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A group decision-making tool for the application of membrane technologies in different water reuse scenarios

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ABSTRACT

A global challenge of increasing concern is diminishing fresh water resources. A growing practice in many communities to supplement diminishing fresh water availability has been the reuse of water. Novel methods of treating polluted waters, such as membrane assisted technologies, have recently been developed and successfully implemented in many places. Given the diversity of membrane assisted technologies available, the current challenge is how to select a reliable alternative among numerous technologies for appropriate water reuse. In this research, a fuzzy logic based multi-criteria, group decision making tool has been developed. This tool has been employed in the selection of appropriate membrane treatment technologies for several non-potable and potable reuse scenarios. Robust criteria, covering technical, environmental, economic and socio-cultural aspects, were selected, while 10 different membrane assisted technologies were assessed in the tool. The results show this approach capable of facilitating systematic and rigorous analysis in the comparison and selection of membrane assisted technologies for advanced wastewater treatment and reuse.

1. Introduction

Fresh water scarcity is due to many interrelated factors and is a growing concern in different parts of the world. To meet increasing water demand and water quality standards, a diversity of water treatment technologies have been employed. Among these are membrane assisted technologies, which have been employed and proven to be suitable and reliable in different urban water reuse scenarios (Shannon et al., 2008). These technologies enable the production of high quality recycled water at reasonable costs and notably small energy input (Rodriguez et al., 2009). One challenge has been how to select an appropriate membrane technology for a

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Abbreviations: AnMBR, anaerobic membrane bio-reactor; CAS, conventional activated sludge; CASP, conventional activated sludge process; CC bar chart, criteria contribution bar chart; CCi, closeness coefficient; CDPH, California Department of Public Health; CDPH-DW, California Regulations Related to Drinking Water; CDPH-RW, California Department of Public Health-Regulations Related to Recycled Water; CEPT, chemically enhanced primary treatment; Cj, criterion; DPWR, direct potable water reuse; EDCs, endocrine disruptive compounds; FCi, farness coefficient; FNIS, fuzzy negative-ideal solution; FPIS, fuzzy positive-ideal solution; iMBR, immersed membrane bio-reactor; IPWR, indirect potable water reuse; MBR, membrane bio-reactor; MCA, multi-criteria analysis; MCMEDM, multi-criteria multi-expert decision making; MF/UF, microfiltration/ultrafiltration; MLSS, mixed liquor suspended solids; NF/RO, nanofiltration/reverse osmosis; NPWR, non potable water reuse; NRC, National Research Council; O&M, operation and maintenance; PhACs, pharmaceuticals active compounds; RO, reverse osmosis; Si, scenario; SOR, surface overflow rate; STP, sewage treatment plant; Ti, technology; TMF, tertiary membrane filtration; TOC, total organic carbon; TOPSIS, technique for order performance by similarity to ideal solution; UV, ultraviolet; WHO, World Health Organization; WHO-AWR, WHO Microbiological Guidelines for Treated Water Reuse in Agriculture; WHO-DWQ, WHO Guidelines for Drinking Water Quality; WRA, water reuse application; WWTP, wastewater treatment plant.

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specific water reuse scenario. The plethora of membrane technologies often increases the complexity of decision making (Sadr et al., 2013). In addition, understanding the implementation of water reuse in different scenarios requires decision making tools that incorporate existing and emerging knowledge regarding novel process developments in order to achieve sustainable water reuse. Since most decision making methods, e.g. multi-criteria analysis (MCA), strive to model human reasoning, and to subsequently incorporate modelled results into procedures, the approach proposed in this paper would attempt to capture the vagueness and imprecision of information using linguistic variables (Anagnostopoulos et al., 2008). Another challenge is how to incorporate diverse opinions from stakeholders in decision making. Kalbar et al. (2013) developed a wastewater treatment technology selection approach that integrates expert opinions by a scenario-based group decision-making process. This group decision-making (GDM) approach was based on an analytical hierarchy process (AHP). Another promising method developed to obtain rankings from engineering experts is the Multi-Criteria Multi-Expert Decision Making (MCMEDM) within a fuzzy environment (Chen, 2000; Dheena and Mohanraj, 2011).

Fuzzy logic can be used to model uncertainty, imprecision, and qualitative information (Bellman and Zadeh, 1970; Chen and Klein, 1997). In addition, Fuzzy sets provide the flexibility required to represent and handle the uncertainty and imprecision which results from lack of knowledge and ill-defined information (Yeh and Deng, 2004; Dheena and Mohanraj, 2011). Over the last decade, several studies applied fuzzy logic theory to overcome uncertainty and subjectivity in multi-criteria decision making (Yeh and Deng, 2004; Dheena and Mohanraj, 2011). Li (1999) developed a model to overcome the problem of multi-judges and multi-criteria decision making where the performance of alternatives and the importance of criteria are imprecisely defined and represented by fuzzy sets. In conclusion, Li (1999) suggested a level weighted fuzzy relation for comparing and ranking sets of criteria and alternatives. This method provides a precise solution for a defuzzified process since the problem is solved analytically.

