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MULTI-OBJECTIVE ANALYSIS FOR THE SELECTION OF A SUSTAINABLE GREYWATER TREATMENT SYSTEM

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Abstract

Greywater reuse is widely accepted as a suitable response to the increasing demand of fresh water in urban areas. On the other hand, strict environmental regulations have obligated the development and implementation of membrane separation technologies for production of municipal potable water, in industrial water supply and in wastewater treatment. Potential energy crisis in the future has highlighted the importance of using renewable source of energy for membrane separation processes. This research aims to compare three solar powered greywater treatment systems and select the most sustainable option based on the environmental, economic and social criteria. The selected systems are cost effective, have satisfactory quality of permeate water, consume minimum or no chemical additives and use solar energy. The three solar greywater treatment systems examined in this study are categorized into physical (vacuum membrane distillation), physico-chemical (electro-coagulation and ultra-filtration) and biological (membrane bioreactor) processes. The multi-criteria decision analysis (MCDA) technique is incorporated to identify the most sustainable technology option. Specifically, an analytic hierarchy process (AHP) is optimized to evaluate the treatment systems against the three sustainability pillars. Twelve sustainability indicators under the three major criteria have been incorporated in AHP for pairwise comparison. According to the analysis performed, the physical process of solar powered vacuum membrane distillation (SVMD) was selected as the most sustainable technology option for greywater treatment. The SVMD system uses both the electrical and thermal energy of solar power and has the ability to produce high quality permeate water within the acceptable standard for potable use.

Keywords: analytic hierarchy process, greywater treatment, solar energy, sustainability pillars

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1. Introduction

Significant stress is exerted on available water and energy sources by a variety of industrial and agricultural activities, population growth, urbanization and affluence together with the effects of climate change. Water and energy scarcity throughout the world is leading to substantial effort to design sustainable water and wastewater treatment systems. Household greywater recycling is now accepted as a supplementary water supply option for urban areas. Greywater reuse as an alternative source not only reduces the massive volume of water consumption in urban areas, but also decreases the rate of wastewater production. The water situation in many countries is reaching critical levels and the challenge is how to find sustainable alternative sources while significant efforts are being made to decrease per capita household water consumption. In central, western and southern arid regions of Australia, lack of finding alternative water sources may cause significant negative effects on one's health and the environment. Several researches illustrated the role of brackish and grey water reuse in a sustainable manner (Al-Zouby et al., 2017; Friedler and Hadari, 2006, Paris and Schlapp, 2010). A typical Australian urban household produces 280 L/day of grey water that has the potential for recycling at the source. About 50% of all the

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wastewater generated within a household can be reused depending on the permeate quality. Also, the Australian guideline for grey water non-potable reuse requires the treated water quality of BOD_5 < 20 mg/L, TSS < 30 mg/L and Faecal coliform count < 10 cfu/100mL (EPA, 2013). A variety of physical, chemical and biological treatment systems have been proposed for greywater treatment and reuse. Depending on the quality of the treated water, they can be reused for toilet flushing, gardening, washing and possibly drinking. Since, greywater includes a variety of contaminations from different sources, single physical, chemical or biological process may not be adequate to perform an efficient treatment. Investigation of the strengths and shortcomings of the available treatment technologies is necessary for comparative analysis. One of the earliest known physical processes for greywater recycling was a coarse filtration developed by Hypes et al. (1975). This, however, had a number of disadvantages, including the necessity of chemical usage for higher quality of the permeate, low product water quality and long payback time (March et al., 2004). These disadvantages are partly due to the physical processes alone that are not adequate for reducing organics, nutrients and surfactants to acceptable levels in the treated water (Li et al., 2009). The only proven physical technologies that can remove the required amounts of impurities are reverse osmosis (RO) and distillation processes, which requires high pressure feed-flow and an appropriate evaporation and condensation technique, respectively (Gryta et al., 2006; Into et al., 2004; Onkal Engin et al., 2011). The evaporation and condensation technique eliminates suspended particles and dissolved impurities in a distillation process that mimics what occurs in nature within a water cycle. In this way, if heat and electrical energy can be provided by a renewable source to enhance evaporation, it not only improves the sustainability but also will reduce the costs of such a system.

In recent years, greywater treatment systems tend to combine biological or chemical processes with membrane filtration to achieve a high quality effluent. Chemical processes such as coagulation, photo catalytic oxidation or advanced oxidation are more suitable for removing turbidity and organic matter from raw water (Pidou et al., 2008). Efficient disinfection can also be achieved via the use of a suitable chemical process such as chlorine or by means of UV (Chin, 2009; Winward et al., 2008). The one major drawback, however, is the high capital cost of such a system. Physico-chemical systems, including a combination of filtration coupled with chemical coagulation and disinfection, produce high quality water with no susceptibility to chemical shocks (Pidou et al., 2008). These systems are easy to scale up, however high costs and chemical consumption are required for operation (Sostar-Turk et al., 2005). Hence, one alternative for greywater treatment is electro-coagulation (EC) followed by filtration. The rate of chemical consumption in the EC process is much less than what occurs in conventional coagulation methods (Emamjomeh and Sivakumar, 2009). The EC process also requires lower maintenance than technologies using chemicals directly. Further, the electro-coagulator is reliable and can be powered by solar energy.

A variety of biological processes, such as the rotating biological contactor, the membrane bioreactor (MBR) and the biological aerated filter are being used for greywater treatment (Friedler et al., 2005; Hernandez Leal et al., 2008; Merz et al., 2007; Paris and Schlapp, 2010). The combination of physical and biological treatment system such as MBR is currently being preferred due to its small footprint, reliability and high quality of final product. The reviewed biological treatment systems show that BOD and COD reduction were excellent in MBR and RBC systems as well as TSS removal. However, the low strength of greywater and shock loading are the two major problems. These systems are easy to scale up and they produce high quality effluent. MBR appears to be an appropriate solution for medium and high strength greywater recycling (Friedler and Hadari, 2006; Lesjean and Gnirss, 2006; Surendran and Wheatley; 1998). The application of renewable energy is essential in order to convert them into a green technology.

