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Evaluation of point-of-use drinking water treatment systems' performance and problems

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ABSTRACT

Applications of Point-of-Use Drinking Water Treatment Units (POU-DWTUs) are common in many parts of the world. This paper presents the operational conditions of POU-DWTUs in Iran (Qom province) as a case and discuses the problems and the possible health-related aspects. The devices which were studied consisted of primary filter, carbon filter, Reverse Osmosis membrane, and storage tank. During a cross sectional study, 240 water samples from the input and output of different POU-DWTUs were collected and analyzed. Half of POU-DWTUs users did not have correct information about the operational principles and 35% of them were not satisfied about taste and odor of the treated water. Analysis showed that POU-DWTUs were able to reduce the dissolved solids content more than 90% and produced soft water. However the amount of heavy metals removed by POU-DWTUs varied from 5% for Al to 86% for Cd and their removal average was 43%. High concentration of Pb in both raw and treated water was remarkable. It was found that POU-DWTUs are not successful and reliable in the complete removal of heavy metals. Moreover, considering possible long-term health effects of soft water consumption and some microbial contamination of treated water, it is imperative to take proper actions for effective provisions on quality of water produced by POU-DWTUs.

Keywords: Drinking water; Chemical quality; Household water treatment; Heavy metal; Iran

1. Introduction

An access to safe and adequate drinking water is an important requirement for life. In arid and semi arid areas of the world for example, the Middle East [1], there are considerable challenges in terms of accessing fresh water and its quantity and quality. In those areas, people are facing limitations for water supply in addition to its quality problems for example, high content of total dissolved solids (TDS) and brackish water [2,3]. According to the World Health Organization (WHO) guideline for drinking water [4], and Iranian national drinking water standard [5],

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quality of drinking water should meet the recommended values of elements in order to protect the health of consumers. In other words, presence of some elements like calcium (Ca) and magnesium (Mg) in drinking water in acceptable levels has nutritional value and is beneficial for health [6]; however, presence of other elements like heavy metals or microbial contamination of drinking water can lead to disease on short or long term consumption.

Currently, people use different water desalination [7] and household point-of-use drinking water treatment units (POU-DWTUs) in many parts of the world especially in the arid areas, in order to provid safe drinking water, which is compatible with recommended standards or removal of toxic materials (e.g. arsenic) [8–14]. Some of POU-DWTUs are based on local low cost materials; however, a part of these devices are made by factories and sold by different countries in various capacities and dimensions. These POU-DWTUs are generally reverse osmosis (RO) units, carbon filter and primary (sand) filter [15], or etc. (Fig. 1) for purifying water and decreasing TDS content of water in addition to, particulate and organic matters. Household application of RO units represents a rapidly growing segment of the home water treatment industry in the world which is convenient and easy to use providing moderately good quality of drinking water.

Since last decade, there has been an increasing trend in the application of POU-DWTUs by Iranian citizens especially in semiarid areas for example, southern or central part of the country. Moreover, in most of cities with either fresh water shortage or no water shortage, wealthy people also use POU-DWTUs at homes.

In view of fresh water supply from unconventional sources in Iran with an annual rain fall equaling to one third of world mean rainfall, in southern parts of the country, over 423,000 m^3 of fresh water produced daily from sea water through evaporative process that is ranked 10th in the world fresh water production from sea water. Historically, the first desalination unit was launched at Bushehr, Iran in Sea Force Residential Town in 1970. Currently, more than 51 desalination plants have been installed at Bushehr, 91 units in Hormozgan located around islands, 20 units in the province of Sistan and Baluchestan, and five units in Khuzestan province [16]. In other parts of Iran, low quality of drinking water is supplied through distribution networks that makes people look for other sources or apply extra treatment methods like POU-DWTUs.

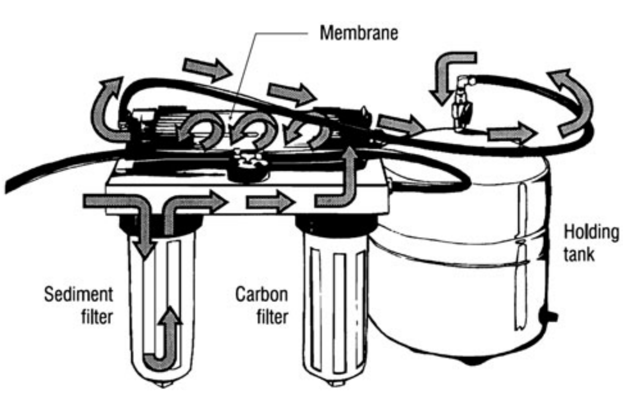

Fig. 1. Point-of-use water treatment device: RO unit, arrows indicate water flow direction through system [15].

