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Techno-economic Analysis of a Sustainable Ablution Greywater Recycling System for Toilet Flushing

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ABSTRACT

In arid and semi-arid countries, it is required to identify alternative potential sources of water and develop sustainable technologies for their recycling. A large amount of less contaminated ablution greywater (AGW) is being produced at the mosques in all Muslim countries including Kingdom of Saudi Arabia (KSA). Therefore, AGW certainly possesses significant potential for recycling. In this study, a simple and cost-effective sustainable ablution greywater recycle system (SAGWRS) is proposed to collect, treat and recycle the AGW within the periphery of a mosque for toilet flushing. A conceptual model for SAGWRS was developed and evaluated through techno-economic analysis. The SAGWRS consists of a AGW collection and storage system, low cost ceramic filtration unit, activated carbon adsorption column, chlorine dispenser, and overhead tank to collect and distribute treated AGW. The SAGWRS meets the water quality standards for toilet flushing as well as for irrigation. A simple operation and maintenances procedure made the system sustainable and cost effective. The estimated cost (0.7-1.0 US$/m^3) of the SAGWRS was found to be considerably less than the municipality water cost (1.71 US$/m^3) in KSA. SAGWRS proposed in this study would be a prospective recycling practice of AGW in KSA for sustainable development. Based on the techno-economic analysis, the proposed system provides a sustainable approach of water conservation by on-site recycling of AGW in Muslims countries around the world.

Keywords: Ablution greywater (AGW); Treatment process; recycling; ceramic filtration; Activated carbon; sustainable development

1. Introduction

Due to continuous development, increasing of water demand in most of the arid and semi-arid countries in Gulf region, including the Kingdom of Saudi Arabia (KSA). As a results the both the quantity and quality of groundwater are considerably decreasing due to presence of

naturally occurring minerals in subsoil and the anthropogenic activities [1-2]. Municipalities in KSA are
spending substantial financial resource to provide safe drinking water to the public using expensive treatment processes [3]. Moreover, climate change is expected to further increase water demand [4]. Therefore, it is essential to identify the alternative sources of water for sustainably managing future water demands.

Due to the limited water resources of freshwater in the middle east countries, reconsidering the greywater recycling could be highly beneficial. Sustainable recycling of greywater may reduce the demand of groundwater and other freshwater resources in these regions [5-6]. Greywater produces from the kitchen, bath and laundry and represents the major part of domestic wastewater [7]. Greywater contents relatively low levels of contaminants than black water and therefore, it can be recycled as a source of non-potable water for sustainable development of resources conservation [8-9]. In recent years, some Middle East countries, including the KSA, have introduced a greywater recycling process and guideline for non-potable recycling. However, the process has some drawbacks including the lack of public and social awareness and acceptability of available treatment systems [10].

The mosques in Muslim world are producing a large amount of ablution greywater (AGW), i.e., wastewater produced from washing of a certain parts of the body (wudhu) to perform prayers in the religion of Islam. Comparing to domestic greywater, AGW is relatively clean and contain low level of contaminants such as turbidity, TSS, COD, BOD and bacteria [9,11]. Hence, the AGW has a great potential for recycling and reuse for non-potable water applications after desired treatment.

The treated water can be recycled within the periphery of mosque either for toilet flushing or for plant watering. Enviornmental and economic benefits of reuse of AGW have been reported in literature [12-14]. There are about 100,000 community mosques in KSA producing a significant quantity of AGW on daily basis. Thus, a considerable amount of water can be conserved through a sustainable small-scale system for AGW treatment at individual mosque and reusing it for toilet flushing through a loop network.

The sustainability of a technology largely depends on its technical, socio-economic, and environmental feasibility. Currently in KSA, the greywater including AGW is sent to centralized government owned wastewater treatment plants. Treated water is mainly being recycled for irrigation application. Small-scale decentralized sewage systems are popular in many developed countries. However, the techno-economic feasibility of decentralized sewage system to treat and recycle wastewater is not clear in arid regions including KSA.

Sustainability of sanitation systems can be improved by introducing small-scale systems as they are closer to the recycling loop. They also offer alternative solutions to centrally managed large-scale infrastructures. The incoming water demand and sewage generation can be reduced and thus the costs of wastewater treatment and resulting impacts on natural environment. However, small-scale greywater system requires an additional investment, including capital cost and operational and maintenance cost. Hence, techno-economic evaluation is mandatory to assess the net impact of these factors to small-scale greywater treatment systems.