According to the reviewed studies, three innovative solar-powered greywater treatment systems have been selected for evaluation in this research. The physical process based treatment system, a solar vacuum membrane distillation (SVMD), is chosen as the best thermally driven separation technique. The physico-chemical treatment system is a solar electro-coagulation and ultrafiltration (SECUF) technology. The biological system, a solar membrane bioreactor (SMBR), is a combination of a bioreactor with a membrane, such as microfiltration (MF) or ultrafiltration (UF).

Many comparative studies focused only on the cost of the systems and ignored other important social and environmental dimensions (Banat and Jwaied, 2008; Dharmappa and Hagare, 1999; Friedler and Hadari, 2006; Mohsen and Akash, 1997; Owen et al., 1995). A sustainable system can be nominated through a comparative study that must include qualitative and quantitative criteria based on environmental, social and technical pillars. Realistic determination of qualitative and quantitative criteria has to be performed through a process involving a relative scale of the criteria and alternative comparison judgments. A systematic and analytic model is employed for decision makers to solve various complicated problems and nominate the best alternative (Garfi et al., 2009). Decision makers are the experts in the area in which the analysis was performed. In this research, the attitudes of academics in the water treatment section were considered for the judgment. Among the six multi-criteria decision analysis (MCDA) methods available, the analytic hierarchy process (AHP) was represented as one of the most widely applied pairwise comparison methods (Hajkowicz and Collins, 2007).

AHP establishes a weighting system for alternatives, and presents the results of the analysis with numerical units in order to sequence the relative importance between criteria (Huang et al., 2011). The AHP is applicable in several areas, such as logistics, manufacturing, government, education and water management (Delgado-Galván et al., 2010; Herath and Prato, 2006). The application of AHP was also incorporated with a simulation-based cost model by Lai et al. (2008). Economic evaluation was established in their study for public building construction projects through a questionnaire survey. The successful application of AHP was shown via incorporating first level and second level criteria. Totally 20 indicators were described and incorporated for this analysis. Delgado-Galván et al. (2010) studied the water leakage management for two alternatives of active and passive control leakage through AHP. Besides the cost factors in economic area, three more parameters associated with the level of leakage and developments of management alternatives were considered. It has been shown that AHP can be applied satisfactorily in water management problems via considering the social and environmental evaluation costs. However, only four parameters: damage to properties, planning development cost, restricted streets and supply disruptions had been evaluated. In the study conducted by Zhang et al. (2014), system dynamics was incorporated with AHP to establish an evaluation system for water ecological carrying capacity. The importance of each factor was determined by this combination as too many economic and environmental criteria were considered.

AHP is an appropriate method in comparative judgment of water treatment alternatives. The most sustainable greywater treatment system was selected through an optimized version of AHP (OAHP) along with an evaluation of environmental, economic and social criteria. A critical review of greywater treatment systems established a comprehensive data base for selected criteria. Consequently, weighting was performed simply for both qualitative and quantitative criteria. A numeral approach was adopted to convert qualitative criteria into quantitative scales. Finally, the three greywater treatment system alternatives (SVMD, SECUF and SMBR), criteria and indicators were assessed and the most sustainable option was nominated.

2. Solar powered greywater treatment systems

In order to compare the three selected greywater treatment processes, similar equipment such as reservoir, pump and PV panel and equivalent operational parameters are set, so economic indicators can be readily estimated. Similar design parameters were considered for the selected greywater treatment alternatives to perform the pairwise comparison. A greywater flow-rate of 280 L/d for a typical Australian household and the availability of solar energy for 5 hours per day were assumed. Available data from different greywater treatment systems are incorporated to identify the specific range for each indicator. Accordingly, the selected information is not limited to the proposed three technologies. A review of the literature assisted in the determination of specific values for environmental and social indicators. Decisions were made based on the reviewed studies for those indicators without sufficient data.

2.1. Solar vacuum membrane distillation (SVMD)

Membrane distillation is essentially a thermally driven separation process, however in a vacuum membrane distillation (VMD) system, greywater in contact with the feed side of the hydrophobic membrane is vaporized and is subsequently condensed back into a liquid state on the permeate side. Greywater is heated up by passing through a solar collector panel, while PV panels provide electrical energy to the pumps.

A hydrophobic membrane usually designed for the removal of volatile organic compounds, bacteria and viruses acts as a barrier between the aqueous and gas phases (Khayet, 2011). A vacuum pump is used to create a lower pressure than saturation pressure of greywater at a given temperature through the condenser at the permeate side of the membrane. The tension force of the hydrophobic membrane surface prevents liquid solutions from entering the pores while the vacuum pump creates a negative pressure on the permeate side. Greywater is also warmed up at the beginning by passing through a condenser to convert vapor to the liquid phase as shown schematically in Fig. 1.

VMD in comparison with conventional separation techniques has the advantage of operating at relatively low evaporation temperatures typically below 60 °C, and low cost energy source requirement to supply heat (Banat et al., 2003). VMD requires 1.2 kWh/m^3 whereas RO requires 2.4 kWh/m^3 to achieve the same flux in terms of energy (Cabassud and Wirth, 2003). Furthermore, it was shown that VMD performance was more economically viable than direct contact membrane distillation (DCMD) in terms of energy consumption, flux and evaporation efficiency (Criscuoli et al., 2008). A higher flux rate of 56.2 kg/m^2h via a lab-made membrane module was achieved at 59.2°C of feed temperature using a permeate side absolute pressure of 1 kPa. Similarly, heat and mass transfer in the VMD system was studied by Mengual et al. (2004) to investigate the effect of temperature and velocity on the flux rate. A shell-and-tube capillary membrane module with pore size of 0.2 μm and an effective area of 0.1 m^2 was used with pure water under absolute pressure of 4 kPa. It was concluded that an increase in feed velocity can raise the flux and heat transfer coefficient.

In brief, an SVMD system has less investment cost and requires a smaller installation area, but the operation and maintenance costs are reasonably high in comparison with a conventional solar still (Wang et al., 2009).

