

Application of multi-criteria decision-making techniques for selection of appropriate household treatment method

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Abstract: Household water treatment technologies have emerged as an important option for providing safe drinking water to people and communities without having access to improved water supplies. Many such technologies are available and selection of an appropriate technology from the set of available alternatives is difficult as it involves multiple criteria and non-quantifiable parameters. An attempt is made in this paper to present application of Analytical Hierarchy Process (AHP) and VIKOR techniques for ranking the household water treatment methods. Six household treatment methods were considered for six criteria weighted according to a panel of experts. The evaluation showed that chlorine disinfection as the most appropriate method followed by boiling by both the techniques. The proposed methodology is a rationalized process for realistic scenarios where multiple stakeholders and priorities are involved in selection of a household water treatment technology.

Keywords: Household water treatment, AHP, VIKOR

1. Introduction

According to a recent WHO report, 785 million people lack even a basic drinking-water service, including 144 million people who are dependent on surface water (WHO/UNICEF, 2019). The household water treatment technology empowers people and communities without access to safe water to improve the water quality by treating it and storing it safely at home (Sobsey et al., 2008). The effectiveness of any household water treatment technology is directly linked with its efficacy in microbial attenuation, compliance of people with the system and route for further contamination (Enger et al., 2013). Many water, sanitation and hygiene interventions suggest that household water treatment technologies have been underestimated in the context of reducing diarrheal diseases (Ojomo et al., 2015). Treating of water at household level often uses basic approaches of filtration, disinfection, thermal exposure, sedimentation or some combinations thereon. Some of the widely used household water treatment technologies are boiling, disinfection using free chlorine (liquid or tablets), coagulation/chlorination, solar disinfection, biosand filters, and ceramic filters. By focussing on point of use rather than point of delivery that is treating water at household level, the risk of recontamination can be minimized (Mintz et al., 2001). Although a variety of household water treatment technologies have been suggested and tested, the effectiveness and sustained use is still in doubt (Fewtrell et al., 2005).

The selection of these household treatment technologies is site specific and implementation of it is circumstantial for a particular population (Clasen, 2007). The selection in particular depends on many criteria like water quantity produced, treatment robustness, ease of operation, reliability, time to treat, cost to treat, supply chain requirements, post contamination etc (Sobsey et al., 2008). Sobsey et al. (2008) attempted a method to select suitable household water treatment technology but since it was simple summation, the criticality of the criterion was not compared which does not give a clear idea as why a particular alternative was chosen over the other. Multiple criteria need to be considered in selection of suitable household water treatment technology which makes it a multi criteria decision making (MCDM) problem.

Any decision making is a function of many attributes which define its suitability. It is a complex procedure which enables the user to state the problem clearly and structure it systematically. It helps the decision makers to examine and scale the problem in accordance with the requirements (Karimi et al., 2011). The outcome of this process is choice of an alternative which is preferred after considering a number of conflicting objectives. More than 50 MCDM techniques are documented in the literature which involve highly sophisticated to simple scoring systems (Kalbar et al., 2012). MCDM helps the decision makers to examine and scale the problem in accordance with the requirements (Karimi et al., 2011). Multi-criteria decision-making allows both quantitative and qualitative criteria to be taken into consideration simultaneously (Srdjevic et al., 2012). In general, they are designed to help decision makers to integrate the different options, which reflect the opinions of the factors involved (Figueira et al., 2005). These are therefore more structured and logical approach to model any complex decision making problems.

Commonly used MCDM methods are the analytical hierarchy process (AHP), the preference and outranking methods of PROMETHEE and ELECTRE (Kalbar et al., 2012) and the ideal point methods such as TOPSIS and VIKOR. All of these methods either fall under scoring models, compromising-stability models or preference ranking models. The AHP is useful for handling multiple criteria and objectives in the decision making process. The AHP approach is a systematic analysis technique