From this perspective, this study aimed to develop a model of sustainable ablution greywater recycling system (SAGWRS) within the periphery of individual mosque in KSA. A cost-effective and sustainable system was proposed based on the analysis of a systemic techno-economic features of the process. The specific objectives of this study are to: i) determine quantity and quality of AGW produced; ii) identify the necessary treatment based on the quantity and quality of AGW; iii) design, construct and investigate the low-cost treatment system; and iv) evaluate the techno-economic sustainability of the ablution greywater recycling system.

2. Materials and Methods

2.1 Methodological Framework

A methodological framework of the approach adopted in this study is presented in Fig. 1. The study starts with the engineering approach including, features of ablution greywater, design and application. Based on the engineering approaches a conceptual model was developed in the second step. Techno-economic analysis of the model was conducted through measuring the water quantity and quality of the system input and output and system cost estimation. Finally based on the study results, operation and maintenance procedures are identified to make the system sustainable.

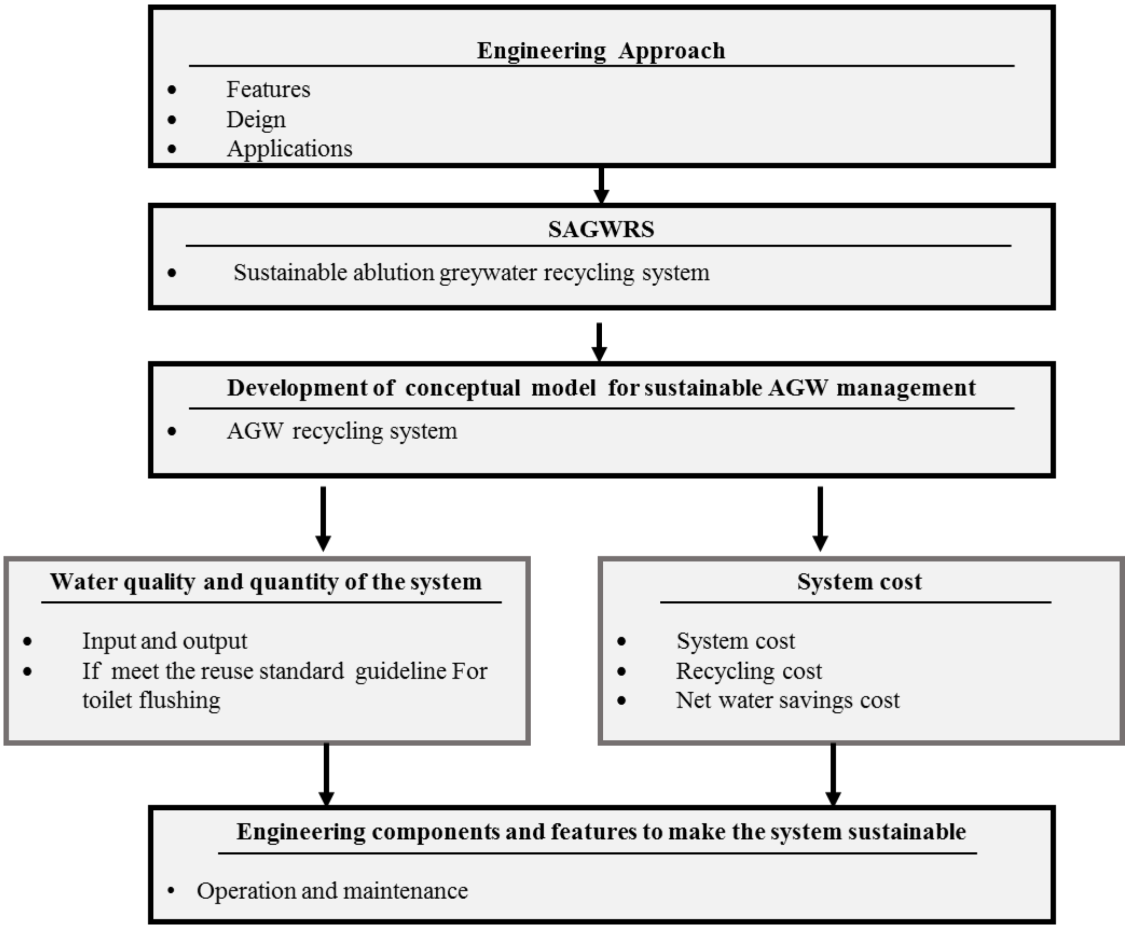

Fig. (1). Techno-economic sustainability evaluation framework for SAGWRS

2.2 Conceptual model for techno-economic analysis of SAGWRS

Figure 2 illustrate the system's water flow and components of conceptual model for AGW recycling. The model was primarily designed to recycle the treated AGW for toilet flushing. The sustainable AGW recycling system consists of the following main components: AGW collection and storage tank, low cost ceramic filtration unit, activated carbon adsorption column, chlorine dispenser and overhead treated AGW storage tank. The AGW water was transported gravitationally through the disposal pipes to AGW storage tank. Subsequently, the AGW water was pumped to the ceramic filtration tank to remove the suspended and colloidal particles. Following filtration, the water was pumped thorough an activated carbon adsorption column to remove the organic. The water after activated carbon adsorption was then pumped to the rooftop treated AGW storage tank through a chlorination dispenser. The treated water will be then recirculated to toilet flushing and if necessary recycle to the plant watering. The AGW storage tank will be connected to the sewerage network in order to drain the AGW in case of over flow as well as during maintenance (cleaning and replacing the filter and carbon) of the system. Water supply storage tank will be connected to the recirculation pipe network and will be functioned for toilet flushing when there is shortage of water in the treated storage tank. The circulation of treated and untreated AGW would be operating by fully automated system with the aid of sensors and pumps.