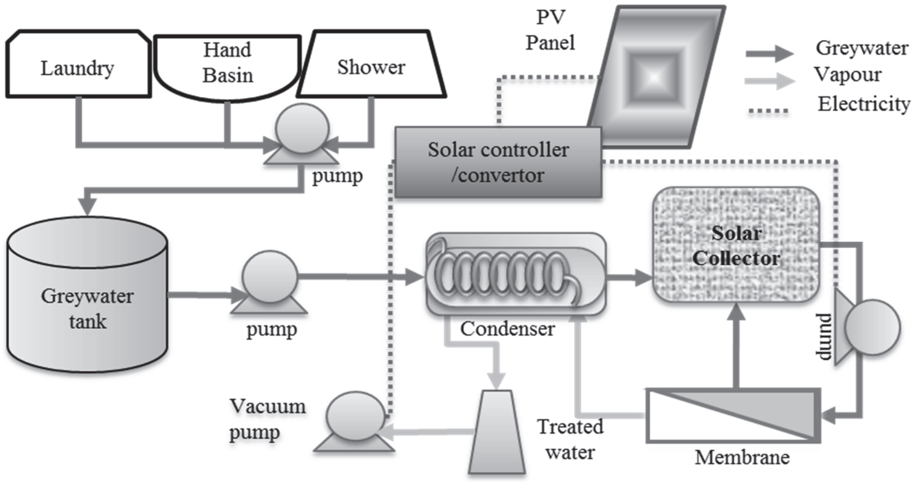


Fig. 1. Solar powered vacuum membrane distillation system

The significant advantage of VMD was reported by Sivakumar et al. (2013). A VMD system was used to treat sea water, mine water, groundwater as well as greywater. Water quality parameters such as TDS, BOD, total coliforms and concentration of Ca, Mg, Fe and Al were reduced from 36,850 mg/L, 285 mg/L, 1,230 cfu/100mL, 14.4 mg/L, 338 mg/L, 0.32 mg/L and 0.18 mg/L in the influent to 2.12 mg/L, 0.00 mg/L, 0.00 cfu/100mL, 0.73 mg/L, 0.48 mg/L, 0.00 mg/L and 0.00 mg/L, respectively in the effluent.

The set-up cost for an SVMD system of a typical Australian household, including solar panels, collectors, reservoirs, pumps, membranes, condenser and pipes has been estimated at $4,235 AUD (retail cost) while ongoing costs, such as membrane replacement, sludge collection and disposal and similar operation and maintenance are estimated at $545 AUD/y within a ten year period. A small cost saving of $217 AUD/y can be obtained since high quality treated effluent can potentially be used for all household purposes including drinking, by replacing the current low cost town water. SVMD requires a relatively low level of membrane cleaning as the rate of flux decline in the SVMD is lower than in SECUF and SMBR. A screening unit is necessary as a pre-treatment in order to increase the efficiency of the process. One of the disadvantages of the SVMD system is the fact that it poses a health risk since the temperature of the feed solution may exceed 60°C and this can cause burns if a leak occurs. Low acceptability among householders is expected due to its low flux rate. Also, a high level of knowledge and technology is assumed since knowledge of membrane and condensation is required. The application of vacuum pressure for vaporization makes the SVMD system technologically complex.

2.2. Solar electro-coagulation and ultra filtration (SECUF)

Coagulation followed by suitable filtration is a well-established water treatment process since it improves effluent quality as well as reducing the rate of fouling in membranes. Therefore, a combination of electro-coagulation, membrane filtration and electro-disinfection operated by solar energy is chosen as the second alternative. Since chemicals are not involved, it requires low maintenance and can be powered by solar energy. Parameters such as the type of electrodes, conductivity of the influent, distance between electrodes, shape and size of an electrode, temperature and flow configuration have to be determined in the design of an electro-coagulator unit. Greywater is first pumped at a given flow-rate through the electro-coagulator. Aluminum electrodes and mono-polar parallel configuration in the EC increases filtration efficiency. A second high pressure pump is used to pass the effluent through a UF membrane as shown in Fig. 2. Finally, electro-disinfection is employed to achieve a high quality permeate.

Coagulation prior to membrane filtration was used to improve the quality of the treated water and also to decrease membrane fouling (Li et al., 2009). The application of EC in wastewater treatment and the effect of significant parameters such as the type of electrodes, conductivity, temperature, shape and size of the electrodes and flow configuration were studied, and it was concluded that upflow configuration of an electro-coagulator followed by electro-flotation provided the better quality of effluent (Mollah et al., 2004). The EC technology is potentially an effective process in dye removal depending on the pH level (Emamjomeh and Sivakumar, 2009).

In this regard, the experimental results showed that aluminum electrodes are more efficient than iron electrodes, and the technology successfully removed heavy metals and nitrate. The evaluation of EC performance in surface water treatment was studied, and it was shown that the EC is more efficient than chemical coagulation in terms of the permeate quality (Bagga et al., 2008). Muller (2008) constructed a new treatment system applying EC, ultrafiltration and electro-disinfection. Clean water flux of 82 L/m2h was pumped at 100 kPa pressure of filtration.

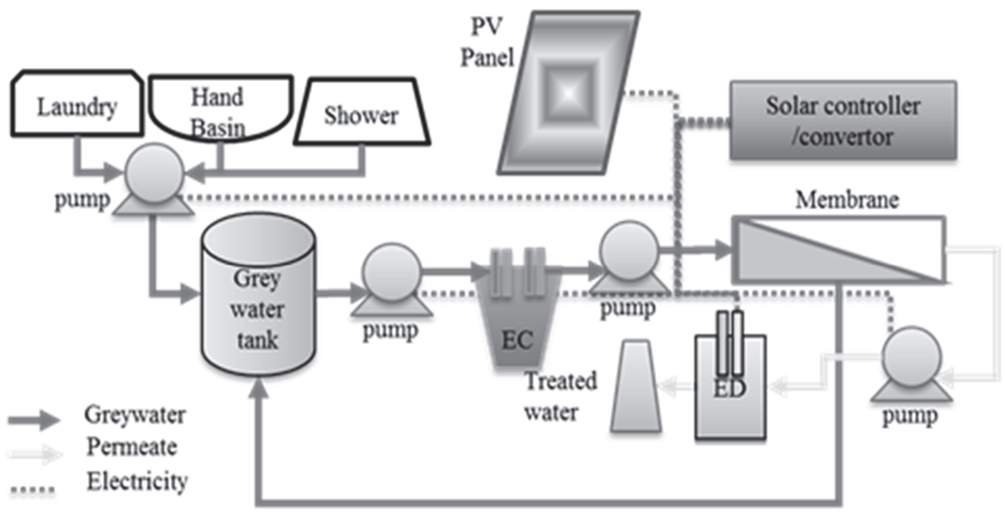


Fig. 2. Solar powered electro-coagulation, membrane and electro-disinfection system

