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Evaluating disinfection techniques of water treatment

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ABSTRACT

In the municipal water treatment process, disinfection is used to remove biological contaminants from the water and to make it safe for the intended purpose. There are several types of water disinfection method used in the water supply. Therefore, the objective of this study is to evaluate different water disinfection techniques using the fuzzy preference ranking organization method for enrichment of evaluations (PROMETHEE) to select the best alternative among water disinfection techniques. The study compares five disinfection techniques: ultraviolet radiation (UVR), chlorination, ozone, chloramination (CM) and chlorine dioxide using eight evaluation criteria. The results of this study reveal that UVR is the most preferable disinfection technique and CM is the least as compared with other methods. The results of PROMETHEE were compared with that obtained from the technique for order of preference by similarity to ideal solution and the UVR method is the most preferable.

Keywords: Chloramine; Chlorination; Chlorine dioxide, Fuzzy PROMETHEE; Ozonation; Ultraviolet radiation

1. Introduction

Water is one of the most abundant and vital resources on the Earth's surface. It is vital to life; every living being on the earth needs water for their survival and growth. Human beings depend on water for drinking, as well as industrial and agricultural production [1]. Today, because of the increasing population, industrialization, and transition to a modern consumer society, contamination of water resources frequently occurs [2–5]. Therefore, water has to be treated using different processes before being supplied to consumers. Therefore, the objective of any water treatment process is to remove contaminants from the water and to make it fit for the intended use. Water treatment includes biological, chemical and physical processes to remove contaminants from the water.

Disinfection is an essential part of the water treatment process that destructs and inactivates waterborne pathogens, thus protecting human health [6]. Therefore, it is indispensable in

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the drinking water treatment process as it protects human health by killing harmful pathogens [7]. Disinfection has been widely used as the standard treatment of wastewater, swimming pools and drinking water [7]. The most common disinfection methods used in water treatment include physical disinfection (e.g., ultraviolet radiation (UVR)) and chemical disinfection (e.g., chloramine, chlorine, ozone, chlorine, and dioxide) [8]. However, a large proportion of the public has significant concerns about disinfectants due to their reliability, efficiency, toxic by-product formation and costs. Many different water disinfection techniques are commonly used worldwide that have different efficiencies, drawbacks, and advantages.

The selection of the best water disinfection process is very crucial before designing and implementing any water treatment plant. Multi-criteria decision-making methods can be used to help decision-makers to evaluate problems systematically and clearly [9]. By using these methods, the decision-makers can easily scale and examine the issues based on their criteria.

Therefore, the main aim of this study is to analyze different water disinfection techniques using the fuzzy preference ranking organization method for enrichment of evaluations (PROMETHEE) decision-making method to select the best alternative among the water disinfection methods.

2. Water disinfectant methods

Disinfection is an essential step that ensures that water is safe to drink. It is commonly the last step in the drinking water treatment procedure for killing or inactivating disease-causing microorganisms that can cause human sickness by using disinfectant. The disinfection process either inactivates or kills pathogens (bacteria, fungi, parasites, etc.) in a municipal water supply.

Currently, there are many disinfectant technologies used for treating the municipal water supply. Generally, there are three types of disinfection techniques used in water treatment, namely chemical, radiation, and heat. The heat method involves "boiling water" and is mostly used during an emergency. However, this study focuses only on the selected physical and chemical water disinfection techniques.

2.1. Ultraviolet radiation

Ultraviolet radiation is one of the most widely used tertiary treatments for the disinfection of effluent in water treatment plants. At present, UVR is a widely used disinfectant in water treatment due to its capacity to inactivate a variety of disease-causing microorganisms. This type of disinfectant is non-residual and does not form any harmful products in the water [10]. In this method, water is exposed to shortwave radiation to kill any microorganisms contained within it. UVR disables the growth and replication of microorganisms by directly affecting its deoxyribonucleic acid [11].