Another technique for group decision making makes use of the ideal and anti-ideal points to find the most preferred alternatives. In this technique, the best alternative is the one with the shortest distance from the positive ideal point and the longest distance from the negative ideal point simultaneously (Anagnostopoulos et al., 2008; Chen and Tzeng, 2004; Kuo et al., 2007; Dheena and Mohanraj, 2011). The ideal point can be described as a point in which all the best criteria values are attainable, whereas the anti-ideal point consists of all the worst criteria values attainable. Therefore, if normalization is considered in a triangular fuzzy environment, the ideal and anti-ideal points would be (1, 1, 1) and (0, 0, 0) respectively. Chen (2000), (2001) developed two of such models in order to solve a group decision making problem. In another study, an extension of the method proposed by Chen (2000) was applied for facility location selection (Ertuğrul, 2011). Ertuğrul (2011) stated that fuzzy numbers were effective in resolving the ambiguity of concepts that are associated with human judgments. In these studies, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) was applied and the vertex method was employed to calculate the distance between two triangular fuzzy numbers to find the best alternative.

The above studies show that Multi-Criteria Multi-Expert Decision Making (MCMEDM), within a fuzzy environment and while employing the TOPSIS and vertex methods, is capable of handling the challenges of group decision making in water reuse applications. Therefore, the aim of this research was to develop a fuzzy logic based multi-criteria group decision making tool for the selection of membrane treatment technologies in four different water reuse scenarios. Robust criteria covering technical, environmental, economic and socio-cultural aspects were selected in order to assess and rank the different technologies.

2. Methodology

Water treatment technology selection for a specific urban setting is challenging due to the diversity of existing treatment technologies (Sadr et al., 2013) and the vast amounts and complexity of information available on these technologies. A methodical assessment of alternatives is therefore essential to amplify the chances of success. Multi-Criteria Analysis (MCA) is a decision making tool which can be used in the systematic appraisal of wastewater reuse technologies (Sadr et al., 2014). Different MCA methods have been applied in various studies (e.g. Akash et al., 1997; De Marchi et al., 2000; Katukiza et al., 2010). This paper takes MCA a step further by developing and applying a tool to aid decision making among a group of experts and decision makers. Therefore, in this paper, a fuzzy logic based multi-criteria group decision making tool is proposed to facilitate the selection of the best membrane assisted treatment technologies for different water reuse scenarios. The schematic of the methodology employed herein is presented in Fig. 1.

2.1. Development of a decision making tool for water reuse scenarios using fuzzy set theory

In the developed tool, decision making by multi-criteria analysis in a complex environment such as water reuse technology selection consists of a set of scenarios $S = \{S_1, S_2, \ldots, S_l\}$, technologies $T_i = \{T_1, T_2, \ldots, T_m\}$, and a set of criteria $C_j = \{C_1, C_2, \ldots, C_n\}$. Rating ($\tilde{x}_{ij}$) of the technologies ($Ti$) with fuzzy numbers with respect to each criterion (C_j) should be applied where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. The multi-criteria problem is expressed in a decision matrix $\tilde{D}$ as follows (Chen, 2000):

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \tag{1}$$

where $\tilde{D}$ is the evaluation matrix with m rows (representing technogies) and n coloumns (representing criteria). The weight ($\tilde{w}_n$) of each criterion is represented by a weighting vector:

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n] \tag{2}$$

where all the elements in the matrix are fuzzy numbers. In this research, triangular fuzzy numbers are used for the criteria weights in order to make computations simpler. The membership function of a triangular fuzzy number, which can be defined as a generalization of the indicator functions in classical sets, has the form presented in Equation (3) (Kaufmann and Gupta, 1985).

$$\tilde{\mu}(x) = \begin{cases} 0 & for\ x < n_1 \\ \dfrac{x - n_1}{n_2 - n_1} & for\ n_1 \le x < n_2 \\ \dfrac{n_3 - x}{n_3 - n_2} & for\ n_2 \le x < n_3 \\ 0 & for\ x > n_3 \end{cases} \tag{3}$$

where n_1, n_2, and n_3 are real numbers that can develop a fuzzy triplet (n_1, n_2, n_3). In a more practical view, the fuzzy set comprising the membership function ($\tilde{\mu}(x)$), the rating of technologies ($\tilde{x}_{ij}$) and