The levels of turbidity, COD, BOD, TSS, TDS and *E.Coli* were reduced from 81 NTU, 282.5 mg/L, 110.12 mg/L, 84 mg/L, 218 mg/L and 4*103 cfu/100mL in greywater to 0.64 NTU, 92 mg/L, 6.82 mg/L, 4 mg/L, 190 mg/L and 800 cfu/100mL in the effluent, respectively.

The set-up cost of a typical SECUF system, including solar panels, reservoirs, pumps, membranes, electro-coagulator and pipes is estimated at $3,740 AUD while the costs of membrane and plate replacement, sludge collection and disposal and similar operation and maintenance are predicted at $790 AUD/y for ten years. By reusing the treated water within the household, a cost saving of $175 AUD/y is possible. The frequency of membrane cleaning is considered moderate in comparison to treatment technologies due to the pre-treatment provided by EC. The quantity of waste to be disposed of from the coagulator and membrane cleaning is relatively moderate. A screening unit and an electro disinfection unit are required as a pre-treatment and post-treatment, respectively. It is envisaged that only low level of knowledge is required to operate this system, however there is a moderate level of risk to health and safety due to the use of the EC process. In addition, there can be some questions of public acceptance of SECUF systems as they potentially require relatively large areas for installation of the treatment units. The system is also comprised of coagulator, filtration and disinfection units and this also makes it a moderately complex system.

2.3. Solar membrane bioreactor (SMBR)

One of the successful technologies for greywater treatment is MBR due to its ability to produce a high quality effluent. The proposed SMBR system using a submerged membrane is presented in Fig. 3. In addition, MBR, as a biological process, has a relatively small footprint and simple operation with minimal chemical consumption. Less energy is required in submerged MBRs than in side stream ones where the membrane is immersed within the bioreactor, and the filtered water is withdrawn via a vacuum pump (Laine, 2001). Greywater is aerated in the bioreactor using a compressor. The feed solution is passed through the submerged membrane module by a vacuum pump into a permeate trap.

Paris and Schlapp (2010) were successful in using MBR with submerged UF modules for greywater treatment. A 92.2% and 97.2% removal of COD and BOD was reported, respectively. Total coliforms level met the Australian NSW guidelines for toilet flushing, laundry washing and irrigation. Four biological processes for greywater treatment were analyzed ant it was found that the submerged MBR and side-stream MBR achieved excellent BOD removal along with high quality effluent (Laine, 2001). In a study conducted by Merz et al. (2007) a submerged ZeeWeed MBR system was operated to treat low strength greywater. The levels of turbidity, BOD, COD, faecal coliforms, total nitrogen and phosphorous were decreased from 29 NTU, 59 mg/L, 109 mg/L, 1.4×105 cfu/100 mL, 15.2 mg/L and 1.6 mg/L to 0.5 NTU, 1.5 mg/L, 1.15 mg/L, 68 cfu/100mL, 5.7 mg/L and 1.3 mg/L, respectively.

Also, Lesjean and Gnirss (2006) used a submerged plate and a frame MBR treatment unit to treat kitchen greywater. The SS, COD, TN and TP were reduced from 90 mg/L, 493 mg/L, 21 mg/L and 7.4 mg/L in the influent to 1 mg/L, 24 mg/L, 10 mg/L and 3.5 mg/L in the effluent, respectively. A good performance was obtained under low hydraulic resistance time (HRT) and solids resistance time (SRT) by the proposed system.

Similarly, using eight submerged hollow fiber membrane modules (Mitsubishi Rayon Co.) in a bioreactor for greywater treatment resulted in turbidity, SS, BOD and COD reduction from 146-185 NTU, 15-50 mg/L, 99-212 mg/L, 130-322 mg/L to 1 NTU, 0 mg/L, 5 mg/L and 40 mg/L, respectively (Liu et al., 2005).

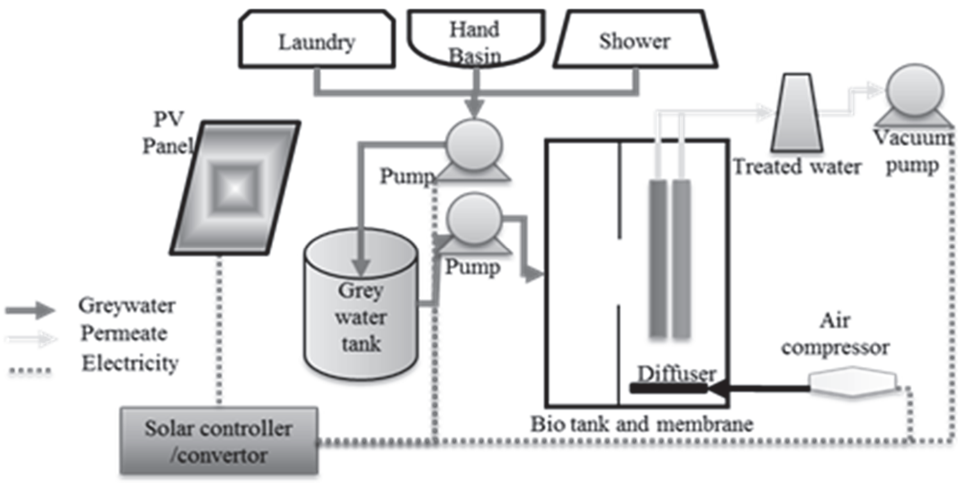


Fig. 3. Solar powered membrane bioreactor system

The treatment of higher strength greywater via a flat plate submerged MBR system was operated for 87 days at a constant flux of 0.22 m^3/m^2d at a mean HRT of 13.6 h and the COD level was reduced from 675 mg/L in the raw water to 26.3 mg/L in the permeate (Huelgas and Funamizu, 2010).