UVR is an effective disinfectant, and it does not influence the quality of water. This is because UVR is a physical means of removing bacteria, that is, no chemical agent is added to the water for disinfection, and the water does not undergo any chemical change. As a result, the smell, taste, and pH are not changed, as the only target is the bacteria. In addition to drinking water treatment, this technique can also be applied in the disinfection of treated wastewater.

UVR has been used in the disinfection of municipal water supply for more than 75 years. The main advantage of using UVR disinfectant in the drinking water supply is that it disinfects the water without using chemicals (no need to handle toxic chemicals). The other advantage of using UVR is that it is an incredibly rapid process (immediate disinfection), cost-effective and straightforward to maintain. On the contrary, the lack of residual disinfection is the main disadvantage of using UVR. Since UVR is a form of physical disinfection, it does not form any harmful by-products. According to Chen et al. [12], disinfection technology is said to be ideal when it is cost-effective and does not produce any adverse environmental impacts (e.g., disinfection by-products).

2.2. Chlorination

The primary objective of disinfection in any water supply system is to remove pathogens that cause waterborne diseases. Chlorination (CL) is a successful method of achieving this objective and is the most commonly applied disinfection technique used on the water supply in the majority of countries. In this technique, chlorine is added into the water in the form of chlorine or chlorine by-products. In this process, the added chlorine or chlorine by-product reacts with water to form hypochlorous acid and hypochlorite ions [13].

Chlorine is a strong oxidizing water disinfectant. It is cheap and effective even at low concentrations, and it forms a residual (no post-treatment is required). The primary preferred standpoint of this method is that chlorine lasts longer in water as residual chlorine; therefore, it is disinfectant action continues during storage and distribution [11–13]. Because of its low cost and strong disinfection capability, CL is a widely used disinfection technology around the world [14]. However, the disadvantages of CL such as the unpleasant odor and taste, ineffectiveness against protozoa eggs and cysts, the formation of trihalomethanes and more than 400 other types of CL by-products have prompted the introduction of other disinfection techniques [15]. The other problem associated with CL is that there is no fixed rule on the quantity that is required. However, the amount needed depends on the water quality and the disinfection requirement. Furthermore, a water treatment plant that uses chlorine gas as the disinfectant requires highly skilled engineers, operators, and maintenance and repair infrastructures [16]. However, a treatment plant that uses diluted chlorine is relatively cost-effective and straightforward. Nevertheless, the worldwide applicability of this method can be ascribed to its convenience and to its exceedingly acceptable performance as a disinfectant, which has been built up by many years of usage.

2.3. Chloramination

Monochloramine is formed by dosing chlorine and ammonia and reacts under well-controlled conditions. This process is generically called chloramination (CM). The process of CM should be performed under well-controlled conditions to prevent the formation of by-products and strong tastes [11,17]. The efficiency of mono-chloramine in reducing microorganisms is low as compared to CL, and it is predominantly used to provide a disinfectant residual during the distribution of treated water.

The advantage of using CM as a type of disinfection is that it does not form harmful by-products such as trihalomethanes under the presence of organic matter. Moreover, the taste threshold is typically much higher than for chlorine alone. Thus, using CM in disinfecting drinking water can significantly reduce customer complaints relating to chlorine tastes. Due to this reason, the use of CM disinfectant is becoming increasingly popular in most developed countries as it provides residual disinfectant in distribution lines. The residue of chloramine protects the water from recontamination.

On the other hand, the CM method has some disadvantages. Some of its drawbacks include that it requires skilled personnel, is dependent on chemical access, is less efficient in pathogen removal than other methods and it is harmful to fish farming enterprises [11,13].

2.4. Ozonation

Ozone (O_3) is generated onsite by passing dry oxygen or air through a system of high-voltage electrodes. Ozone is a powerful oxidizing agent that is extensively applied in the water supply to achieve water quality and disinfection improvement [18]. Due to its high oxidizing capacity, it is now one of the most effective disinfection techniques used for water treatment.