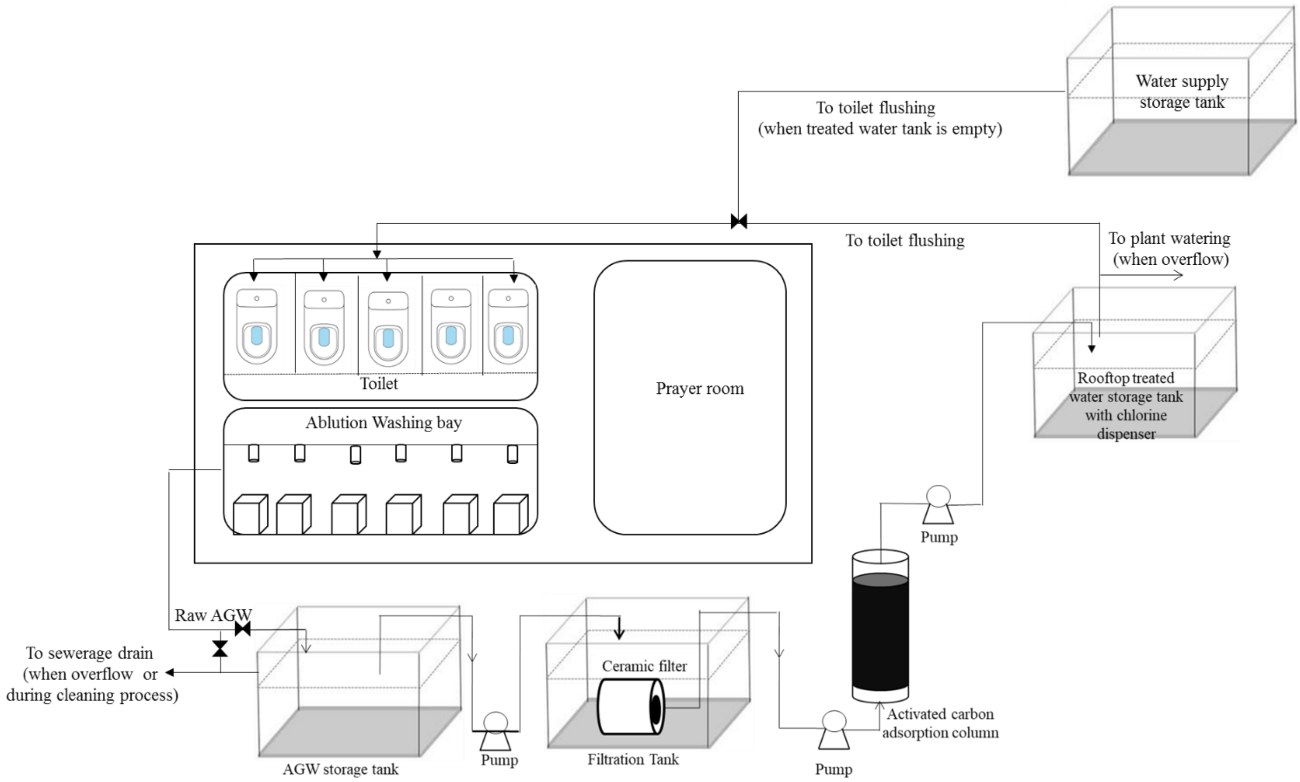

Fig. (2). Conceptual model for sustainable AGW recycling system (SAGWRS)

2.3 AGW Production and Sampling

A small to medium-size mosque (Al-Ajaji mosque) located in Buraidah, KSA was selected for this study. AGW, mixed with black water, is currently being discharged into the municipal sewerage system. Ablution greywater flows out from the ablution room to the municipal sewer through a 100 mm drain pipe. To estimate AGW production and collect AGW samples, a cylindrical container (diameter 400 mm and height 1.2 m) was connected at the outlet of the ablution drain pipe. The number of people performing ablution was counted and the amount of water in the cylinder was measured daily for each of five daily prayers for 12 days' period. The production of ablution greywater (L/prayer/person) was calculated by dividing the total number of people by the amount ablution greywater received by the collection cylinder in one prayer. During the monitoring of AGW production, AGW samples were collected to analyze the physical, chemical, and biological qualities as well as used for the experiments.

2.4 SAGWRS Treatment Unit

As shown in Fig. 2, the main treatment components of SAGWRS included the low-cost ceramic filter and activated carbon adsorption column. Laboratory experiments were conducted to investigate the efficiencies of the system that consists of ceramic filter followed by activated carbon adsorption column. The low-cost ceramic filter used in this study was adopted [15] from our previous study. A cylindrical shaped (100 mm outer diameter, 60 mm inner diameter and 100 height) filter was made of clay soil and rice bran. Details manufacturing process of the filter were previously described [16]. The filter has a pore size of 1-5 μm and manufacturing cost of 0.2-0.3 US$/filter. In the experimental setup, the ceramic filter was placed horizontally