Parameters such as temperature, SRT, HRT, trans membrane pressures (TMP), flux and aeration rate will determine the operating conditions of this system. The two major problems are membrane fouling and long HRT. The MBR set-up costs, including solar panels, reservoirs, pumps, membranes, diffuser and pipes are estimated at $3,610 AUD while the ongoing costs for membrane replacement, sludge collection and disposal and similar operation and maintenance are predicted at $575 AUD/y for ten years.

A small cost saving of $175 AUD/y is achievable if the treated water can be reused within the households. The high level of membrane cleaning is required due to the fouling rate in this process. A screening and a disinfection unit are required to increase the efficiency of the treatment system. The quantity of waste disposal is assumed to be high in this technology. People are likely to accept it due to its high flux rate. Also, it is a simple process to operate and there is low level of risk to health and safety due to the low temperature of the feed solution. A moderate level of knowledge and technology is necessary to use this system.

2.4. Environmental, economic and social comparison

Table 1 presents information for the proposed three treatment options based on various environmental, economic and social indicators. The levels of BOD, turbidity, TSS, TDS and total coliforms in the effluent are considered as suitable environmental quality indicators.

The level of turbidity, TSS, BOD_5 and fecal coliform counts of treated water should be less than 2 NTU, 5 mg/L, 10 mg/L and 2.2 cfu/100mL, respectively for unrestricted non-potable urban water reuse (Meays and Nordin, 2013). These values tolerated for outdoor gardening purposes are 5 NTU, 45 mg/L, 10 mg/L and 10 cfu/100mL for turbidity, TSS, BOD_5 and fecal coliforms, respectively (Al-Jayyousi 2003). For restricted urban water reuse such as outdoor washing and toilet flushing, the turbidity, TSS, BOD5 and fecal coliform counts of treated water should be less than 5 NTU, 20 mg/L, 6 mg/L and 3 cfu/100mL, respectively (Ernst et al., 2007).

In order to align the five quality parameters, first the value of log removal was converted to percentage, and then the average of all parameters was calculated. A factor of two for total coliforms parameter was employed due to its importance among the selected ones. The level of fouling and cleaning requirement is selected as the second environmental criterion.

The indicator "pre-treatment and post-treatment" reflects the number of treatment processes required before or after treatment, such as screening, mineralization and disinfection. Also, the quantity of waste disposal ("solid/brine treatment") is specified for each treatment alternative. Capital costs are estimated in Australian dollars and maintenance costs and cost savings in Australian dollars per year. The estimated solar energy consumption of each system is given in kWh/m^3. Social indicators are also evaluated.

The abbreviations for levels used in Table 1 are employed to compare indicators such as: fouling and cleaning requirements, solid/brine treatment, public acceptance, simplicity, knowledge and technology and the level of risk to health and safety.

3. Methodology

The analytic hierarchy process (AHP) is a mathematical technique for multi-criteria decision making (Saaty, 1990). It enables designers to make decisions about complex problems based on principles, benefits, the best alternatives and resources.

Table 1. Comparison of major criteria and indicators of the proposed treatment systems

Criterion	***Indicator***		***Unit***		***Systems◊***					
					SVMD†		***SECUF‡***		***SMBR♦***	
Environmental	Quality of effluent	BOD	mg/L	% removal	0	100	10	94.9	1	99.3
		Turbidity	NTU	% removal	0.1	99	5.23	95.3	0.2	99.3
		TSS	mg/L	% removal	2	99	10.5	90.3	1.5	96.1
		TDS	mg/L	% removal	2.12	99.9	363	3.46	782	19.5
		Total	CFU/100	Log	0	7	800	4.18	68	5.9
	Fouling and cleaning		-		L		L		M	
	Pre-treatment and post-treatment		-		Screening		Screening and Disinfection		Screening and Disinfection	
	Solid/brine treatment		-		M		M		H	
Economic	Capital cost *		AUD		4,235		3,740		3,610	
	Operation and maintenance		AUD/y		545		790		575	
	Energy consumption		kWh/m³		1.2		1.12		1.5	
	Recycled water saving		AUD/y		218		175		175	
Social	Public acceptance		-		L		M		H	
	Simplicity		-		C		MC		S	
	Knowledge and technology		-		H		L		M	
	Level of risk to health and safety		-		H		M		L	

*Note: * Source: Friedler and Hadari (2006); † Source: Sivakumar et al. (2013); ‡ Source: Muller (2008); ♦ Source: Merz et al. (2007); ◊ Level : extremely high (EH), very high (VH), high (H), medium (M), low (L), very complex (VC), moderately complex (MC), complex (C), simple (S) and very simple (VS).*

In this method, decision makers have to specify the preference of each indicator versus the others. It makes the judgment difficult when two indicators from different criteria are compared directly. The indicators can be classified in major criteria groups in order to simplify the comparison judgment. This is incorporated in an optimized analytic hierarchy process (OAHP) under economic, environmental and social criteria. Three major criteria (economic, environmental and social), twelve indicators (quality, fouling and cleaning, pre-treatment and post-treatment units, waste management, capital cost, operation and maintenance, energy consumption, water saving, public acceptance, simplicity, knowledge and technology and safety) and three systems (SVMD, SECUF and SMBR) are compared by assigning a weighting ratio based on information shown in Table 2. OAHP is applied for relative criticality weighting of indicators and relative criticality weighting of evaluators. Two levels of major criteria and indicators are selected in the OAHP. This helps decision makers to compare sustainability pillars as major criteria within the treatment topic. Nominated indicators in each criterion are then pair-wise compared rather than in a disorganized group. The real weight of each indicator was determined through the comparative judgment of both criteria and indicators.

The four main steps of the methodology are:

- Problem definition;
- Criteria identification and selection;
- Calculating relative weights:
  - Perform pairwise comparisons;
  - Compute the relative weights;
  - Assess consistency of pairwise judgment;
- Comparison decision alternatives.