There are limited studies on the evaluation of performance of small scale treatment devices (RO units) for desalination of domestic water in the field, [17] particularly in countries with low income. Considering the widespread use of POU-DWTUs, the present study aimed at surveying performance of POU-DWTUs and probable health issues related to application of these devices. Studied devices in this project were combinations of primary filter, carbon filter, RO membrane, and storage tank. For this purpose, Qom is the seventh largest city in Iran was considered as a suitable case for this study. Groundwater of the city is brackish and there are many problems in the supply of drinking water. Low quality of public water system requires residents to cater drinking water as a commodity from providers of fresh water with central RO unites or use their own POU-DWTUs. In this city, fresh water is provided via three different manners:

- The first manner is the central water purifier installations which belong to Water and Wastewater Company (WWC), as the main source of potable water.
- Second manner belongs to private sector with 20 desalination units.
- The third manner is using POU-DWTUs which are being used not only at homes but also in public and trade centers.

WWC and province health center, control central water purifier and private sector installations function, and some limited researches have been conducted on the quality of water [18]. However, despite wide application of POU-DWTUs, the efficiency and effluents quality of these units has not been examined yet. Therefore, the main objective of this present study is to investigate health issues related to POU-DWTUs, quality of raw and treated water, and the operational problems in Qom as one of the cities where POU-DWTUs is widely used.

2. Materials and methods

2.1. Study area

Qom province is one of the 31 provinces of Iran with a population approximatelyof 2×10^6 located in north-central Iran just 156 km southwest of the capital city of Tehran (Fig. 2). Qom is the seventh largest city in the country. According to statistics provided by municipality, the city is divided into four zones. The climate of Qom varies between a desert and a semi-desert climate which is dry with low humidity and marginal rainfall, due to being located near an arid region and distant inland.

2.2. Data collection

The required data in this study were collected from questionnaires and conducting interviews with people who were users of POU-DWTUs and also sampling and analysis of raw and treated water from input and output of POU-DWTUs. The questionnaires completed during the study included information about the type of POU-DWTUs, origin, country, condition of operation and maintenance, user's knowledge, information and satisfaction, conducting quality tests, amount of rejected water, final mixing of demineralized water, education, and guidance by device providers. Part of information about POU-DWTUs was gathered from WWC, manufacturers and sellers. Information about the condition of operation of POU-DWTUs and main users was collected through site visiting, observation, and interviews.

In order to study the performance of POU-DWTUs in providing suitable water quality, a totally 240 samples of raw and treated water were analyzed. The number of required samples was estimated after conducting a pilot study and primary analysis. The samples were randomly selected from homes, banks

Fig. 2. Location of the study area (Qom) on Iran map.

and shopping centers, and in 30 points from each zone of Qom city. Water samples were collected randomly from inlet and outlet of POU-DWTUs.

For physicochemical analysis, two sets of sample were collected in polyethylene terephthalate acid-washed bottles. The first sample was refrigerated at 4˚ C in an icebox without any preservative, and the second sample was acidified with nitric acid to pH <2 for heavy metal analysis. Considering the importance of heavy metals, the analysis using Inductively Coupled Plasma Mass Spectrometry was conducted for As, Al, Cd, Cr, Hg, Pb, Cu, and Zn in both raw and treated water samples.

For bacteriological test, sterilized glass bottles (300 mL) pretreated with sodium thiosulfate was used. An ice box (4℃) was used for the transporting of microbiological samples to the laboratory of WWC. All the experiments were conducted according to the standard methods for the examination of water and wastewater (twentieth-edition) [19]. Residual chlorine was determined onsite using test kit based on the DPD (NN-De-ethl-feniline-D-Amin) method.

