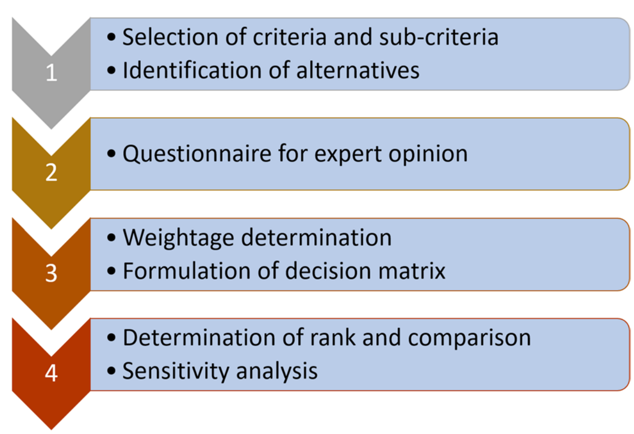

Fig. 2 Stepwise process for selecting the most preferred alternative using MCDM technique

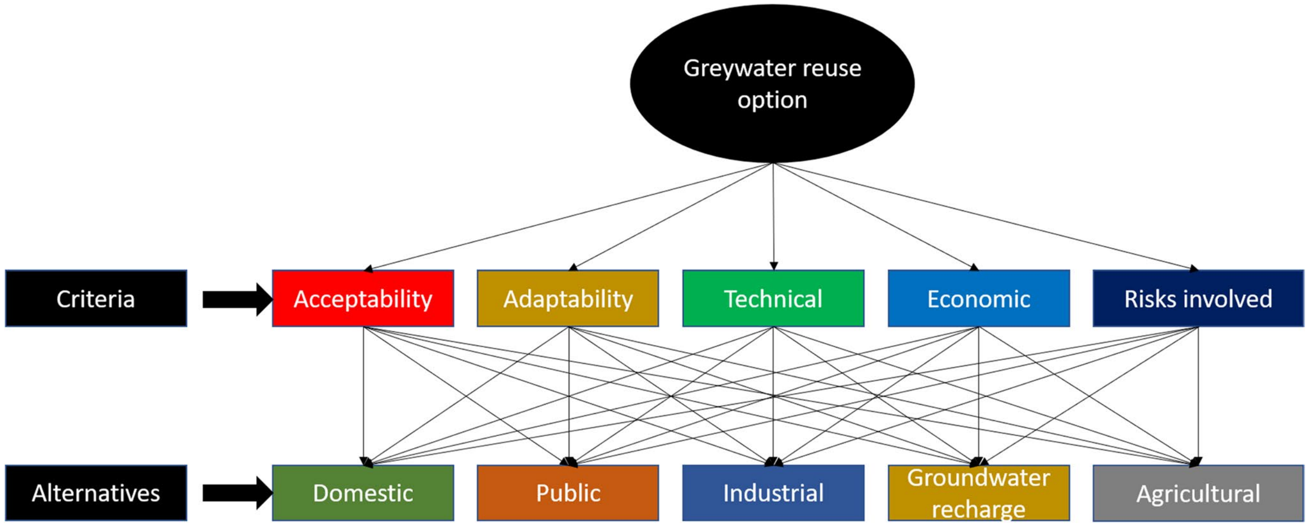

Fig. 3 Greywater reuse criteria and alternatives

water are the main factors governing acceptance [29]. In most situations, the local government body needs to create awareness among the people for such projects. Gaining people's acceptance is important for selecting the type of greywater reuse application. Disgust among the people is a major factor that can restrict them from using treated greywater for a particular purpose. Reuse of treated greywater should gain acceptance from the neighbourhood as well [13].

Adaptability of the greywater reuse system is the main concern with respect to its implementation. Every system which is developing should be able to meet the demand. The system should be suitable for long-term use without difficulty. Availability of low-cost or locally available treatment techniques for the treatment of greywater affects the adaptability of the project. Treated greywater should meet different reuse standards and legislation gives the authority for reuse for different purposes. For the smooth running of the system several regulations and policies need to be developed [30].

Several technical considerations such as quality and quantity characteristics of greywater sources play a major role in selecting the reuse options as variation in both quantity and quality can lead to multiple problems which may or may not be easy to rectify [31]. The extent of treatment required depends on the end-use. The scalability of the treatment method is also important since the treatment system should be able to meet the demands at different capacities. Based on different studies, it is clear that the treatment technology required is different for different reuse options [32, 33]. Technology and methods used are combined in the technical criteria along with the quantity and quality of the greywater.

The cost of treating greywater depends on the intended reuse. Reuse results in savings in water bills. Different reuse options require different levels of treatment and thus capital cost requirements will be different. The load on sewage treatment plants can be reduced by certain percentages by greywater reuse, thus reducing the expenses of sewage treatment. Reuse also reduces the dependency on freshwater, which results in annual savings from the water bill. The savings, income generated, financial opportunities and costs involved are included in the economic criteria. Hadipour et al. [10] also selected capital cost, operation and maintenance cost along with income generated from greywater reuse in economic criteria while selecting wastewater reuse alternatives using MCDM.