The pairwise comparison matrix is derived through a scale of 1 to 9 as defined in Table 2. These steps must be applied to major criteria, indicators and systems. The pairwise comparison yields a reciprocal n-by-n matrix where n is the number of criteria considered.

Table 2. Numerical scale for comparative judgments (Saaty, 1990)

Intensity of importance	***Definition***
9	Extremely preferred
7	Very strongly preferred
5	Strongly preferred
3	Moderately preferred
1	Equally preferred
2,4,6,8	Preferences between the intervals

The "intensity of importance" values from Table 2 are values to be selected for C_{11} to C_{nn} in Eq. (1). In the comparison matrix, for all indices i and j the condition is $C_{ij}=1/C_{ji}$. Using n as the number of criteria, the pairwise comparison matrix (C) yields a reciprocal n-by-n matrix as:

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \quad (1)$$

A normalized matrix (N) is achieved by dividing each element in the pairwise comparison matrix by its column summation as shown in Eq. (2).

$$N=\begin{bmatrix} N_{11} & N_{12} & \cdots & N_{1n} \\ N_{21} & N_{22} & \cdots & N_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ N_{n1} & N_{n2} & \cdots & N_{nn} \end{bmatrix}=\begin{bmatrix} \frac{C_{11}}{\sum_{i=1}^{n} C_{i1}} & \frac{C_{12}}{\sum_{i=1}^{n} C_{i2}} & \cdots & \frac{C_{1n}}{\sum_{i=1}^{n} C_{in}} \\ \frac{C_{21}}{\sum_{i=1}^{n} C_{i1}} & \frac{C_{22}}{\sum_{i=1}^{n} C_{i2}} & \cdots & \frac{C_{2n}}{\sum_{i=1}^{n} C_{in}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{C_{n1}}{\sum_{i=1}^{n} C_{i1}} & \frac{C_{n2}}{\sum_{i=1}^{n} C_{i2}} & \cdots & \frac{C_{nn}}{\sum_{i=1}^{n} C_{in}} \end{bmatrix} \quad (2)$$

The average of the elements in each row of the normalized matrix is obtained by dividing the summation of normalized weights of each row by the number of criteria. Therefore, the weight matrix can be obtained by Eq. (3).

$$W=\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}=\begin{bmatrix} \frac{\sum_{i=1}^{n} N_{1i}}{n} \\ \frac{\sum_{i=1}^{n} N_{2i}}{n} \\ \vdots \\ \frac{\sum_{i=1}^{n} N_{ni}}{n} \end{bmatrix} \quad (3)$$

The weight matrices for each major criteria and indicators can be achieved by Eqs. (1-3). As a result, the total weight of each criterion can be expressed as

$$w_{ij}^{t}=w_{i}^{indicator}\times w_{j}^{criteria} \quad (4)$$

Also, three systems are compared together based on each indicator in order to assess the performance or characteristics of a system. Accordingly, the weight of a system allocated by each indicator, *s*, can be found by the pairwise comparison of m-by-m matrix where m is the number of the systems. Finally, the score of each system (*M*) is obtained using Eq. (5).

$$M=\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_n \end{bmatrix}=\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{bmatrix}\times\begin{bmatrix} w_1^t \\ w_2^t \\ \vdots \\ w_n^t \end{bmatrix} \quad (5)$$

Different systems are compared based on each indicator in order to estimate the performance. This comparison will result in matrix *S*. Thus, the reciprocal m-by-m matrix, *S*, has to be created for each indicator. The final score of each system is obtained using the matrix *S* and the system weights. The consistency ratio is determined to evaluate the reliability of paired comparison as expressed in Eq. (6) (Saaty, 1990).

$$CR=\frac{\lambda-n}{RI(n-1)} \quad (6)$$

where, *n* is the number of columns, λ is the average value of the consistency vector and *RI* is a random index that depends on the number of elements being compared.

The compatibility vector *(λ-n)/(n-1)* indicates the probability of random correspondence degrees. To calculate the compatibility vector, initial weight of each indicator was multiplied by its corresponding paired score. This function was performed for all indicators and the total results of multiplication were added together. The sum was then divided by the weight assigned to each indicator result in λ. Table 3 shows the random average indices for various n (Saaty, 1990). The consistency ratio of less than 0.1 indicates consistent judgment.

Table 3. Average random indices (RI) for various n

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

So the pair wise comparison for the three major criteria, twelve indicators and three systems is performed and the final score of each system is derived by Eq. (5).

4. Results and discussion

The assigned scores for each criterion and indicator of the system must be scaled from 1 to 9 or 0.11 to 1 in pairwise comparison. Indeed, the conversion factor is determined using the specific numerical scale of each indicator defined from 1 to 5 or 0.2 to 1 for the comparison ratio of two systems. These numerical scales are developed to cover all possible data from a variety of water distillation systems. Lexical indicator ratios are converted into a scale of 1 to 5, as given in Table 4, since five groups of comparative judgments are proposed. The ratio of similar abbreviations results in a factor of 1 in this category. A numerical scale for comparative judgments is necessary for all indicators. Lexical indicators were defined using the abbreviations in Table 1 and the ratio is given a numerical value via the factors identified in Table 4.

Table 4. Comparison factors referring to ratios of indicator levels obtained by comparative judgment of two systems (for abbreviations see footnote of Table 1)

EH/L=VC/VS=5
EH/M=VH/L=VC/S=MC/VS=4
EH/H=VH/M=H/L=VC/C=MC/S=C/VS=3
EH/VH=VH/H=H/M=M/L=VC/MC=MC/C=C/S=S/VS 2

A range of data is used for other numerical indicators. This range is derived using all possible treatment systems for comparison. This will determine a consistent ratio between the alternatives against each indicator. Finally, a conversion factor for each indicator is presented in Table 5 to establish the importance of one alternative against the second one on a scale of 1 to 9. If the importance of one alternative against the second one is less than 1, a value between 0.11 to 1 from the Table has to be selected.