which facilitates in definition of priorities and preferences of the decision makers. It is used to determine the weights of different factors (Saaty, 1977; Karimi et al., 2011). Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The VIKOR method was developed to solve decision making problems with conflicting and non-commensurable criteria assuming that compromise is acceptable to resolve the conflict thus enabling the decision maker to obtain a solution called compromise which is closest to the ideal (Opricovic et al., 2007). These MCDM techniques have wide application in the field of environmental decision making. Some used MCDM techniques in finding optimal wastewater treatment alternative (Kalbar et al., 2012) and ranking contaminated area according to the sediment management (Kiker et al., 2005). Curiel-Esparza et al. (2014) used AHP in selecting suitable disinfection technique for wastewater reuse projects. AHP has found its application in selection of chemical for physico-chemical treatment of textile wastewater (Beltran et al., 2009), in computing condition rating index for wastewater treatment plants (Srdjevic et al., 2012) and in selection of optimal process in removal of reactive dye from textile wastewater (Ehrampoush et al., 2016).

In this study, six most widely used household water treatment technologies namely boiling, chlorination, solar disinfection, ceramic filters, biosand filters, and coagulation and flocculation are evaluated and ranked. Two different MCDM techniques namely AHP and VIKOR technique were used for ranking. AHP incorporates all criteria relating to reliability, cost and other non-quantifiable criteria. VIKOR technique gives the compromise solution closest to the ideal in decision making.

2. Methodology

The hierarchy for selection of a suitable household water treatment technology used in this study is presented in Figure 1. The first level of hierarchy depicts the goal to be achieved. The second level decomposes the entire goal accomplishment as a function of criteria considered, and finally the third level of alternatives.

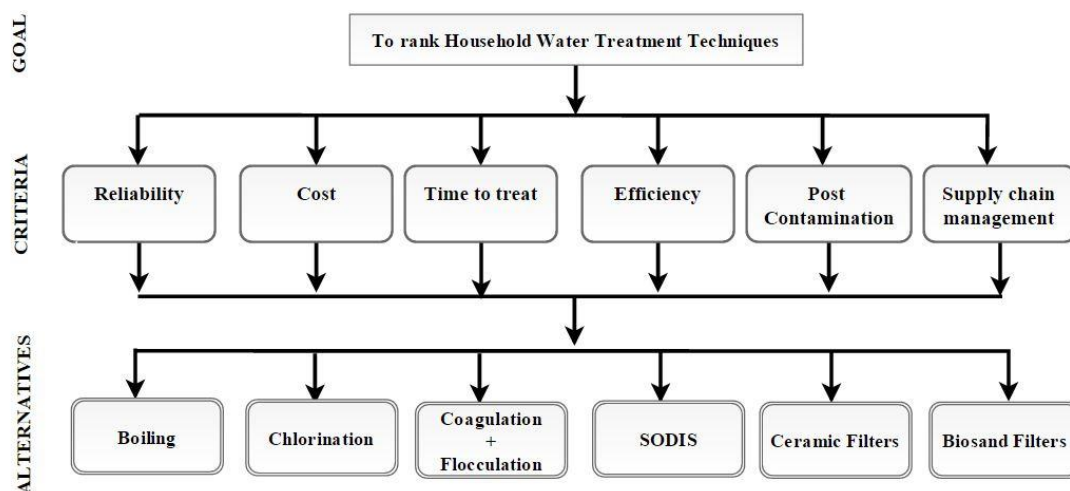


Figure 1 Hierarchy for selection of suitable household water treatment technology

2.1 Alternatives of the hierarchy

Six alternative household treatment methods were considered in this study. These are described here.

(i) Boiling : Boiling water to rolling boil for 1 to 5 minutes kills most of the pathogens as most pathogens are killed below 70°C. Boiling is faster and can be applied anywhere. High energy consumption and difficulty to treat large quantities of water are the disadvantages (Sobsey, 2002)

(ii) Chlorination: It is most widely used for disinfecting drinking water. Contact time plays vital role. Chlorine is supplied as concentrated liquid or tablets, designed for treatment of large quantities of water with a small volume of chlorine, allowing users to treat multiple unit volumes. It can treat large quantities of water and has residual power. Waters with high organic matter and particles can interfere with chlorine disinfection efficacy, cause production of compounds with objectionable taste and odor, and create consumer scepticism about effectiveness due to the unchanged appearance of the water (Clasen 2008)