Environmental benefits and ecological risks are considered in the risk criteria. For any scheme or project, several uncertain parameters which prevent the implementation can be present [29]. For any greywater reuse project, certain reuse options may not be possible due to religious or cultural considerations. Long-term reuse of treated greywater can also result in problems in certain reuse options. For any kind of reuse option, minimal contact is generally preferred, so that the direct and indirect health impacts can be minimized to some extent. Different reuse options present different health risks. Prolonged use of treated greywater can cause environmental imbalance and social impacts [6, 34].

Questionnaire Survey

The questionnaire used for the present study consisted of two parts. The first part dealt with the criteria and sub-criteria while the second part dealt with alternatives and their importance over each criterion. In this study, there were 5 main criteria and 16 sub-criteria. The format of a typical five-level Likert item and the 5-point linguistic variable with positive trapezoidal fuzzy numbers defined for the present study is shown in Table 1 [16, 35]. In the questionnaire, each of the sub-criteria was defined separately for better understanding. Linguistic variables were used to elicit the expert option. Linguistic variables represent crisp information in a form and precision appropriate for the problem [36]. The linguistic variables are considered based on a 5-point Likert scale [37]. A Likert scale of 1–5 was used to transform qualitative criteria into quantitative criteria, where 1 demotes strongly disagree while 5 denotes strongly agree.

Defuzzification is a task to convert fuzzy numbers into numerical crisp values. Many different techniques can be used for this transformation, but the most commonly used trapezoidal defuzzification method is the area compensation method and it is given in Eq. 1 [35]. The normalized average of each response was considered weightage after finding out individual sub-criteria weightage. Yahya et al. [16] also adopted a linguistic fuzzy scale for obtaining the importance of the weights of criteria among space requirement, water flux, pressure, BOD removal efficiency and energy requirement for selecting appropriate wastewater treatment technology.

$$X = \frac{\frac{1}{3}\left[\left(X_4 - X_3\right)^2 - \left(X_2 - X_1\right)^2\right] - X_1X_2 + X_3X_4}{-X_1 - X_2 + X_3 + X_4} \tag{1}$$

The response from the questionnaire was converted to numerical value as per the above method and prepared the decision matrix in the standard form. The average of each response was considered the final value of each question. In the present study, opinions were taken from experts from academics, industry and policy-making with sufficient background in wastewater reuse. About 100 experts were contacted for this survey. Figure 4 shows the distribution of 49 experts who responded to the questionnaire.

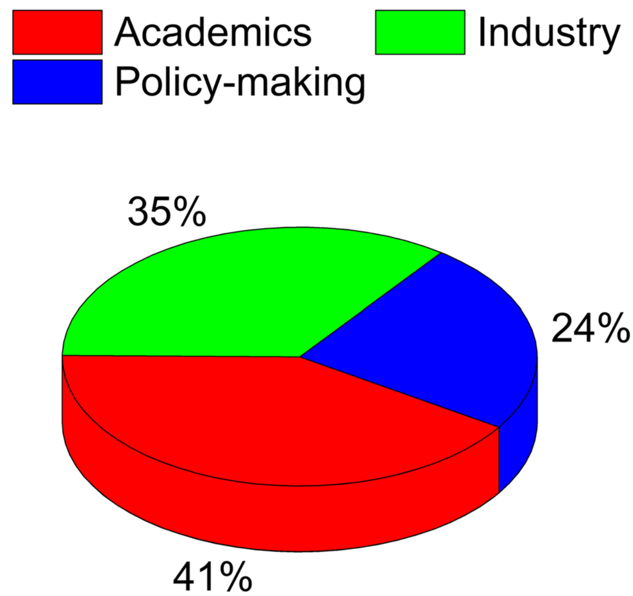

Fig. 4 Distribution of the experts responded to the questionnaire

MCDM Techniques Used

TOPSIS

TOPSIS method was developed by Yoon and Hwang Ching-Lai in the year 1981 [38]. In the TOPSIS method, the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS) [39, 40] while the highest relative closeness value holds the first rank. The detailed procedure of the TOPSIS method is discussed with the help of Eqs. 2–7 in the following steps:

Step 1: form the decision matrix (A) using alternatives (m) in rows and criteria (n) in columns with the intersection of each alternative and criteria given as x_{ij}:

$$A = \left[x_{ij}\right] \tag{2}$$

where $i = 1, 2, 3, \ldots m$; $j = 1, 2, 3, \ldots n$;

Step 2: construct the normalized decision matrix (r_{ij}) using the below formula:

Table 1 Linguistic variables and scores

Linguistic variable	Likert score	Linguistic variable	Fuzzy score
Strongly agree	5	Extremely important	(8,9,10,10)
Agree	4	Very important	(4,7,8,9)
Neither agree nor disagree	3	Moderately important	(3,4,5,7)
Disagree	2	Slightly important	(1,2,3,4)
Strongly disagree	1	Not at all important	(0,0,0,2)