Ozone is a popular disinfection alternative used instead of chlorine. In comparison to chlorine, it is a highly effective disinfectant that readily oxidizes chemical residuals, pesticides, various microbes and organic matter in short contact times and low concentrations [19]. Ozonation (OZ) is a more effective disinfectant compared with chlorine dioxide (CD) and chlorine. It requires less concentration and contact time than CD, chloramine, and CL to achieve the required disinfection [11,13]. This method is primarily effective against cysts and spores. OZ is the only chemical disinfectant that can inactivate *Cryptosporidium* and *Giardia*. Its most significant advantage is that it does not produce unwanted by-products since ozone becomes oxygen. Therefore, its use in water treatment has increased in popularity in recent years.

The drawback of OZ is that its concentration in water decays rapidly in comparison to other methods. Therefore, when using this method, it is likely that there could be recontamination in the distribution system [11]. Furthermore, OZ is very expensive, especially in terms of operational and capital costs (CC). It requires a highly skilled workforce for maintenance, onsite generation, high energy input, and post-treatment to remove organic carbon formed during the oxidation process. Ozone also reacts with bromide and organic matter to produce by-products such as ketones, aldehydes, and bromate [11].

2.5. Chlorine dioxide

Chlorine dioxide (ClO_2) is one of the methods used in drinking water treatment for disinfectant, especially for algae control. Moreover, the CD also removes odor, taste, iron, and manganese from the drinking water. As CD is unstable, it is sensitive to pressure, temperature, and light. Thus, it is highly explosive in the air if its concentrations are 4% and above. Therefore, CD is usually generated and used onsite to avoid problems of bulk storage and distribution.

3. Material and methods

Fuzzy PROMETHEE is a technique widely applied around the world in different decision-making processes. It is a combination of fuzzy logic and the PROMETHEE method [20]. Fuzzy logic was first introduced by [21] and since then, it has been applied in a variety of fields. The fuzzy PROMETHEE method is the best method for comparing different alternatives where the parameters are not numerical [22].

In practical circumstances, it is hard to gather crisp data to investigate a system; fuzzy logic enables the decision-makers to analyze the given system even in dubious conditions and to convert linguistic variables into mathematical variables. Thus, fuzzy values are compared in the fuzzy PROMETHEE technique. Different studies have used and discussed the fuzzy PROMETHEE procedure in detail [23–26]. In recent years, fuzzy logic and the fuzzy PROMETHEE technique have been applied for evaluating alternatives in different fields to select the best among them [27–35] All of these studies used the fuzzy PROMETHEE technique in different fields to select the best among different alternatives. In this study, a similar method is used to evaluate different water treatment disinfection methods.

The basic steps of the PROMETHEE method [36]:

- *Step 1*: For each criterion j, determine a specific preference function $P_j(d)$;
- *Step 2*: Characterize the weights of every criterion; $W_T = (w_1, w_2, \ldots, w_k)$. At the circumspection of the decision-makers, each weight of criterion can be taken similarly if just their significance is equivalent. Furthermore, standardization can be utilized for the weights;

$$\sum_{i=1}^{k} w_k = 1 \tag{1}$$

- *Step 3*: For all the alternatives $a_t, a_t' \in A$ define the outranking relation π;

$$\pi(a_t, a_t') = \sum_{k=1}^{k} w_k \left[P_k\left(f_k(a_t) - f_k(a_t') \right) \right], \text{AXA} \rightarrow [0,1] \tag{2}$$

where, $\pi(a, b)$ represents the preference index which is a measure for the intensity of preference of the decision-maker for options a_t in evaluating alternatives a_t' while considering all criteria at the same time.

- *Step 4*: Determine the positive and negative outranking flows;
  Positive flow for the option a_t:

$$\Phi^+(a_t) = \frac{1}{n-1} \sum_{t'=1}^{n} \pi(a_t, a_t') \tag{3}$$

where $t' \neq t$.