3. Results

3.1. Operational condition and problems

According to questionnaire's information and data collected from different sources, some important operational conditions of POU-DWTUs were found as follows:

- All of POU-DWTUs were generally imported from China, Korea, Taiwan, and USA (United States of America).
- Treatment capacity of POU-DWTUs ranged from 100–200 L/day and price is ⩾300$.
- Upto 75% of input raw water rejected from device as the rejected brine water that requires attention when disposal to the environment.
- POU-DWTUs were operated 65% by male and 35% by females.
- Half of POU-DWTUs users did not have correct information about the treatment process and operational principles of the device.
- POU-DWTUs were installed by dealers as the main source of information about POU-DWTUs. However some general, brief, and undocumented information was provided for users by them.
- Judgment about performance of POU-DWTUs by users was based on the taste of treated water and proper instruction; operation manual were not provided by sellers for users.
- None of POU-DWTUs users had conducted quality test for performance of the device.
- About 35% of users were not satisfied with the taste and odor of treated water.
- Almost half of users were not aware of mixing of treated water with saline water for adjustment of mineral composition of final consumed water.
- Only 4% of users were mixing treated water with raw saline water. The reason for this low percentage was found to be the probable pollution of raw tap water and its unsuitable composition for drinking purpose and finally unawareness about required mixing ratio.
- None of users were aware about nutritional value of drinking water, and all of them believed that high content of solids in water will lead to diseases such as stone formation in bladder and kidney, and blocked arteries.
- Cleaning and replacing of POU-DWTUs filters and membranes were not implemented according to specified time period and users did it if they felt deterioration in taste and odor of treated water.
- Users of POU-DWTUs were not aware of regular washing and cleaning of treated water reservoir in order to prevent biofilm formation and bacterial regrowth.
- Most of users (89%) were satisfied with support services provided by vendors.

3.2. Water quality (raw and treated)

Tables 1 and 2 present quality of raw water in Qom city as input of POU-DWTUs and treated water, respectively. According to Table 1, sources of water supply in the studied area include brackish water with high content of solids (Concentration of cations, anions = 42 meq/L). Between the cations and anions, Na^+ (sodium) and Cl^+ (chloride) with 23.9 and 22.5 meq/L, respectively have the highest concentration indicating a sodium chloride type like the condition in arid and semi-arid regions. Also, Mg^{2+} and SO_4^2 (sulfate) were present at high levels. Free residual chlorine differed from 0 to 1.2 mg/L. However, there was no contamination of the coliform bacteria in any sample. According to Table 2 and in the treated water samples, total concentration of main cations and anions has been reduced to 3.73 and 3.89 meq/L, respectively showing 91% reduction in the ions content (Fig. 3). Free residual chlorine in treated water was zero and the heterotrophic plate count (HPC) indicator is upto 1,250 PFU/mL. Table 3 shows the presence of heavy metals in both raw and treated

Table 1
Quality of POU-DWTUs input raw water in the study area

Parameter	Unit	Mean	Minimum	Maximum
Temperature	℃	24	18	29
Color	True color unit (TCU)	0	0	0
Electric conductance	μmhos/cm	4,130	3,605	5,890
pH	–	7.82	7.2	8
Turbidity	Nephlometric turbidity unit (NTU)	0.8	0.3	1.3
Total dissolved solids	mg/L	2,610	2,350	3,205
Total alkalinity	mg/L as $CaCO_3$	170	157	185
Total hardness	mg/L as $CaCO_3$	933	532	1,201
Calcium	mg/L	166	153	233
Magnesium	mg/L	124	111	154
Sodium	mg/L	550	510	620
Potassium	mg/L	10	8	13.5
Chloride	mg/L	800	702	921
Sulfate	mg/L	790	589	870
Nitrate	mg/L as $N\text{-}NO_3$	25.3	3.6	48.5
Fluoride	mg/L	0.8	0.5	0.95
Residual free chlorine	mg/L	0.7	0	1.2
Total coliform (MPN/100mL)	Most probable number in 100 mL	0	0	0
HPC	CFU/mL	55	0	200