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (3)$$

where $i = 1, 2, 3,\ldots m$; $j = 1, 2, 3,\ldots n$;

Step 3: construct the weighted normalized decision matrix (v_{ij}):

$$v_{ij} = w_i * r_{ij} \quad (4)$$

where $i = 1, 2, 3,\ldots m$; $j = 1, 2, 3,\ldots n$;

Step 4: determine PIS and NIS:

$$A+ = \{V1+, V2 + \ldots, Vn+\},$$

where:

A + best alternative

$Vj+$ {(maxi (Vij) if j€J); (mini Vij if j€J')}

A- {$V1$-, $V2$-…, Vn-},

where:

A- worst alternative

Vj- {(mini (Vij) if j€J); (maxi Vij if j€J')}

J is associated with the beneficial attributes

J' is associated with the non-beneficial attributes

Step 5: calculate the separation measure:

Positive ideal separation

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2} \quad (5)$$

Negative ideal separation

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2} \quad (6)$$

where:

S_i^+ and S_i^- are L^2 distances from the largest alternative i to the best and worst conditions

$$i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n;$$

Step 6: calculate the relative closeness (C_i^*) to the ideal solution:

$$C_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad (7)$$

C_i* varies between 0 and 1

The high C_i* value indicates the best alternative as it is more closely related to the ideal solution and vice versa.

VIKOR

VIKOR method was proposed by Serafim Opricovic in 1998 [27]. VIKOR method is a compromise ranking method used for multi-criteria decision making which is used to optimize the multiple response processes [27]. VIKOR method is based on the principle of maximum group utility of the majority as well as the minimum individual regret of the opponent [41] and the alternative with the least VIKOR value holds the first rank. Mutual concession in VIKOR helps in finding a compromise conclusion. The method considers both the mean and the standard variation of quality losses associated with several multiple responses and assures a small variation in quality losses among the responses, along with a small overall average loss [42]. This is applied to derive an integrated quality measurement of several conflicting and compromising responses. Similar to TOPSIS here also decision-making starts with a matrix that is prepared by the decision-maker after expert advice. The detailed procedure of the VIKOR method is discussed with the help of Eqs. 8–12 in the following steps:

Step 1: form the decision matrix (A) using alternatives (m) in rows and criteria (n) in columns with the intersection of each alternative and criteria given as x_{ij}:

$$A = [x_{ij}] \quad (8)$$

where $i = 1, 2, 3,\ldots m$; $j = 1, 2, 3,\ldots n$;

Step 2: construct the normalized decision matrix (r_{ij}) using the below formula:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (9)$$

where $i = 1, 2, 3,\ldots m$; $j = 1, 2, 3,\ldots n$;

Step 3: determine PIS and NIS:

$f+$ = {$V1+$, $V2+$ …, $Vn+$}, where $Vj+$ = {(maxi (Vij) if j€J); (mini Vij if j€J')}.

f- = {$V1$-, $V2$-…, Vn-}, where Vj- = {(mini (Vij) if j€J); (maxi Vij if j€J')}.

where:

f+ is best alternative

f- *is worst alternative*

J is associated with the beneficial attributes

J' is associated with the non-beneficial attributes.

Step 4: determine utility (*Si*) measure and regret (*Ri*) measure:

$$S_i = \sum_{j=1}^{n} W_j * \frac{(f^+ - r_{ij})}{(f^+ - f^-)} \tag{10}$$

$$R_i = Max_j\left[W_j * \frac{(f^+ - r_{ij})}{(f^+ - f^-)}\right] \tag{11}$$

where W_j are weights of criteria.

tep 5: computation of VIKOR index (*Qi*):

$$Q_i = \vartheta\left[\frac{(S_i - S^*)}{(S^- - S^*)}\right] + (1-\vartheta)\left[\frac{(R_i - R^*)}{(R^- - R^*)}\right] \tag{12}$$

$$S^* = Min_j(S_i) \quad S^- = Max_j(S_i) \quad R^* = Min_j(R_i) \quad R^- = Max_j(R_i)$$

Θ is the weight of the maximum group utility (usually it is to be set to 0.5)

1-ϑ is weight of an individual regret

The alternative having the smallest VIKOR value is determined to be the best solution.