Negative flow for the option a_t:

$$\Phi^-(a_t) = \frac{1}{n-1}\sum_{t'=1}^{n}\pi(a'_t, a_t) \quad (4)$$

where n = number of alternatives and each alternative is compared with other alternatives.

$\Phi^+(a_t)$ = positive flow which represents the strength of alternative $a_t \in A$.

$\Phi^-(a_t)$ = negative flow representing the weakness of alternatives $a_t \in A$.

Following the outranking flows, partial pre-order of the alternatives is given by the PROMETHEE I method, and a complete pre-order is given by the PROMETHEE II method based on net flow. However, it does not provide much information about the preference relations.

- *Step 5*: Partial pre-order for the alternatives should be determined based on the following conditions;

  PROMETHEE I alternatives at is preferred to an alternative $a_t'(a_tPa_t')$ if it satisfies one of the following conditions.

  (a_tPa_t') if;

$$\begin{Bmatrix}\Phi^+(a_t) > \Phi^+(a_{t'})\text{and}\Phi^=(a_t) < \Phi^=(a_{t'}) \\ \Phi^+(a_t) > \Phi^+(a_{t'})\text{and}\Phi^=(a_t) = \Phi^=(a_{t'}) \\ \Phi^+(a_t) = \Phi^+(a_{t'})\text{and}\Phi^=(a_t) < \Phi^=(a_{t'}.a_{t'}) \end{Bmatrix} \quad (5)$$

If we have two alternatives, a_t and a_t' with similar entering and leaving flows, the a_t is different to a_t' (a_tIa_t'):

$$(a_tIa_{t'})\,if : \Phi^+(a_t) = \Phi^+(a_{t'})\text{and}\Phi^=(a_t) = \Phi^-(a_t) \quad (6)$$

a_t is incomparable to a_t' (a_tRa_t') if:

$$\begin{Bmatrix}\Phi^+(a_t) > \Phi^+(a_{t'})\text{and}\Phi^=(a_t) > \Phi^=(a_{t'}) \\ \Phi^+(a_t) < \Phi^+(a_{t'})\text{and}\Phi^=(a_t) < \Phi^=(a_{t'}) \end{Bmatrix} \quad (7)$$

- *Step 6*: The net outranking flow can be determined for each alternative using the formula below:

$$\Phi^{\text{net}}(a_t) = \Phi^+(a_t) - \Phi^-(a_t) \quad (8)$$

Through PROMETHEE II, the complete preorder for net flow can be found and b is defined as:

a_t is preferred to a_t' (a_tPa_t') if $\Phi^{\text{net}}(a_t) > \Phi^{\text{net}}(a_t')$
a_t is indifferent to a_t' (a_tIa_t') if $\Phi^{\text{net}}(a_t) = \Phi^{\text{net}}(a_t')$

Usually, the better alternative is the one with the higher $\Phi^{\text{net}}(a_t)$ value.

3.1. Criteria for evaluation

The selection of the best technological technique for water treatment (disinfection) is critical and is always undertaken based on different multi-objective [26]. To compare different disinfection methods, certain criteria have to be set. The criteria considered mainly consist of sustainability of the technique, economic feasibility, and technical performance. The decision-maker uses different indices for the comparison of different disinfecting methods. In this study, the criteria used for evaluating different disinfectants are reliability, residue formation, CC, operation and maintenance cost, safety risk (SR), pathogen removal efficiency (PRE), operational simplicity (OS) and formation of undesirable by-products.

3.1.1. CC and maintenance and operation cost

Cost is the economic criteria that should be considered when selecting a particular disinfection technology. The cost in this context includes capital, maintenance, and operational costs. CC, therefore, refers to the costs related to installing and constructing the electromechanical equipment necessary for implementing the full system [22]. This criterion also includes costs for civil and mechanical works [37]. It also includes the cost of land, which is necessary for accommodating the facilities. However, maintenance and operation costs (MOC) consist of those costs related to the different maintenance and operation processes such as energy costs, repair costs, chemical product costs and personnel costs [23]. Economic criteria's (CC and MOC) have been extensively used as the main criteria's for selection of different water and wastewater treatment process alternatives in many studies [36–39]

3.1.2. Operational simplicity

The section of the technique should also take into account the special needs of each disinfectant method. If the operation disinfection process requires highly skilled human resources, it cannot be accepted by decision-makers, especially in remote areas [36]. Simplicity and flexibility in maintenance and operational are primary objectives in selecting different disinfection techniques because simplicity can determine the long-term working accomplishment of the treatment techniques [11,37].