(iii) Coagulation + Flocculation: If water contains large amount of suspended solids this technique is useful. Coagulation takes place during rapid mixing/stirring and flocculation during slow mixing. It removes turbidity, organic matter, and microbes

through flocculation and settling, aesthetically improving waters and facilitating chlorine effectiveness. Proper stirring mechanism is required for improving the effectiveness (Clasen, 2009)

(iv) Solar Disinfection (SODIS): UV radiation in sunlight will destroy most pathogens. It is a simple method wherein half blackened bottles are exposed to sunlight for disinfection. Safe period of exposure is about five hours centred around mid-day. 1-2-L PET bottles are used, 10-20 bottles are required per day for 20 L of daily household water. No fuel is required and no working parts. It is less effective in waters having high turbidity and color and in bottles that become scuffed from daily use. (Meyer et al., 2001)

(v) Ceramic filters : Purifying elements in these filters are porous, unglazed, ceramic cylinders (candles). Flow rates are about 1-3 L per hour, but decline with use and accumulation of impurities on filter element surfaces. At optimal flow rates, a filter can produce approximately 8 L in 4 h. It can remove turbidity, organic matter and microbes. It is simple to clean manually to restore efficacy. Periodic cleaning is required (Lantagne, 2001)

(vi) Biosand filters: It is a modification of the large-scale slow sand filter. Water flow rates from biosand filters are 0.25-1 L per minute, easily allowing for the production of tens to hundreds of liters of water per day. It can remove turbidity, organic matter, and microbes. It is simple to clean manually to restore efficacy. Capital cost is high and cleaning can reduce efficiency. Maturation time is long in new filters (Elliott et al., 2015).

2.1 Criteria of the hierarchy

Six criteria were used in this study to evaluate the alternatives. These are briefly discussed below.

(i) Reliability (R)

The selected technology must be reliable, that is, the system must have adequate performance, under specific conditions and for a period of time. This criterion considers the following aspects of reliability:

Treatment robustness: The applicability of the treatment technology to a wide range of water qualities is the key because of differences in water sources and seasonal fluctuations in water quality. Technologies that improve water quality and reduce microbes under a wide range of source water quality conditions provide households with high quality water regardless of source water quality. Technologies that can provide consistent microbial reductions in waters with high turbidity and organic matter are better with respect to treatment robustness (Sobsey et al., 2008).

Ease of operation: Adoption and consistent use of HWT technology is influenced by treatment process performance. The more straightforward the operation better it is for long term use.

Quantity: The ability of a household water treatment technology to produce sufficient volumes is critical.

Sustainability: Although HWT technologies may demonstrate effectiveness both in laboratory and field studies, this does not necessarily mean that they will do so over long periods of time in actual use (Sobsey et al., 2008; Curiel-Esparza et al., 2014).

(ii) Cost (C):

It defines the overall feasibility of the treatment process that will be adopted. Capital cost and operation and maintenance costs are considered in this.

(iii) Time to treat (TT)

It depends on the process mechanism whether it is a single step or multiple step process. Adequate quantity must be obtained after a brief period of treating the water (Sobsey et al., 2008).

(iv) Efficiency (E)

Efficiency means the ability of system to consistently produce sufficient quantities of microbiologically and aesthetically safe water to meet daily household needs and effectiveness in treating water qualities over a large range.

(v) Post contamination (PC)

It is necessary that water is not contaminated post treatment. This aspect depends on

Storage and handling: As the dirty vessels and hands used for handling the treated water overall jeopardise the treatment efficiency (Stubbe et al., 2015).

Regrowth of microbes: Even if a process is 100% efficient in killing the pathogens there still is an uncertainty in regards to the regrowth of the microbes after treatment (Regyadas et al., 2015)

Residual power: Capability to keep the water safe from further contamination.

(vi) Supply chain management (SCM)

The criterion refers to logistical components the user requires to continue using the technology once received or introduced. Availability of different components of system is critical when the system is complex and analysing fault in unit becomes very difficult for person without much idea about its functionality (Sobsey et al., 2008).