ELECTRE

The ELECTRE method was first developed by Bernard Roy and his colleagues in the mid-1960s [43]. The basic ELECTRE method is a procedure that sequentially reduces the number of alternatives the decision-maker is faced within a set of no-dominated alternatives. The detailed procedure of the ELECTRE method is discussed with the help of Eqs. 13–22 in the following steps:

Step 1: form the decision matrix (*A*) using alternatives (*m*) in rows and criteria (*n*) in columns with the intersection of each alternative and criteria given as x_{ij}:

$$A = [x_{ij}] \tag{13}$$

where $i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n;$

Step 2: construct the normalized decision matrix (r_{ij}) using the below formula:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} {x_{ij}}^2}} \tag{14}$$

where $i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n;$

Step 3: construct the weighted normalized decision matrix [v_{ij}]:

$$v_{ij} = w_i * r_{ij} \tag{15}$$

where $i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n;$

Step 4: find the concordance [C_{ab}] and discordance [D_{ab}] interval sets:

$$C_{ab} = \left\{ j \middle| X_{aj} \geq X_{bj} \right\};\ D_{ab} = \left\{ j \middle| X_{aj} < X_{bj} \right\} \tag{16}$$

Step 5: calculation of concordance interval matrix (*c*):

$$C_{ab} = \sum_{j \epsilon C_{ab}} W_j \tag{17}$$

$$c = \sum_{a=1}^{m} \sum_{b}^{m} \frac{c(a,b)}{m(m-1)} \tag{18}$$

Step 6: calculation of discordance interval matrix (*d*):

$$D_{ab} = \frac{max_{j \in D_{ab}} \left| V_{aj} - V_{bj} \right|}{max_j \left| V_{aj} - V_{bj} \right|} \tag{19}$$

$$d = \sum_{a=1}^{m} \sum_{b}^{m} \frac{d(a,b)}{m(m-1)} \tag{20}$$

Step 7: calculation of net superior (c_a) and inferior value (d_a):

$$c_a = \sum_{b=1}^{n} C_{(a,b)} - \sum_{b=1}^{n} C_{(b,a)} \tag{21}$$

$$d_a = \sum_{b=1}^{n} D_{(a,b)} - \sum_{b=1}^{n} D_{(b,a)} \tag{22}$$

The highest c_a value will be ranked as 1 and that alternative is preferred over other options.

PROMETHEE

PROMETHEE method was developed by J. P. Brans in 1982 [44]. A pairwise comparison among alternatives was done in the PROMETHEE method and the most preferred alternative was outranked and the net flow value was calculated based on leaving and entering flow values while choosing the highest positive flow value as first rank [45]. The scores a_{ij} need not necessarily be normalized or transformed into a common dimensionless scale. We only assume that, for the sake of simplicity, a higher score value means better performance. It is also assumed that the weights w_j of the criteria have been determined by an appropriate method [46]. The detailed procedure of the PROMETHEE method is discussed with the help of Eqs. 23–30 in the following steps:

Step 1: form the decision matrix (A) using alternatives (m) in rows and criteria (n) in columns with the intersection of each alternative and criteria given as x_{ij}:

$$A = \left[x_{ij}\right] \tag{23}$$

where $i = 1, 2, 3, \ldots m$; $j = 1, 2, 3, \ldots n$;

Step 2: normalize the decision matrix (r_{ij}) using the following equation:

For beneficial criteria

$$r_{ij} = \left[\frac{x_{ij} - min_{(x_{ij})}}{max\left(x_{ij}\right) - min\left(x_{ij}\right)}\right] \tag{24}$$

For non-beneficial criteria

$$r_{ij} = \left[\frac{max\left(x_{ij}\right) - x_{ij}}{max\left(x_{ij}\right) - min\left(x_{ij}\right)}\right] \tag{25}$$

Step 3: find out the difference between alternatives ($d_{j(ab)}$) of criteria r_j:

$$d_{j(ab)} = r_{j(a)} - r_{j(b)} \tag{26}$$

Step 4: calculate the preference function value over the difference calculated:

$$\pi(a,b) = P_i[d_{j(a,b)}]$$

Where P_i is a positive non-decreasing preference function.

Step 5: calculate the aggregated preference:

$$\pi(a,b) = \sum_{i=1}^{n} P_i(a,b) * w_j \tag{27}$$

where w_j is weight if criteria r_j.

Step 6: determine the leaving flow ($\varphi+$) and entering flow (φ-):

$$\varphi_a^+ = \frac{1}{(m-1)} \sum_{b \in A} \pi(a,b) \tag{28}$$

$$\varphi_a^- = \frac{1}{(m-1)} \sum_{b \in A} \pi(a,b) \tag{29}$$

Step 7: determine net outflow (φ):

$$\varphi_i = \varphi_i^+ - \varphi_i^- \tag{30}$$

The highest net outflow will be the best alternative among the options.

Comparison of Rankings

In the present study, the relative ranking of all the MCDM techniques is compared by Kendall's coefficient of concordance and Spearman's rank correlation coefficient methods. Determination of overall ranking agreement among all the considered methods was calculated using Kendall's coefficient of concordance [Z] (Eq. 31).

$$Z = \frac{12 \sum_{i=1}^{m} \left(S_i - \frac{\sum_{i=1}^{m} s_i}{m}\right)^2}{k^2(m^3 - m)} \tag{31}$$

where:

Z concordance value

S_i sum of ranks of the same alternative in different methods

m No. of methods considered

k count of alternatives

To know the pairwise comparison between two methods at the same time Spearman's rank correlation coefficient is used (Eq. 32).

$$r_s = 1 - \frac{6 \sum_{i=1}^{m} D_i^2}{m\left(m^2 - 1\right)} \tag{32}$$

where:

r_s Spearman's rank correlation coefficient

D_i difference between the two ranks of each observation

m No. of alternatives

Sensitivity Analysis

A sensitivity analysis was done since chosen criteria and their weight calculation decide the ranking given by different MCDM techniques and the results obtained might not be similar for each technique. The input parameters for the sensitivity analysis were the weights of the criteria or the evaluation matrix. In this study, the weightage for each criterion was increased by 0% to 25% one at a time and the weightage of the rest of the criteria was proportionally decreased. Different simulations were run on MATLAB software with different weightages. With the new set of weightage values for each criterion, ranking was done.