3.1.3. Pathogen removal efficiency

Water treated using different techniques must be disinfected until the final quality of water meets the World Health Organization (WHO) standards for drinking water supply [11]. This criterion evaluates both the ability of the disinfectant technique to remove pathogens and other undesirable contaminants in the treated water. The effectiveness of a specific disinfection method can be evaluated based on experience from full-scale treatment plant studies [40]. Removal efficiency has been used as a criterion for selection of best alternative by many studies [36,37,39–41].

3.1.4. Safety risk

In selecting the best out of many disinfection techniques, the safety of workers in different processes should be taken into account. This is because, during operation or maintenance, accidents could happen involving workers [36]. Safety for workers is one of the criteria used in the evaluation of different water treatment processes [36,37].

3.1.5. Reliability

In this study, the reliability of the system is a very important criterion for comparing different types of disinfection methods. The reliability of the disinfection method refers to the probability of achieving adequate performance for a specific period under specific conditions [42]. In terms of the performance of water disinfection methods and wastewater treatment, reliability can be assumed as the percentage to which the quality of the effluent complies with the standards set by country and WHO [43]. The selected water disinfection method must be reliable, that is, it must have the best performance under specific conditions [26]. Reliability includes issues related to the disinfection method's effectiveness during both emergencies and normal operations, the likelihood of machine failures, the effect on the quality of effluent, and how the process reacts to effluent changes [36]. Therefore, reliability in water treatment is measured in terms of the quality of effluent and its variability, which must be consistent with the drinking water quality requirement [37]. Hence, in this study, long term reliability is considered.

3.1.6. Residue formation

It refers to the ability of the disinfectant to create a residue that gives additional protection against conceivable post-treatment contamination generated by shortcomings in the distribution system [36]. Therefore, an assessment should be made to ensure that a residual disinfectant is present in the treated water storage and distribution network [11]. The best disinfectant should have the ability to persist in a residual state, even after treatment [11,36].

3.1.7. Undesirable by-product formation

By-product formation is one of the criteria used to evaluate different disinfection techniques [36]. Disinfection by-products are formed when disinfection chemicals react with other inorganic or organic compounds. Many studies show that when humans are exposed to these by-products, they may have adverse health effects [11]. By-product formation has been extensively used in the selection and comparison of disinfection alternatives [11,44,45].

3.2. Scale of evaluation criteria's

The importance scale of each evaluation criterion used is shown in Table 1.

After all the evaluation parameters were collected for the water treatment disinfection methods, the Gaussian preference function was used for each criterion, as shown in Table 1. The preference weight applied for each evaluation criterion is presented in Table 2.

After the importance scale of each criterion was determined, the visual PROMETHEE decision lab program was then applied.

4. Results and discussion

The application of fuzzy PROMETHEE methods in the selection of the best water disinfection method is effective because of the consistent results in the ranking of those methods. For analyzing and comparing different disinfectant methods of water treatment, triangular fuzzy was used (Table 1) to determine the importance of each criterion and

Table 1
Linguistic (fuzzy) scale for the importance of the criteria

Linguistic scale for evaluation	Triangular fuzzy scale	Criterion's importance rating
Very important	(0.75, 1, 1)	CC, MOC, SR, R, UB, PRE and OS
Important	(0.5, 0.75, 1)	RF
Medium	(0.25, 0.5, 0.75)	
Low	(0, 0.25, 0.5)	
Very low	(0, 0, 0.25)	