in the filtration tank (Fig. 2). Raw AGW was fed to the filtration tank and a suction pump connected to the effluent tube was used to perform filtration. AGW filtered through the outer surface of the filter to the effluent tube. Filtration was carried out at a flow rate of 55 mL/min for consecutive 6 days. Corresponding flux at this flow rate was calculated to be 1400 L/m2/d which is average AGW production in a small to medium size mosque in KSA. Following ceramic filtration, the permeate was fed to an up flow activated carbon adsorption column. An activated carbon filter (CTO-10, Riverpure, Taiwan) purchased from the local market was used as adsorption column (Fig.2). The adsorption was performed in up flow mode using a peristaltic pump at a constant flow rate of 2.25 L/h and empty bed contact time (EBCT) of 35 min. Water samples at the effluent of AC column were collected in daily basis and water qualities were measured.

3. Results and Discussions

3.1 AGW production

AGW production at Al-Ajaji mosque was monitored for 12 days in March 2017. The Daily AGW production of an average 50 persons/ prayer is presented in Fig. 3. Daily AGW production at the Al-Ajaji mosque ranged from around 450 L to 1400 L with an average of 950 L/d. The AGW production found in this study is consistent with a previous study [13] reported that daily AGW production at a medium-sized mosque in Oman is ranging from 770 to 1940 L/d (with an average of 1220 L/d). From the results, AGW production per person per prayer was estimated to be 3.5 L. As shown in Fig.3, a high degree of variation of AGW production was observed at Al-Ajaji mosque indicating the variation in the number of worshipers between days. Therefore, the variation of AGW production will lead to an instability of treatment process. Hence, a storage tank should be included in a treatment system to make the stable flow to the system.