Results and Discussion

Determination of Weightages

Figure 5 shows the weightages of all the criteria for accomplishing the goal as a radar plot.

Response received for the questionnaire was utilized for determining the weights of each criterion. Weights were determined separately for each category of experts. After the defuzzification using the area compensation method as per Eq. 1, the average of each sub-criteria was calculated and normalized so that the total weightage will be unity. Scores are needed to be normalized since the majority of the criteria are measured in various units. Yahya et al. [16] also used the defuzzification method to normalize the criteria while evaluating wastewater treatment technologies in Turkey.

High weightage for a specific attribute indicates that the criterion is more important in the assessment of the suitable greywater reuse option [47]. It can be seen from Fig. 5 that only slight variations were observed in criteria weightage from different categories. The highest weightage is given for acceptability by academic experts while industrialists and policy-makers gave the highest weightage for adaptability and technical considerations, respectively. It is interesting to note that the risk involved was least weighted by experts from different fields except policy-makers who ranked acceptability the least. With the help of the second part of the questionnaire, an evaluation matrix was formulated for the entire category and is presented in Table S1 (Supplementary information).

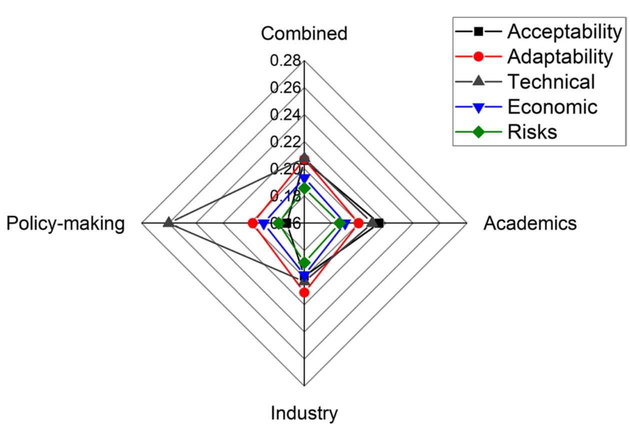

Fig. 5 Radar plot indicating weightage of all the criteria given by different groups of experts

Ranking Using Different MCDM Techniques

The ranks obtained by different MCDM methods for the alternatives by different categories of experts are shown in Table 2. The decision matrix given in Table S1 (Supplementary information) was used for the determination of the ranks.

Ranking by TOPSIS

The ranking of the alternatives by the TOPSIS method was done by calculating the relative closeness of each alternative as per Eq. 7. As per this method, the alternative having the highest relative closeness value has the first rank. The TOPSIS method results in selecting alternative 1, i.e. household reuse as the best-preferred reuse option for all the categories of experts. Household reuse scored 0.7630, 0.8361 and 0.9051 for academics, industry and policy-making respectively. While combining all the responses from different categories the score for household reuse was 0.8349 which holds the same position in the ranking. Experts from academics and industry gave the least preference to the agricultural reuse of greywater while public reuse was ranked last by the policy-makers.

Ranking by VIKOR

In this method, the first rank is associated with the alternative which scores the least VIKOR value and the results obtained are presented in Table 2. Great variation in the opinion of different categories of experts was observed. However, the first rank was given to household reuse by all the categories. Public reuse, groundwater recharge and industrial reuse of treated greywater was the second choice of the experts from academics, industry and poly-making, respectively. Academicians least preferred the agricultural reuse of the greywater which might be due to the concern of experts regarding the accumulation of contaminants in soil irrigated with greywater as reported in the literature [30]. Experts from industry and policy-making gave least preference to the public reuse of greywater.