Table 2
Weight for each criterion

Criteria	CC	MOC	OS	PRE	SR	R	RF	UB
Preferences								
Maximum/Minimum	Minimum	Minimum	Maximum	Maximum	Minimum	Maximum	Maximum	Minimum
Weight	0.92	0.92	0.92	0.92	0.92	0.92	0.75	0.92
Evaluations								
UVR	0.5	0.4	0.8	0.9	0.4	0.9	0.3	0.1
CL	0.6	0.5	0.6	0.7	0.8	0.7	0.8	0.8
CM	0.7	0.6	0.4	0.5	0.5	0.5	0.6	0.5
OZ	0.9	0.8	0.8	0.8	0.5	0.8	0.4	0.4
CD	0.7	0.7	0.5	0.4	0.8	0.4	0.6	0.6

then triangular fuzzy numbers were defuzzified to calculate each criterion's weight. The obtained results are shown in Table 3.

Table 3 shows the complete ranking of different water disinfection methods based on the selected criteria. As clearly shown in the tables, with minimal operation and maintenance cost, higher reliability and OS, highest PRE and no harmful by-product formation, UVR is the best alternative for the disinfection of drinking water supply. However, due to its low efficiency in removing pathogens, high SR (explosive), low reliability, lower OS, higher production of unwanted by-products, CM is ranked last. Fig. 1 shows the positive and negative aspects of each disinfectant method.

Fig. 1 shows the positive and negative sides of the treatment alternatives for each selected criterion. This result was obtained by using the decision Lab Visual PROMETHEE program. This program was applied because it is easy to use and the user can easily change the criteria and the weight for the criterion. Thus, they can make a comparison between disinfection methods based on the criteria they wish. To compare the results obtained from PROMETHEE, a technique for order of preference by similarity to ideal solution (TOPSIS) was applied using the same data and weights. It is another frequently used multi-criteria decision-making technique created by Hwang and Yoon [46] that was subsequently improved by other researchers. The weight of the criteria was first normalized and finally calculated the weighted normalized data of the disinfection methods as in Table 4. In this method, the net ranking is dependent on the distance of the alternatives to the positive and negative ideal solution sets.

Using the TOPSIS method we obtained the same net ranking for the given disinfection methods.

Positive ideal solution set:

(0.04, 0.03, 0.08, 0.08, 0.04, 0.07, 0.06, 0.01)

Negative ideal solution set:

(0.07, 0.08, 0.04, 0.02, 0.07, 0.04, 0.03, 0.09)

Table 3
Complete ranking of disinfection methods

Rank	Alternatives	Positive outranking flow	Negative outranking flow	Net flow
1	UVR	0.3562	0.0257	0.3305
2	Ozonation	0.1777	0.1360	0.0417
3	Chlorination	0.0838	0.1605	–0.0767
4	Chlorine dioxide	0. 0538	0.1625	–0.1087
5	Chloramination	0.0462	0.1624	–0.1161