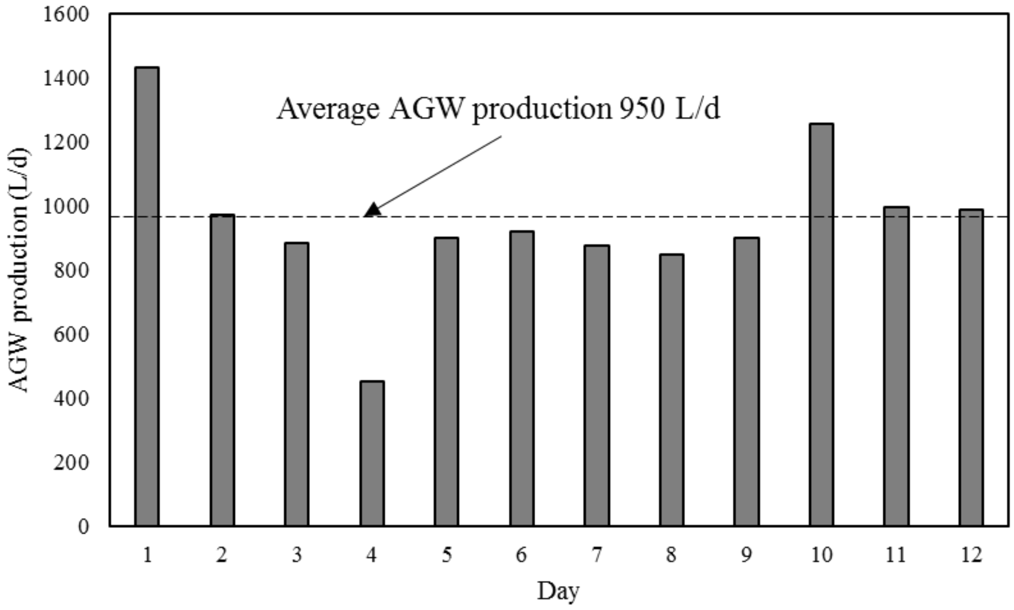

Fig.(3). Daily AGW production at Al-Ajaji mosque

3.2 Quality of raw AGW produced at Al-Ajaji mosque

Table 1 presents the minimum, maximum and average contaminant concentrations of 10 AGW samples collected from the Al-Ajaji mosque. A comparison of analyzed AGW quality with greywater reuse standard in KSA indicate that pH, alkalinity, TDS, NH_4-N, PO_4-P, Oil and grease, free Cl_2 of produced AGW are within the acceptable limits for both toilet flushing and irrigation. However, turbidity, chemical oxygen demand (COD), biological oxygen demand (BOD), TSS and fecal coliform levels exceeded permissible concentrations for irrigation and toilet flushing. Therefore, treatment of AGW is required before reuse. Based on the AGW quality determined in this study and the methods used to treat greywater in previous studies [16-19], the treatment method was identified as following: a) a storage tank for untreated AGW to settle the suspended solids and ensure the constant flow, b) a filtering unit such as low-cost ceramic filter to remove the SS, turbidity and improve the other water quality parameter such as BOD and COD, c) Chlorination unit is necessary since the fecal coliform levels were above the acceptable limit and d) finally a storage tank included in the process to ensure reliable supply of treated water

Table 1: Quality of AGW at Al-Ajaji mosque and KSA standard for recycling greywater

Parameter	Min*	Average*	Max*	SD	Re-use Standard**	Acceptable
pH	7.7	7.9	8.1	0.1	6.0-8.4	Yes
TSS (mg/L)	19.0	24	35.0	6.1	10	No
Alkalinity (mg/L)	67.2	77.1	86.0	8.4	-	-
Turbidity (NTU)	11.2	14.8	18.1	2.1	5	No
COD (mg/L)	38	63	88	19.1	-	No
BOD (mg/L)	19	37	51	12.6	10	No
TDS (mg/L)	192	213	245	17.5	2500	Yes
Oil & grease (mg/L)	0.001	0.004	0.009	0.003	nil	Yes
PO_4-P (mg/L)	0.07	0.2	0.28	0.1	-	-
NH_4-N (mg/L)	0.27	0.34	0.44	0.1	5	Yes
Free Cl_2 (mg/L)	0.0	0.0	0.0	0.0	0.2	Yes
Total coliform (MPN/100 ml)	1011	1011	1011	0.0	-	-
Fecal coliform (MPN/100 ml)	756	884	982	74.4	<2	No

** Values are the average of 10 Raw AGW samples*
***KSA Reuse standard for unrestricted irrigation and toilet flushing, [20]*

3.3 Treated water quality of SAGWRS unit

In order to evaluate the water quality of SAGWRS, samples were taken from the pre - and post treatment (before chlorination) and the following parameters were examined: pH, alkalinity, TSS, turbidity, COD, BOD, TDS, PO_4-P, NH4-N, total coliform (TC) and fecal coliform (FC). All water quality was measured according to EPA standard method for water and wastewater. Results of the water quality on both raw AGW and final water are given in table 2. Referring to Table 2, the pH value is increased from an average 7.5 to 8.1 at the final water. As pH increased, the alkalinity also increased from 70.0 mg/L to 89 mg/L. However, reduction of turbidity and TSS were found to be significant having average residual turbidity and TSS of 1.4 NTU and 0.64 mg/L, respectively.