Ranking by ELECTRE

In this method, the normalized matrix was used to find out the concordance and discordance matrix by using Eqs. 17–20. With the help of these two matrices, superior flow and inferior flow were determined using Eqs. 21 and 22, respectively. The ranking system was implemented in two flow systems. In the superior flow highest positive value was assigned with the first rank and in the inferior flow highest

Table 2 Ranks and scores by different MCDM methods

Alternative	Category							
	Combined		Academics		Industry		Policy-making	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
TOPSIS								
Household reuse	0.8349	1	0.7630	1	0.8361	1	0.9051	1
Public reuse	0.5660	2	0.7330	2	0.4818	3	0.1453	5
Industrial reuse	0.4784	4	0.5854	4	0.3551	4	0.6038	2
Agricultural reuse	0.0000	5	0.0054	5	0.2154	5	0.3556	3
Groundwater recharge	0.5433	3	0.5986	3	0.6228	2	0.3119	4
VIKOR								
Household reuse	0.0000	1	0.0000	1	0.0000	1	0.0000	1
Public reuse	0.3751	2	0.1193	2	0.9220	5	0.9965	5
Industrial reuse	0.5701	3	0.4581	3	0.6620	3	0.4777	2
Agricultural reuse	1.0000	5	1.0000	5	0.9128	4	0.8087	3
Groundwater recharge	0.6836	4	0.5289	4	0.4217	2	0.8585	4
ELECTRE								
Household reuse	2.3678	1	1.5838	1	1.2006	1	0.3124	1
Public reuse	− 0.0462	4	1.1996	2	− 1.2860	5	− 0.1627	4
Industrial reuse	0.4498	3	0.4244	3	0.0342	3	− 0.0206	3
Agricultural reuse	− 3.2418	5	−3.2498	5	− 0.8418	4	− 0.2505	5
Groundwater recharge	0.4704	2	0.0420	4	0.8930	2	0.1212	2
PROMETHEE								
Household reuse	0.9051	1	0.0000	1	3.0836	1	0.6203	1
Public reuse	0.1453	5	0.9965	5	− 1.7726	4	− 0.3345	4
Industrial reuse	0.6038	2	0.4777	2	2.1898	2	0.2908	2
Agricultural r euse	0.3556	3	0.8087	3	− 0.5416	3	− 0.2353	3
Groundwater recharge	0.3119	4	0.8585	4	− 2.9592	5	− 0.3413	5

negative value was assigned with the first rank. In most of the cases by these two flows, the ranking will be similar. Results obtained after analysis are presented in Table 2.

Here also the result obtained was very similar to the previous MCDM methods. Household reuse was ranked first by all categories of experts and agricultural reuse was the least preferred alternative.

Ranking by PROMETHEE

Similar to the ELECTRE method here, also the ranks were assigned by determining the net flow. At first, the PROMETHEE method compares pairs of alternatives on each criterion. The normalized decision matrix for PROMETHEE was evaluated by Eqs. 24 and 25. To express the difference in priority between pairs of alternatives on each criterion preference function was used. Aggregated preference value was calculated based on Eq. 27 and the leaving flow and entering flow values were found by using Eqs. 28 and 29, respectively. The net flow is the summation of leaving flow and entering flow (Eq. 30). Here also the ranking is similar to previous methods and household reuse was the most preferred alternative. All expert groups ranked household reuse as the most preferred one among the different alternatives. In the PROMETHEE method, industrial reuse and agricultural reuse were ranked second and third by experts from different fields.

Household reuse was given preference by all experts from different fields. This might be due to the ease and economy of greywater reuse in households compared to other reuse options. Amaris et al. [48] reported toilet flushing, laundry, garden irrigation, hand washing and bathing in decreasing order by public when asked for greywater reuse preferences. Public reuse was the second most ranked alternative in this study indicating the adaptability of treated greywater in public places such as garden irrigation. Difficulty in the conveyance of treated greywater to the agricultural fields and less acceptability and adaptability for reuse of treated greywater for agricultural purposes make it the least preferred alternative. Greywater is less polluted than wastewater but accounts for 50–80% of wastewater generated [31]. Hence, on-site reuse of treated greywater for household activities such as toilet flushing, garden irrigation and car washing could be an economical and environmentally sustainable alternative.

Table 3 Ranks comparison between four MCDM methods for the combined category

Alternatives	TOPSIS		VIKOR		ELECTRE		PROMETHEE	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Household reuse	0.8349	1	0.0000	1	2.3678	1	0.9051	1
Public reuse	0.5660	2	0.3751	2	−0.0462	4	0.1453	5
Industrial reuse	0.4784	4	0.5701	3	0.4498	3	0.6038	2
Agricultural reuse	0.0000	5	1.0000	5	−3.2418	5	0.3556	3
Groundwater recharge	0.5433	3	0.6836	4	0.4704	2	0.3119	4

Table 4 Spearmen's coefficient for different categories

Spearman's coefficient	TOPSIS-VIKOR	TOPSIS-ELECTRE	TOPSIS-PROMETHEE	VIKOR-ELECTRE	VIKOR-PROMETHEE	ELECTRE-PROMETHEE
Combined	0.9	0.7	0.7	0.6	0.9	0.7
Academics	0.9	0.9	0.9	1.0	1.0	1.0
Industry	0.7	0.7	0.9	1.0	0.9	0.9
Policy-making	1.0	0.9	0.9	0.9	0.9	1.0