The comparative judgment is accomplished based on an identified problem in hand which is determining a sustainable greywater treatment system. Future water and energy crises must be solved in an environmentally friendly and cost effective manner. In addition, the successful technology needs public acceptance. Therefore, the economic criterion is selected as the most important parameter in decision-making. The preference level of economic versus environmental criteria is small due to the environmental significance of the treatment system. The tendency of decision makers to consider economic and environmental aspects more important than social criteria is observed in the comparative judgment. A ratio of 2 and 4 are selected for economic versus environmental and economic versus social, respectively as given in Eq. (7). According to Table 2, these values show the importance of moderate and strong preference of economic versus environmental and social criteria, respectively. On the other hand, a ratio of 3 is considered for environmental versus social criteria. Thus, the pairwise comparison matrix of major criteria can be represented as:

$$C^{criteria} = \begin{array}{c} \\ Environmental \\ Economic \\ Social \end{array} \begin{array}{c} \begin{array}{ccc} Environmental & Economic & Social \end{array} \\ \begin{bmatrix} 1 & 0.5 & 3 \\ 2 & 1 & 4 \\ 0.33 & 0.25 & 1 \end{bmatrix} \end{array} \quad (7)$$

Based on Eq. (2) and Eq. (3), the normalized matrix and the weight of major criteria can be expressed as:

$$N^{criteria} = \begin{bmatrix} 0.3 & 0.29 & 0.38 \\ 0.6 & 0.57 & 0.5 \\ 0.1 & 0.14 & 0.13 \end{bmatrix} \quad (8)$$

$$W^{criteria} = \begin{bmatrix} W^{criteria}_{Environmental} \\ W^{criteria}_{Economic} \\ W^{criteria}_{Social} \end{bmatrix} = \begin{bmatrix} 0.32 \\ 0.56 \\ 0.12 \end{bmatrix} \quad (9)$$

The pairwise comparison and normalized matrices of indicators are obtained by the same mathematical procedure, using Eq. (2) and Eq. (3). The weight of indicators in economic, environmental and social criteria can be denoted respectively as:

$$W^{indicator}_{Environmental} = \begin{bmatrix} W^{indicator}_{Quality} \\ W^{indicator}_{Cleaning} \\ W^{indicator}_{Treatment\_units} \\ W^{indicator}_{Solid\_treatment} \end{bmatrix} = \begin{bmatrix} 0.55 \\ 0.26 \\ 0.12 \\ 0.07 \end{bmatrix} \quad (10)$$

$$W^{indicator}_{Economic} = \begin{bmatrix} W^{indicator}_{Capital\_cost} \\ W^{indicator}_{O\&M} \\ W^{indicator}_{Energy\_consumption} \\ W^{indicator}_{Water\_saving} \end{bmatrix} = \begin{bmatrix} 0.53 \\ 0.29 \\ 0.11 \\ 0.07 \end{bmatrix} \quad (11)$$

$$W^{indicator}_{Social} = \begin{bmatrix} W^{indicator}_{Public\_acceptance} \\ W^{indicator}_{Simplicity} \\ W^{indicator}_{Knowledge\&technology} \\ W^{indicator}_{Health\&saftey} \end{bmatrix} = \begin{bmatrix} 0.49 \\ 0.22 \\ 0.05 \\ 0.24 \end{bmatrix} \quad (12)$$

The consistency ratios are calculated for both *W* and *S* matrices. Table 6 indicates that all values are under 0.1 which shows satisfactory result for comparative judgment. The total weight (w^t) of each indicator can be determined by multiplying the weight of indicators ($w^{indicator}$) to the weight of related major criteria ($w^{criteria}$).

Table 5. Numerical scale for comparative judgment of system 1 *vs.* system 2

conversion factor / ***Indicator***	***Range***								
	0.11	***0.14***	***0.2***	***0.33***	***1***	***3***	***5***	***7***	***9***
Quality	0.5	0.57	0.67	0.8	1	1.25	1.5	1.75	2
Fouling and Cleaning requirement	5	4	3	2	1	0.5	0.33	0.25	0.2
Pre-treatment and Post-treatment	5	4	3	2	1	0.5	0.33	0.25	0.2
Solid/Brine treatment	5	4	3	2	1	0.5	0.33	0.25	0.2
Capital Cost	2.5	2.1	1.8	1.4	1	0.7	0.56	0.48	0.4
O & M	2.5	2.1	1.8	1.4	1	0.7	0.56	0.48	0.4
Energy Consumption	5	4	3	2	1	0.5	0.33	0.25	0.2
Recycled water saving	0.67	0.73	0.8	0.9	1	1.12	1.24	1.37	1.5
People acceptance	0.2	0.25	0.33	0.5	1	2	3	4	5
Simplicity	5	4	3	2	1	0.5	0.33	0.25	0.2
Knowledge and Technology	5	4	3	2	1	0.5	0.33	0.25	0.2
Level of risk to Health and Safety	5	4	3	2	1	0.5	0.33	0.25	0.2

Table 6. Consistency ratios for weighting matrices

Matrix	$W^{criteria}$	$W^{indicator}_{Environmental}$	$W^{indicator}_{Economic}$	$W^{indicator}_{Social}$	S_1	S_2	S_3	S_4
CR	0.016	0.011	0.008	0.020	0.004	0	0.001	0.000
Matrix	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
CR	0	0.001	0.000	0.000	0.000	0.035	0.001	0.046

$$M=\begin{bmatrix} m_{SVMD}\\ m_{SECUF}\\ m_{SMBR}\end{bmatrix}=\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n}\\ s_{21} & s_{22} & \cdots & s_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ s_{m1} & s_{m2} & \cdots & s_{mn}\end{bmatrix}\times\begin{bmatrix} W^t_{Quality}\\ W^t_{Cleaning}\\ W^t_{Treatment\_units}\\ W^t_{Solid\_treatment}\\ W^t_{Capital\_cost}\\ W^t_{O\&M}\\ W^t_{Energy\_consumption}\\ W^t_{Water\_saving}\\ W^t_{People\_acceptance}\\ W^t_{Simplicity}\\ W^t_{Knowledge\&technology}\\ W^t_{Health\&saftey}\end{bmatrix}=$$

$$\begin{bmatrix} 0.58 & 0.60 & 0.43 & 0.43 & 0.20 & 0.43 & 0.40 & 0.71 & 0.43 & 0.26 & 0.20 & 0.14\\ 0.11 & 0.20 & 0.14 & 0.43 & 0.40 & 0.14 & 0.40 & 0.14 & 0.14 & 0.11 & 0.60 & 0.33\\ 0.31 & 0.20 & 0.43 & 0.14 & 0.40 & 0.43 & 0.20 & 0.14 & 0.43 & 0.63 & 0.20 & 0.53\end{bmatrix}\times$$

$$\begin{bmatrix} 0.18\\ 0.08\\ 0.04\\ 0.02\\ 0.30\\ 0.16\\ 0.06\\ 0.04\\ 0.06\\ 0.03\\ 0.01\\ 0.03\end{bmatrix}=\begin{bmatrix} 0.40\\ 0.26\\ 0.34\end{bmatrix} \tag{13}$$