The residual BOD and COD were achieved less than 10 mg/L which were below the KSA standard for toilet flushing and irrigation (MOE, 2006). TDS was almost unchanged in the pre- and post-AGW and remained below 400 mg/L, which is well below toilet flushing and irrigation threshold. Although a little increase of PO4-P was observed, however, the nutrients concentration (NH_4-N) were well below the acceptable limit. As for removal of biological contaminant as shown in Table 2, both TC and FC were well above the KSA standard threshold for toilet flushing and irrigation. The results are expected as no disinfection process were examined in this study. However, it is presumed that biological contents (total coliform, fecal coliform and E-coil) of AGW can be eliminated by introducing a conventional chlorination practice for water [21]. Previous study reported that conventional disinfection effectively eliminates the total coliform and E-coil from AGW below the acceptable limit [8]. At a glance, for all the water quality parameter examined, the treated AGW was found to be in compliance with the permissible limit of KSA wastewater reuse standard for toilet flushing as well as for irrigation.

Table 2: Treated water quality of SAGWRS unit

Parameter	Raw AGW	SD	After Treatment	SD	Acceptable*
pH	7.4	0.06	8.1	0.10	√
TSS (mg/L)	10.8	0.56	1.27	0.33	√
Alkalinity (mg/L)	69.6	2.4	89.3	5.0	-
Turbidity (NTU)	13.7	0.23	0.78	0.68	√
COD (mg/L)	52.58	1.9	9.3	11.1	√
BOD (mg/L)	30.6	2.1	9.3	2.75	√
TDS (mg/L)	329	16.3	394	20.4	√
PO_4-P (mg/L)	0.22	0.121	1.5	0.65	-
NH_4-N (mg/L)	1.45	0.25	1.02	0.04	√
Total coliform (MPN/100 ml)	1035	58	997	10.5	-
Fecal coliform (MPN/100 ml)	865	65	167	69	√**

**= KSA Standard for unrestricted irrigation and toilet flushing [20]*
***= Disinfection is necessary*

3.4 Operation and maintenance of the SAGWRS

As stated before, the SAGWRS would be operated by fully automated system with the aid of sensors and pumps. The water will be continuously filtered at constant flux of 1400 L/m^2/d followed by flow through a carbon adsorption column to a treated water collection overhead tank in where a chlorine dispenser will be installed. Required surface area of the filter was estimated based on the flux. The dimension of activated carbon column and required amount of carbon was previously estimated [22]. Although disinfection performance was not evaluated however, it is presumed that normal chlorination practice for water would be suitable as the turbidity of treated AGW is less than one [21]. Required area of filter and details of AC column at different feeding rate is given in table 3. Based on the maximum AGW flow rate of 1400 L/m2/d, it was estimated the total land area required for footprint of the system is approximately 12 m^2.

Table 3: Details of ceramic filter and AC column of SAGWRS unit

AGW feeding rate (m^3/day)	*Required filter area (m^2)	**Mass of AC required (kg)	Volume of AC column (m^3)	Diameter of AC Colum (cm)	Height of AC column (cm)
1.4	1.0	12.65	0.034	30	40
3.0	2.0	27.12	0.073	30	55
5.0	3.5	45.20	0.122	30	70
10.0	7.0	90.39	0.243	30	100
20.0	14.0	180.78	0.486	30	150

**Filter will be replaced every 2 year*
*** AC will be replaced every 40 days*

Based on the estimation, it is anticipated that the ceramic filter would need to be replaced after every 2 years and the AC would require to be replaced every 40 days. Here we consider that ceramic filter and activated carbon would not be regenerated. Ceramic filter would be easy to maintain due to prolonged operation without clogging. Instead of a conventional backwash process, it is recommended to clean the filter weekly basis using soft brush [23]. During the cleaning process, the AGW flow to storage tank will be stopped and drained directly to the sewerage network (Fig.2).