Table 2
Quality of POU-DWTUs effluents in comparison with recommended limits

Parameter	Unit	Mean	Minimum	Maximum	Admissible limit	MCL[a]	
						National	WHO (2011)
Temperature	℃	25	20	27	–	–	NGV
Color	TCU	0	0	0	8–12	–	–
Electric conductance	μmhos/cm	251	43.3	704	–	–	–
pH	–	6.45	5.7	7.9	6.5–8.5	6.5–9	NGV
Turbidity	NTU	0.4	0.2	1.9	1 ⩾	5	<1
Total dissolved solids	mg/L	159	26.8	450	1,000	1,500	NGV
Total alkalinity	mg/L as $CaCO_3$	38.2	6.8	80	–	–	NGV
Total hardness	mg/L as $CaCO_3$	60	28	115	200	500	NGV
Calcium	mg/L	7.5	0.78	20	300	–	
Magnesium	mg/L	9.5	5.34	15.59	30	–	
Sodium	mg/L	58	20	160	200	200(250)	50* NGV
Potassium	mg/L	2.42	1.4	5	–	–	NGV
Chloride	mg/L	77	30	200	250	400	NGV
Sulfate	mg/L	46.4	20	100	250	400	NGV
Nitrate	mg/L $N\text{–}NO_3$	8.5	3.6	15.4	–	50	50
Aluminum	mg/L	0	0	0	0.1	0.2	0.2
Fluoride	mg/L	0.05	0	0.34	0.5	1.5	1.5
Residual free chlorine	mg/L	0	0	0	At least 0.2	–	5
Total coliform (MPN/100mL)	Most probable number in 100 mL	0	0	0	0	0	0
HPC[2]	CFU/mL	235	0	1,250	500	–	–

Notes: [a]Maximum Contaminant Level, No Guideline Value (Not of health concern at levels found in drinking-water [4]), *As sodium dichloroisocyanurate.

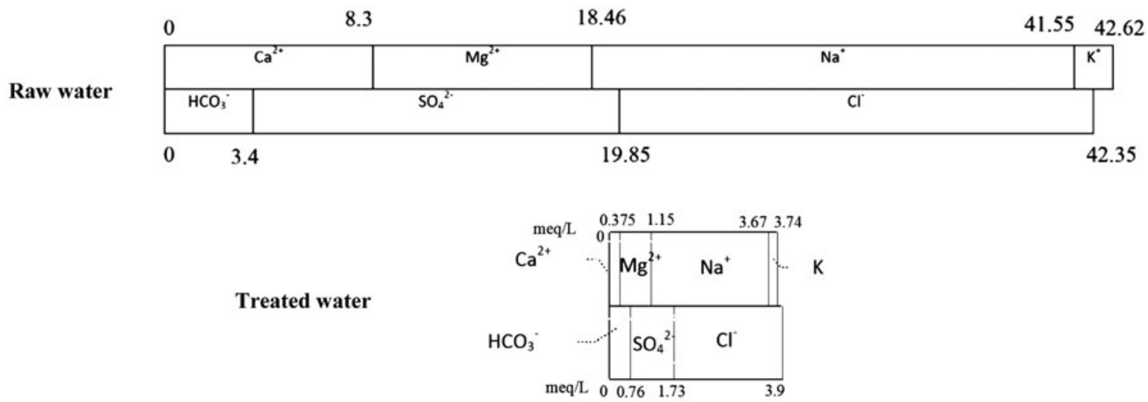

Fig. 3. Ions balance of raw water and treated water by POU-DWTUs.

water samples. In all the samples heavy metals were detectable at different concentrations. In contrast, Cd (cadmium) has the lowest and Zn (zinc) has the highest concentration among heavy metals. Fig. 4 illustrates the removal efficiency of heavy metals by POU-DWTUs. The amount of metals removed by POU-DWTUs varies from 5% for Al (aluminum) to 86% for Cd, and metals can be removed by an average of 43%. Considering total hardness, treated waters are categorized between soft and moderate hard water with low TDS (Table 2).

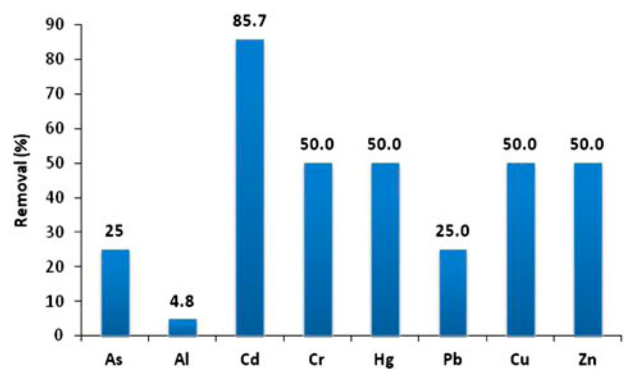

Fig. 4. Comparison of mean removal efficiency of heavy metals by POU-DWTUs.

4. Discussion

For a long time, quality of drinking water and its probable health effects has been a concern for scientists. It is currently estimated that about 1.1 billion people lack access to improved water supplies. Hardness of drinking water as an important quality aspect and its relation with cardiovascular diseases and mortality has been studied in different countries since past decades [20–23].