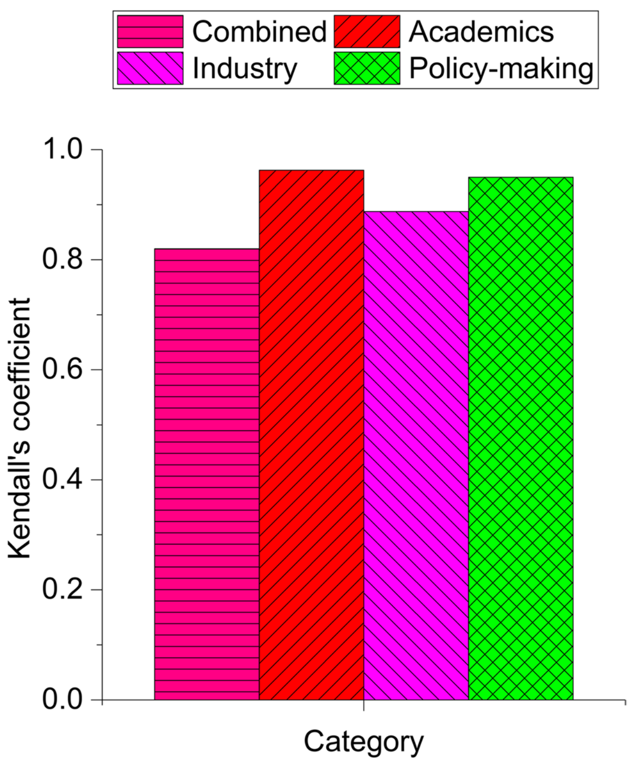

Fig. 6 Kendall's coefficient of concordance value

Comparison of Rankings

Table 3 shows the rank comparison between all the methods for the combined category while Table 4 presents Spearman's rank correlation coefficients for different expert groups as per Eq. 32. Figure 6 shows Kendall's coefficient of concordance value calculated as per Eq. 31. In the present study, relative ranking of different MCDM methods was compared using two methods namely Spearman's rank correlation coefficient and Kendall's coefficient of concordance. While the former does a pairwise comparison of ranks, the latter gives the concordance value altogether.

Household reuse was the highest ranked alternative by all the four MCDM methods. TOPSIS and VIKOR gave public reuse as the second preference while according to ELETRE and PROMETHEE, groundwater recharge and industrial reuse were ranked second reuse alternatives, respectively after household reuse of treated greywater. Agricultural reuse was least ranked by all the MCDM methods except PROMETHEE which gave public reuse the least preference.

It can be observed that Spearman's rank correlation coefficient is varying from 0.7 to 1.0 indicating a good correlation in ranking obtained by different methods [15, 16]. For the combined category, the highest correlation was obtained between TOPSIS-VIKOR and VIKOR-PROMETHEE methods. Kendall's coefficient of concordance value for all the four methods was calculated for different expert groups and is shown in Fig. 6 and the values ranged from 0.8875 to 0.9625. These values suggest that there exists more than a partial agreement between rankings generated by these four MCDM methods [49]. Kendall's coefficient of concordance value was highest for academic experts while the lowest value was for experts from industry.

Sensitivity Analysis

The performance scores obtained for all the cases with respect to six scenarios are presented in Fig. 7. Sensitivity analysis is used to ascertain the robustness of methodologies