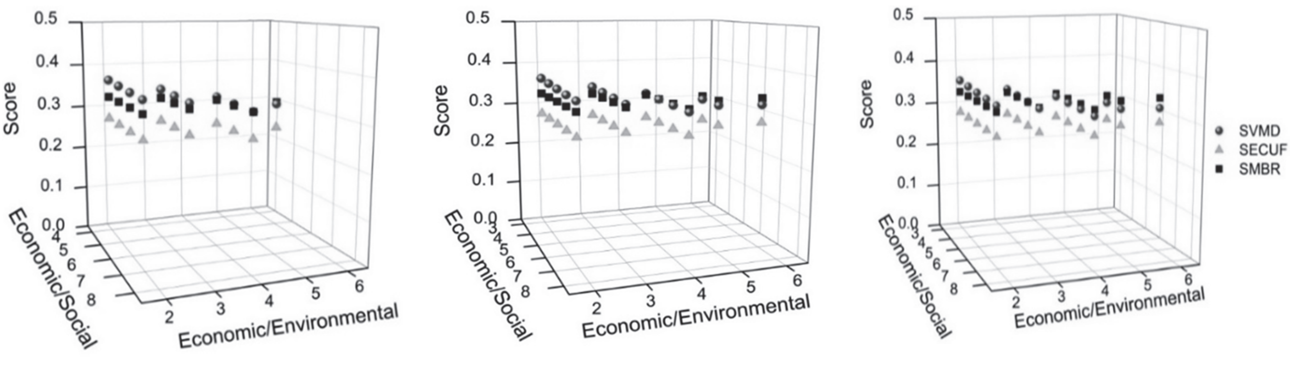
The proposed treatment systems were compared based on each indicator. The *s* arrays are also identified by the information given in Tables 1 and 6. Finally, using Eq. (5), the final score of each system is represented using Eq. (13).

The first row of arrays, s_{11}, s_{12}, …, s_{1n}, illustrate the weight of the SVMD system based on twelve indicators. The second and third rows are allocated to SECUF and SMBR, respectively. The important role of indicators such as capital cost, water quality and O&M in technology selection can be recognized from the total weight (w^t) matrix. The weight of the economic criterion versus environmental and social criteria, the effect of water quality indicator among the environmental indicators and the importance of capital, operation and maintenance costs in comparison with energy consumption and water savings are the reasons for the total weight of 0.30, 0.18 and 0.16 allocated to capital cost, quality and O&M indicators, respectively.

Therefore, as indicated in Eq. (13), the proposed treatment systems SVMD, SECUF and SMBR are ranked by the score of 0.40, 0.26 and 0.34, respectively. Consequently, the SVMD system is considered as the most sustainable greywater treatment system. A variety of comparison ratios was used in Eq. (7) to show the flexibility of the OAHP method in treatment technology selection. Some realistic ratios between the three major criteria were assumed to investigate the flexibility of the OAHP method through all six possible priority ranks of the major criteria (economic > environmental > social, economic > social > environmental, environmental > economic > social, environmental > social > economic, social > environmental > economic and social > economic > environmental).

The ratios of 4, 3 and 2 were selected for the first two criteria in each case while the ratios of the second versus the third and the first versus the third one varied between 2 and 8. In all projected cases, consistency ratio of less than 0.1, was observed. The SMBR process was determined to be the most sustainable technology when the priority rank of social > economic > environmental was used. The score of SMBR was 5% more than SVMD on average.

For the priority rank of economic > environmental > social, either SVMD or SMBR was specified as the most sustainable technology for each proportion set as illustrated in Fig. 4. SVMD technology was the most sustainable one in the other four priority ranks. The score of SVMD was between 5 to 47% higher than the SMBR score.



(a) (b) (c)

Fig. 4. The score of each system against economic/social and economic/environmental criteria while a) environmental/social is 4, b) environmental/social is 3 and c) environmental/social is 2

A constant ratio of 4, 3 and 2 of the environmental criterion versus the social one is assumed in Figs.4 a, b and c, respectively. As shown in Fig. 4, the SVMD technology scored better than SMBR in the majority of proportion sets except in those cases where the economic criterion was strongly, very strongly or extremely preferred over the environmental and social criteria. In such a situation, the SMBR system achieves the highest score with a maximum of 6% difference.

5. Conclusions

A complex multiple objective problem was defined in MCDA with a view to determine the most sustainable solar-powered greywater treatment system considering different logical and realistic comparative judgments. It involved an optimized analytic hierarchy process (OAHP) to compare and evaluate three solar powered treatment systems: SVMD, SECUF and SMBR.

The OAHP method assessed the alternatives using a multiple objective decision-making method and employing major sustainability criteria and indicators. Three major sustainability criteria (Economic, Environmental and Social) and twelve indicators were incorporated to avoid subjectivity in decision making and raise awareness of the actual effect of each parameter. This comprehensive method provided a practical analysis for sustainability comparison between greywater treatment options. Based on the analysis performed, the SVMD system was shown to be the most sustainable system due to its weights obtained in comparative judgment of systems and total weight of indicators.

On the other hand, the diverse nature of the proposed systems was verified through various combinations of economic, social and environmental proportions. SVMD was the first rank in the majority of possible priority rankings of the major criteria due to its high quality effluent and reasonable maintenance costs.

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