Application of POU-DWTUs can result in the reduction of solid content and hardness of water. Results of our study showed that POU-DWTUs in Qom city are able to reduce dissolved solids content of raw water (removal >90%) to a level under admissible limit of National Drinking Water Standard and

Table 3
Concentration of heavy metals in raw and treated water and removal efficiency by POU-DWTUs

Heavy metal (mg/L)	Raw water			Treated water			National MCL (WHO guideline)
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	
As	0.02	0.01	0.06	0.015	0.002	0.04	0.01(0.01)
Al	0.21	0.025	0.40	0.20	0.02	0.30	0.2 (NGV)
Cd	0.007	0.001	0.01	0.001	0.0015	0.006	0.003 (0.003)
Cr	0.03	0.01	0.05	0.015	0.01	0.03	0.05 (0.05)
Hg	0.01	0.005	0.02	0.005	0.005	0.01	0.006 (0.006)
Pb	0.04	0.005	0.10	0.03	0.003	0.09	0.01 (0.01)
Cu	0.06	0.03	0.08	0.03	0.02	0.05	2 (2)
Zn	0.1	0.02	0.31	0.05	0.01	0.20	3* (NGV)

Notes: *Admissible limit, No Guideline Value (Not of health concern at levels found in drinking-water [4]).

produce soft water. In other words, POU-DWTUs can act as a good barrier for dissolved solids and microbiological agents [24]. However, a significant amount of raw water (up to 75%) is rejected by treatment unit that can be regarded as an important aspect considering the climate of the region and shortage of water. Furthermore, disposal of rejected brine current with high content of TDS to the environment requires special attention [25]. The findings of our study are similar to those of Elfil et al. [17]. Low pH, alkalinity and hardness, and partly high concentration of chloride and sulfate ions make treated water by POU-DWTUs show tendency for corrosion. Differences in produced water quality by studied POU-DWTUs can be attributed to different operational condition such as, age of filters and different quality levels of raw water or operational pressure. According to the literature, filed and epidemiological studies have shown that consumption of water with low content of TDS can lead to adverse effects on the mucous membranes of the intestines, impaired blood production and other body functions, reduced absorption of calcium and magnesium, low absorption of nutritional elements, loss of calcium, magnesium, and other nutritional elements of food prepared with low-mineral water. It can also lead to an increase in the uptake of heavy metals from storage containers and pipes transporting soft water, regrowth of bacteria, reduction in body electrolytes, increase of urination (20% on average), increase of water volume in the space between cells, increase of sodium and decrease of potassium (K) concentrations in serum, increase in the excretion of sodium, K, chloride, calcium, and magnesium ions from the body, increase in the risk of hypertension and coronary heart disease, gastric and duodenal ulcers, goiter, pregnancy complications, various complications in infants and children, such as jaundice, anemia and growth in structural damage, reduction of 60% of calcium and magnesium, 66% copper (Cu), 70% manganese, and 86% cobalt in the food cooked with soft water, increase in death by arthrosclerosis diseases due to soft water, decrease in secretion of hormones, aldosterone and ADH, and increased urinary sodium excretion, loss of a considerable part of the essential elements of food, especially meat, beans, and vegetables washed during preparation and cooking style in the water, increase of cholesterol level, increase in the retention of cadmium in the body due to low daily intake of calcium absorption, and finally damage to teeth and bones due to low levels of fluoride (F) [26–30].

According to WHO report [31], calcium, magnesium, F, sodium, Cu, selenium (Se), and K are nutrients which are sometimes present in drinking water at potentially significant levels of particular interest. Ca and Mg are micronutrients with the largest proportion of intake from drinking water in relation to food and water which can provide upto 20% of the required total daily intake. For other elements, less than 5% of total intake water is provided by drinking water. Ca and Mg are important in bone and cardiovascular health, F^- has a role in preventing dental caries, Na^+ is an important extracellular electrolyte, Cu is important in antioxidant function, iron utilization and cardiovascular health, Se is important in general antioxidant function and in the immune system, and finally K^+ is important for a variety of biochemical effects.