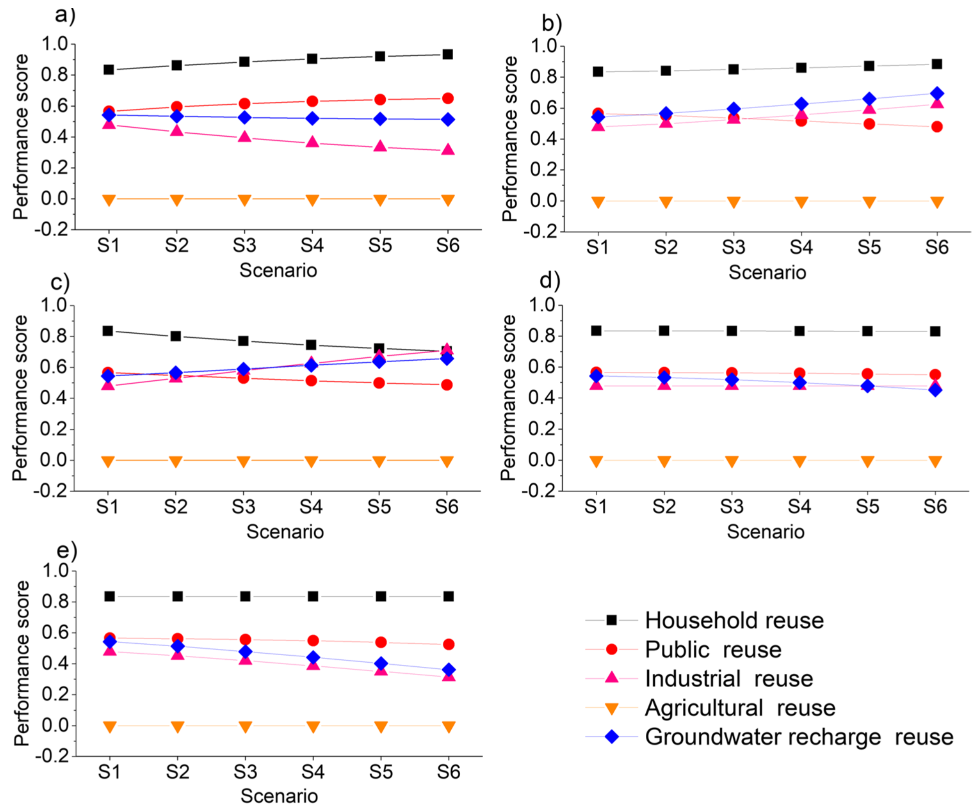

Fig. 7 Performance score variation for (**a**) acceptability, (**b**) adaptability, (**c**) technical, (**d**) economical, and (**e**) risks involved

adopted in the study [50]. Generally, this assessment is done by making slight changes in the values of input parameters. In the present study, sensitivity analysis was done by changing the criteria weightage by some factor ranging from 0 to 25% for each criterion one at a time. A set of weights was created and used in the calculation of performance score and rank. Each criterion was increased by the factors keeping other criteria proportionally decreasing. The factors are defined for 5% increment such that 0%, 5%, 10%, 15%, 20% and 25% are considered scenarios S1, S2, S3, S4, S5 and S6 respectively. Thus, there are six scenarios and each scenario was calculated for different sets of weights for each criterion. For example, in the first case, criteria 1 was considered and increased its weightage based on the factors defined above. At the same time, all other four criteria weights are decreased proportionally. Similar to this, each of the criteria was considered. Likewise, a total of five cases of sets of weights were created and all the weightage values are mentioned in Table S2 (Supplementary information).

In the present study, sensitivity analysis was performed only for the TOPSIS method. The performance scores obtained for all the cases with respect to six scenarios are presented in Fig. 7. Figure 7e shows sensitivity analysis for risk involved criteria. It can be observed that all the alternatives have shown disturbance from the original data. However, the ranking of alternatives did not change. The performance score for groundwater recharge was changed from 0.5432 to 0.5140 which indicates the reduction percentage is less than 5%. This implies that the alternative groundwater recharge is least sensitive to the change in acceptability criteria. Upon changing the weightage value for acceptability, the performance score of household reuse shows a 11% increase and at the same time, industrial reuse shows around a 34% decrease. So, the most sensitive alternative for the acceptability criteria is industrial reuse. Hadipour et al. [10] also studied the effect of changes in weights of the criteria in sensitivity analysis and reported the changes in results of the analytic hierarchy process (AHP) model with changes in weights of the criteria. This exercise was repeated for all the other four criteria (Fig. 7b–e).

Technical criteria had imposed greater change or variation on performance scores for all the alternatives except agricultural reuse (Fig. 7c). Variation of agriculture reuse for all the cases is very similar. Only for technical criteria, it can be observed that rank reversal has happened. When the weightage was disturbed by the factor 5% itself, the performance score began to change for all the alternatives except agricultural reuse. Industrial reuse scored the highest performance score by a factor of 48%. Economic and risk criteria varied similarly in the entire sensitivity analysis. It may be noted that in risks criteria analysis there was very little change happened in the performance score of household reuse and public reuse alternatives. Based on the variation of each criterion it can be concluded that household reuse is the best followed by public reuse.

In economic criterion, industrial reuse, public reuse and household reuse were least sensitive criterion with less than 3% variation in weights. Agricultural reuse was the most sensitive alternative with a decrease of 28%. Similarly, weight of the agricultural reuse alternative was reduced by a factor of 47% in risk criterion making it the most sensitive criterion. Industrial and groundwater recharge varied similarly in risk criterion with decrease of 34% each, whereas household reuse and public reuse showed less than 7% variability with the variation in weights.

Conclusions

Using acceptability, adaptability and the risk involved along with technical and economic considerations as criteria, the present study used four different MCDM techniques to select the most preferred greywater reuse alternatives among domestic, public, industrial, agricultural reuse and groundwater recharge. Results showed that domestic reuse was the most preferred reuse option by all the four MCDM techniques and by different group of experts. Different MCDM methods gave different ranking while results reported by VIKOR and PROMETHEE methods were nearly similar. It was observed that Spearman's rank correlation coefficient was varying from 0.7 to 1.0 indicating a good correlation in ranking obtained by different methods. Kendall's coefficient of concordance values further suggested that there existed more than a partial agreement between rankings generated by the four MCDM methods. Sensitivity analysis showed that the technical criterion was the most sensitive among the five criteria considered.

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Author Contribution Melvin Daniel and M. Mansoor Ahammed contributed to the study conception and design. Material preparation, data collection and analysis were performed by Melvin Daniel and M. Mansoor Ahammed. The manuscript was written by Irshad N. Shaikh. All authors read and approved the final manuscript.

Data Availability All data generated or analysed during this study are included in this published article (and its supplementary information files).

Declarations

Competing Interests The authors declare no competing interests.

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