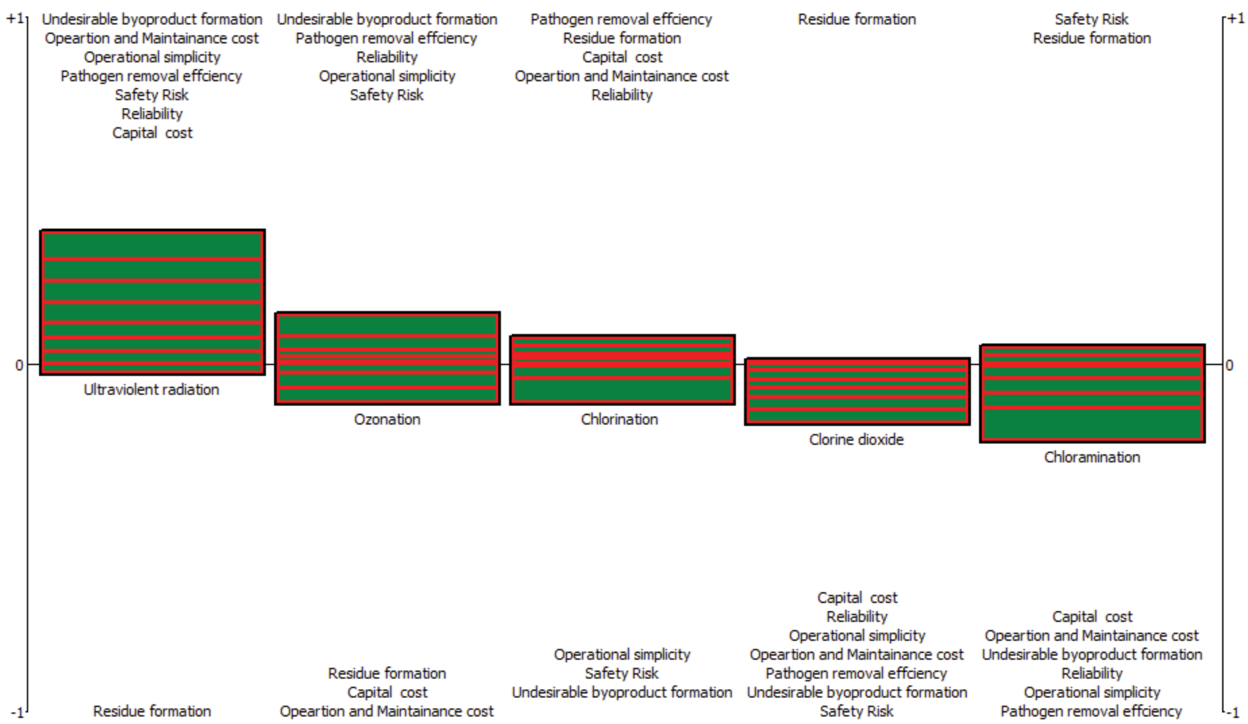

Fig. 1. PROMETHEE evaluation results.

Table 4
Weighted normalized disinfection methods

S.No.	Disinfection methods	Criteria							
		CC	MOC	OS	PRE	SR	R	RF	UF
1	UVR	0.04	0.03	0.08	0.08	0.04	0.07	0.03	0.01
2	OZ	0.05	0.05	0.05	0.06	0.07	0.06	0.06	0.09
3	CL	0.06	0.06	0.04	0.02	0.04	0.04	0.06	0.06
4	CM	0.07	0.08	0.06	0.07	0.05	0.06	0.03	0.02
5	CD	0.06	0.07	0.04	0.04	0.07	0.05	0.05	0.06

Table 5
Relative closeness of disinfection methods to the positive ideal solution using TOPSIS technique

S.No.	Disinfection methods	Relative closeness to the positive ideal solution
1	UVR	0.84
2	OZ	0.57
3	CL	0.42
4	CM	0.32
5	CD	0.32

A most preferable disinfection method is the one with higher relative closeness to the positive ideal solution. Based on this method UVR is the ideal and most preferable disinfection method as indicated in Table 5. The results show that the TOPSIS method also validates the net ranking results of the fuzzy PROMETHEE technique.

5. Conclusions

This study presents fuzzy PROMETHEE to select the best disinfection method for drinking water treatment using different evaluation criteria. The study has considered technical, economic, safety and health requirements to evaluate different water disinfection methods. The results of this study show that the UVR technique is the best method as it meets all the criteria used except the provision of residual disinfectant. UVR disinfection is the best because it is less expensive, most effective in removing pathogens, simple to operate, the most reliable and it has no harmful by-products. The result obtained from the fuzzy PROMETHEE was compared with that obtained from the TOPSIS model. The comparison result revealed that TOPSIS can also validate the net ranking results obtained from the fuzzy PROMETHEE method. In both methods, UVR is the most preferable disinfection method and chloramine is the least preferable water disinfection method.

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