3.5 Economic Analysis of SAGWRS

The total cost of a SAGWRS is estimated as the sum of the costs of major components including initial capital cost (Construction of tanks and plumbing, pump, pipes and valves, electrical components), filter cost, operating cost including energy cost and chemical consumption cost. The total annualized cost was estimated using the equation (1) below:

$$C_{total} = C_{Acap} + C_{Afilter} + C_{Aop} + C_{Achem} \quad (1)$$

Where, annualized capital cost (C_{Acap}, US$/year), filter cost ($C_{Afilter}$, US$/year), operating costs (C_{Aop}, $/year) and chemical consumption cost (C_{Achem}, $/year) were estimated using a method given by Nandi et al. [24].

Total optimum costs for the SAGWRS at different feeding rates of AGW (1.4 to 20 m^3/d) are presented in Table 4. These range of feeding rates represent the AGW production at different sizes of mosques in KSA. The optimum cost was estimated based on the life time of treatment system, which was assumed to be 30 years and adopted from the previous studies [25-26]. The lifespan of the ceramic filter was assumed to be 2 years and the pumps are replaced in every 10 years. From the Table 4, estimated costs of the SAGWRS system ranged from 0.7 to 1.0 US$/$m^3$ and the cost decreases as the feeding rates increase. The lowest cost contribution was from the filter cost (8-9%) followed operating cost (energy cost) of around 10.5-15.7%.

and chemical cost contribution of around 11-16%. The major cost contribution was from the capital cost (59-69%). The lower contribution of the filter cost and operating cost (energy cost) to the overall cost is anticipated due to the lower filter cost and lower operating pressure require lower energy. The cost (0.7-1.0 US$/m3) of the SWGWRS system is considerably lower than the water cost (1. 71 US$/$m^3$) of KSA. From the results, a net value of water saving could be reached 30 to 626 US$/month (Table 4), if introducing the proposed SAGWRS in every mosque around the KSA. In addition, such reuse practices will reduce the existing groundwater withdrawals (or consumption of desalinated water) and will be a great step towards sustainable development in line with KSA Vision 2030. On the contrary, comparatively lower cost and easy maintenance would make the SAGWRS feasible for other Middle east as well as Muslims countries to conserve their limited water resources

Table 4: Water production costs and net water savings costs of SAGWRS at different feeding rates (small to large size mosques)

Mosque size	AGW feeding rate (m^3/day)	Total cost (US$/ year)	Total Cost (US$/ m^3)	% Contribution				Net value of water saving (US$/month)
				Capital cost	Filter cost	Operating cost (Energy cost)	Chemical cost	
Small	1.40	513	1.00	69.16	8.97	10.54	11.33	29.69
	3.00	933	0.85	65.20	9.32	12.22	13.26	77.20
Medium	5.00	1422	0.78	63.27	8.93	13.29	14.50	139.65
	10.00	2602	0.71	60.87	8.53	14.76	15.85	299.11
Large	20.00	4865	0.67	59.32	7.93	15.79	16.96	626.16

4.Conclusions

The SAGWRS showed a feasible and sustainable process that can be implemented in Middle east as well as all other Muslim countries. The AGW recycling system is easy to fabricate with a low cost ceramic filter made of locally available materials and locally available activated carbon. The system is also easy to operate and maintain with simple cleaning process instead of conventional backwashing of filter. Also a prolonged life time of filter (2 years) and low activated carbon requirements made the system cost-effective and sustainable. Most importantly, the treated AGW was found to be in compliance with the permissible limit of KSA wastewater reuse standard for toilet flushing as well as for irrigation.

The total cost including capital cost, filter cost, operation cost and chemical cost was estimated as 0.7 to 1.0 US$/$m^3$ which was significantly lower than the water production cost in KSA (1.71 US$/m^3). Based on the mosque size, the net values of water saving were estimated ranged from 30 to 626 US$/month. Therefore, the reuse practices of AGW using proposed SAGWRS will reduce the existing groundwater withdrawals (or consumption of desalinated water) and will be a great step towards sustainable development of KSA. Also, a comparatively lower cost and easy maintenance would make the SAGWRS feasible for other Middle east as well as Muslims countries to conserve their limited water resources

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