2.2 Analytic Hierarchy Process (AHP)

Once the criteria and alternatives were finalised, a questionnaire was prepared to evaluate the selected alternatives by obtaining the opinions of experts. Questionnaire was sent to 30 experts who had experience in the field of household water treatment technology. The experts included faculty of engineering institutes, engineers, project managers in private sectors and research scholars. Out of the 30 experts approached 18 responded making it a response rate of 60%. By using the questionnaire, the participants compare the alternatives pair-wise with respect to criteria and the goal.

The pairwise comparison technique was employed in AHP which helps in making the problem simpler as only two elements are compared at the same time. The process involves formulation of comparison matrix at each level for criteria and alternatives with respect to each criterion, determination of priority vector for each element of the hierarchy and finally analysing consistency and synthesizing the results.

The relative weights of each element of the hierarchy were obtained from the questionnaire filled by the experts on scale of 1-9, where 1 is equally preferred and 9 is extremely preferred. The data obtained from this questionnaire survey were extracted and the opinion of each expert was checked for its consistency. The pairwise comparison matrix for each criterion was constructed using the value obtained by the geometric mean of each expert value (a_{ij}). A square matrix of size 6x6, matrix $A = [a_{ij}]$, where elements along the principal diagonal, $a_{ii}=1$ and $a_{ij}=1/a_{ji}$. The eigen vector obtained was the priority vector ω . To compute this linear normalisation was done, $A\omega=\lambda\omega$ was solved and $\det[A-\lambda I]=0$ was calculated (Curiel-Esparza et al., 2014).

The consistency check for the Saaty's AHP methodology was obtained from an index called consistency ratio (CR). The maximum CR is obtained in accordance with the size of the matrix. The consistency index was calculated using the following equation:

$$CI = \frac{\lambda_{max}-1}{n-1} \quad (1)$$

where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix of size n.

The consistency ratio is the ratio between the consistency index (CI) and random consistency index (RCI):

$$CR = \frac{CI}{RCI} \quad (2)$$

where RCI is 1.25 for a matrix size of 6.

2.3 VIKOR

This method was used to rank the household treatment technologies D_i according to the values of the scalar quantities S_j , R_j and Q_j . Input is the elements d_{ij} of the decision matrix. This methodology involved the following steps:

Step 1 : For each criterion, the best d_j^* and worst d_j^- performances among all the household water treatment technologies were determined, $d_j^* = \max(d_{ij}, j=1, \dots, J)$, $d_j^- = \min(d_{ij}, j=1, \dots, J)$, if the i -th function is benefit type; $d_j^* = \min(d_{ij}, j=1, \dots, J)$, $d_j^- = \max(d_{ij}, j=1, \dots, J)$, if i -th function is cost type

Step 2: Calculated the value S_j and R_j , $j=1, 2, J$, by using the following relations:

$$S_j = \sum_{j=0}^n \frac{p_j(d_j^*-d_j^-)}{d_j^*-d_j^-} ; R_j = \max_j \left[\frac{p_j(d_j^*-d_j^-)}{d_j^*-d_j^-} \right] \quad (3)$$

where p_j is the priority of each criterion expressing their relative importance.

Step 3: Computed the values Q_j , $j=1, 2, \dots, J$ by the relation:

$$Q_j = v \frac{S_i - S^*}{S^- - S^*} + (1-v) \frac{R_i - R^*}{R^- - R^*} \quad (4)$$

where

$$S^* = \min_j S_j ; \quad S^- = \max_j S_j \quad (5)$$

$$R^* = \min_j R_j ; \quad R^- = \max_j R_j \quad (6)$$

The parameter v shows the weights of most of the criteria strategy or the largest group's utility value, this value is fixed between $[0,1]$. If $v > 0.5$ it implies that more importance is given to first term and the performance was evaluated with respect to whole of the criteria. If $v < 0.5$ more weightage is given to second term which is related to worst performances exhibited by

household water treatment technologies with respect to a criterion. In this study $v \approx 0.5$ was considered with a strategy of maximum group utility (Opricovic et al., 2004; Curiel-Esparza et al., 2014)

Step 4: Ranking the household water treatment technologies by the values S , R , Q in decreasing order, resulting in three ranking lists.

Step 5: The compromise solution obtained for household water treatment technologies was ranked by the measure Q (minimum) when the following two conditions were satisfied:

- Acceptable advantage: When $QD(2)-QD(1) \geq \Delta Q$, where $QD(2)$ is the household water treatment technology in second position in rank list as per Q ; $\Delta Q=1/(J-1)$, where J is the number of household water treatment technologies evaluated (Opricovic et al., 2004).
- Acceptable stability: The compromise solution is stable if also it is best ranked by S or by R or by both, as well. This compromise solution is stable within a decision making process, which could be voting by majority rule $v > 0.5$, by consensus $v \approx 0.5$ or with veto $v < 0.5$ (Opricovic et al., 2004).

When any of these conditions are not met, a set of compromise solutions is proposed:

- Household water treatment technologies $D(1)$ and $D(2)$ if only second condition is not satisfied.
- Household water treatment technologies $D(1), D(2), \dots, D(k)$ if only first condition is not satisfied. $D(k)$ is obtained by the relation $QD(k)-QD(1) \approx \Delta Q$ (the positions of these techniques are in closeness) (Opricovic et al., 2004; Curiel-Esparza et al., 2014).

The suitable household water treatment technology was obtained by compromise ranking method. This compromise solution provides a maximum group utility of the majority with measure S representing concordance and R representing disapproval or disagreement.

3 Results and Discussion

In this study six different household water treatment technologies were compared using two MCDM techniques namely AHP and VIKOR.

3.1 Ranking using AHP

The data for comparing household water treatment technology by AHP was obtained from the questionnaire. The consistency of each expert's opinion was checked by Equation 2 and inconsistent opinions were omitted to obtain consistent results by taking geometric mean. These data were used to construct a pairwise comparison matrix which were analyzed using the MATLAB for obtaining the weightages. Figure 2 presents the weightage of each criterion in achieving the goal. High weightage indicates that the particular criterion is more critical in evaluation of the suitable household water treatment technology. As can be seen from Figure 2, efficiency scored the highest followed by reliability and post-contamination in ranking the household water treatment method. Final ranking of the alternatives is highly depended on weights of the criteria as even small changes in the criteria weights can cause significant changes in the ranking. Similarly, alternatives were compared with respect to each other to obtain the priority vector with respect to criterion considered. A pairwise comparison matrix was constructed for alternatives with respect to all criteria (Table 1). The priority vector matrix of alternatives for each criterion was multiplied with criteria weightage to obtain overall score. Figure 3 is a radar plot which depicts the weightage of each household water treatment technique for each criterion. Figure 4(a) presents the ranking of household water treatment technologies obtained by AHP.

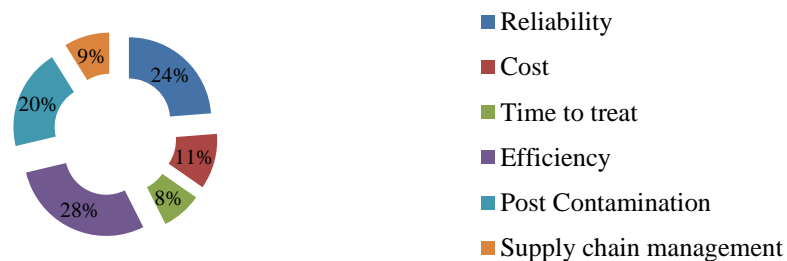


Figure 2 Priority of each criterion to rank the household water treatment technique

Table 1 Matrix of priority vectors of all criteria and overall score

	R	C	TT	E	PC	SCM	Global priority
Boiling	0.29	0.11	0.2	0.24	0.13	0.29	0.2194
Chlorination	0.24	0.22	0.36	0.23	0.51	0.2	0.2973
SODIS	0.1	0.31	0.06	0.09	0.11	0.24	0.1326
Ceramic filter	0.11	0.11	0.14	0.14	0.09	0.09	0.1164
Biosand filter	0.17	0.14	0.12	0.21	0.1	0.12	0.1575
Coagulation + flocculation	0.1	0.12	0.12	0.08	0.06	0.07	0.0883

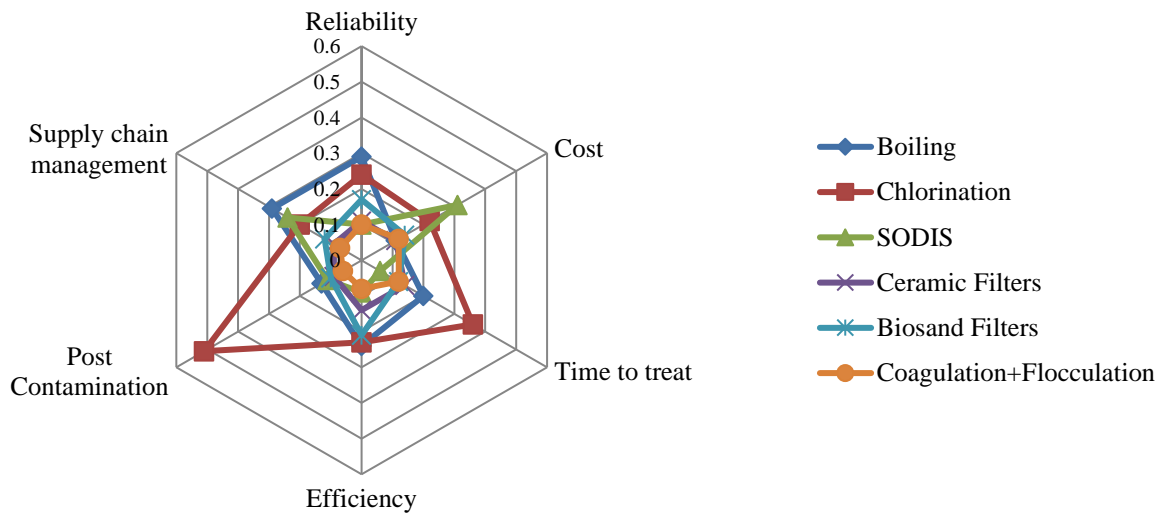


Figure 3 Weights of each household water treatment technique for each criterion.

3.2 Ranking using VIKOR

Using VIKOR the ranking was obtained by compromise method. This compromise solution provides a maximum group utility of the majority with measure S representing concordance and R representing disapproval or disagreement. The analysis shown below was applied for the decision matrix for alternatives with respect to each criterion and criteria weightage. Table 2 shows the VIKOR analysis for the input data of selecting suitable household water treatment technique assuming the value of $\nu=0.5$. Ranking using different parameter such as S_j , R_j and Q_j can be chosen separately, but the advantage of considering Q_j is that it incorporates both S_j and R_j and therefore is more reliable. The analysis by parameters S_j , R_j , Q_j indicates that lower the value of these constants, more suitable is the household water treatment technology. As shown in Table 2, chlorination is the best ranked by Q and also satisfies both the conditions, and it is followed by boiling and biosand filters. The ranking by VIKOR is shown in Figure 4(b).

Table 2 Analysis of HWT using VIKOR. S_j , R_j , Q_j values ($\nu=0.5$) for each household water treatment technology

HWT technique	S_j	Rank as per S_j	R_j	Rank as per R_j	Q_j	Rank as per Q_j
Boiling	0.2116	2	0.1689	2	0.2590	2
Chlorination	0.1786	1	0.0605	1	0.0000	1
SODIS	0.9001	6	0.2719	5	0.9606	5
Ceramic filters	0.7358	4	0.2274	4	0.7497	4
Biosand filters	0.5382	3	0.1822	3	0.5144	3
Coagulation+Flocculation	0.8895	5	0.2900	6	0.9927	6
S^*/R^*	0.1786		0.0605			
S^-/R^-	0.9001		0.2900			

- i. Q (Boiling)- Q (Chlorination) = 0.2590 > $[1/(6-1) = 0.2]$; Acceptable advantage.
- ii. Chlorination is best ranked by S and R . Acceptable stability.

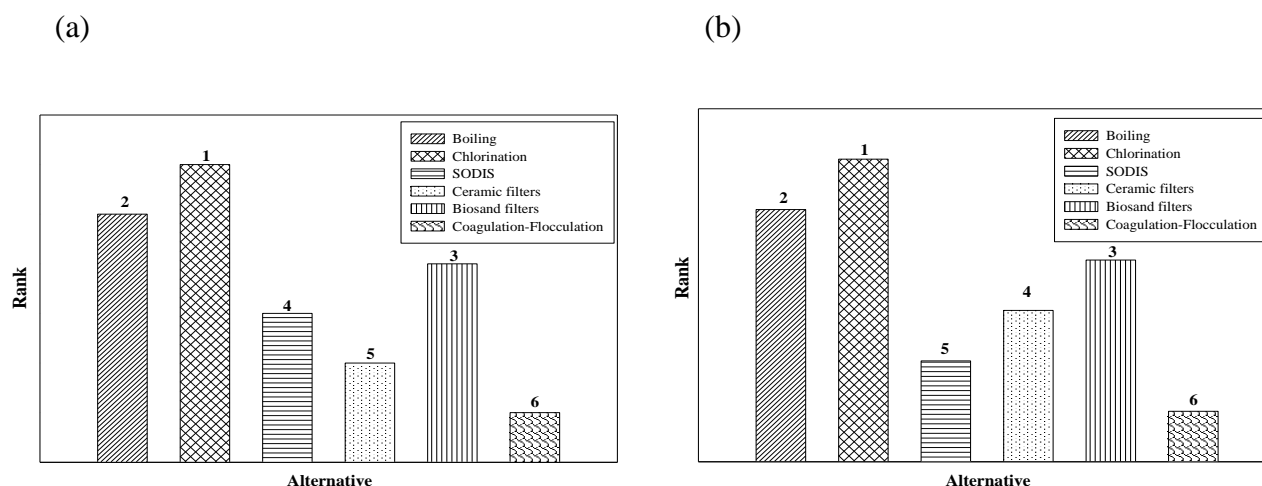


Figure 4 Ranking of household water treatment technologies as per (a) AHP (b) VIKOR

A comparison of ranking by the two MCDM techniques shows that both AHP and VIKOR gave chlorination as the best method followed by boiling and biosand filter (Figure 4). Chlorination showed high weightages with respect to all criteria except supply chain management. Chlorination got very high weightages with respect to the criteria post-contamination and time to treat (Figure 3). It is known that chlorination can take care the post-contamination of treated water due to the residual available after treatment. It may be noted that post-contamination had the third highest weightage among the six criteria considered in this study (Figure 2). The second ranked method boiling scored high on reliability and supply chain management while it scored low on the cost criteria. In both the MCDM techniques, coagulation + flocculation ranked the lowest as it scored low in all criteria. It may be noted that Sobsey et al. (2008) based on a literature review compared five widely used household treatment methods such as solar disinfection, biosand filter, ceramic filter, chlorination, and combined coagulant-chlorination and ranked biosand filter as the best treatment technology. Their evaluation was based on sustainability criteria such as treatment robustness, ease of process use and cost to treat. In an another study by Pagsuyoin et al. (2015) using the MCDM technique TOPSIS found coagulation/flocculation with natural coagulant *Moringa* as the highest ranked method among the six alternatives considered in a site specific study in a rural area of Philippines. This was primarily because of the local availability of the coagulants. The present study utilised opinion of 18 experts working on/familiar with household treatment technology, and the results are contradictory to those obtained by Pagsuyoin et al. (2015). This shows that the ranking is scenario based depending on the site conditions.

4. Conclusions

In this study, two different MCDM techniques namely AHP and VIKOR were used to rank six alternative household treatment methods such as solar disinfection, boiling, biosand filter, ceramic filter, solar disinfection, chlorination and coagulation based on six sustainability criteria. Among the six criteria, reliability and efficiency had the highest weightages. Both the MCDM methods gave chlorination as the best household water treatment technique. This study shows that AHP and VIKOR systems are reliable methods in selecting a suitable and sustainable household water treatment technology. This methodology can be extended to a scenario based approach which is more site-specific.

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