Intake of essential nutrients is expressed in terms of recommended daily intakes, recommended nutrient intake, recommended dietary allowances (RDA), population reference intakes, and adequate intake (AI). For male (age $\geqslant$19) the amounts (in mg) for Ca, Mg, P, and F are 1,300 (AI), 400 (RDA), 700 (RDA), and 4 (AI), respectively. For females (age $\geqslant$19) the amounts (in mg) for Ca, Mg and P are 1,000 (AI), 310 (RDA), 700 (RDA), respectively, and for F it is 3 mg (AI, age 18 years). In the case of Na, K, and Cl in persons aged $\geqslant$18 years, the minimum requirement is 500, 2000, and 750 mg, respectively [31].

Therefore, regarding the above-mentioned facts about consumption of soft water and nutritional value of elements for example, Ca and Mg, and the role of drinking water in providing parts of required nutrients, it is expected to observe similar adverse health effects in the long run in Qom citizens who consume treated water by POU-DWTUs without remineralization or final mixing with primary raw water for adjustment of mineral content of water. Bodzek et al. reported that RO process is not favorable for the production of drinking water because of too high retention of water elements that are responsible for the water health virtues [32]. He suggests mixing of water softened on RO by other waters. It should be considered that application of RO units for desalination of water provides an important opportunity especially in larger plants. However, including a final step for selective remineralization often mainly consisting of injection of carbon dioxide ahead of a bed of limestone or its equivalent [33], and increasing alkalinity for the purpose of reducing corrosivity of water is required [31]. Adding of Mg^{2+} ions to desalinated water using packed bed column has been also suggested [34].

As expected, unfortunately in all samples of treated water with POU-DWTUs, residual chlorine was zero. This means that in the case of probable secondary pollution during storage of treated water, consumers' health can be threatened. In addition, biofilm growth in the storage containers is expected. During the distribution of treated water by water supply network, post disinfection is necessary to control microorganisms, as well as to eliminate pathogens from post treatment for example, the blending process [31]. HPC test in our study showed an increase in level of heterotrophic bacteria from average 55 PFU/mL in raw water to 235 PFU/mL in treated water. However, it should be noted that some of RO membrane are not chlorine resistant and if not suitably protected by pretreatment filtration, and thus could be damaged by residual chlorine in the raw water.

In the study of Yari and et al. on the quality of water treated with central water desalination unites (RO) of Qom city, it was reported that concentration of residual chlorine; total hardness, and F were below the minimum required level. Moreover, pH in nearly all of samples was under the acceptable range [18]. Bacteriological test showed presence of *Escherichia coli* in 6% of samples. In a similar study, Miranzadeh and et al. conducted a research on quality of water produced by 16 desalination plants (RO) in Kashan city [35]. Based on his findings on desalinated water, except fluoride, other parameters were in accordance with the optimum concentration for drinking water. While, pH of outlet water was relatively decreased with respect to the raw water, none of them were compatible with drinking water standards. High value of HPC in some samples during our study indicates the potential for microbial growth and contamination. Storage of treated water in an unclean reservoir for a long time, and especially high temperature (25˚C) of the environment can provide suitable conditions for growth of microbial agents. Increasing odor and taste of water will be a possible consequence that may cause some form of disease. Thus regular cleaning of storage reservoirs and preventing biofilm formation is deemed very important. According to Trevett and et al., in household water management, there are multiple points during the collection to use sequence where pollution could occur [36]. In the study of Jafaripour and et al. on technical, economical, and health-related issues of household RO units in Qom, it was reported that for production of 157,680 m^3/year required for 36,000 family in work pressure equaling to 6–10 Kg/cm^2, with recovery percentage of 30, flux of 1 L/min and temperature 4–38˚C, 14191200 kWh power is consumed and 367,920 m^3 brine effluent is generated and disposed without suitable consideration. Also 198,000 replaced filters are disposed to the environment [37].

For heavy metals concentration, our results showed presence of Pb (lead) in high concentration in both of raw and treated water. Unfortunately, about 25% of Pb is removable by POU-DWTUs. In an output of POU-DWTUs the level of Pb was three times higher than that of National MCL. This high concentration can be attributed to leaching of Pb form distribution network and pipelines because of high Cl^- and SO_4^{2-} anions in raw water that makes water corrosive. It should be considered that soft water passing through the pipes can also increase the concentration of dissolved metals after treatment units.

Aluminum is virtually eliminated by POU-DWTUs so that minimum removal efficiency was for Al (5%). As (arsenic) also had low removal efficiency (25%). Thus, when the raw water contains a high level of As sufficient attention should be paid to this quality issue of water because of toxicity of those elements [38].

5. Conclusion

Based on the findings of the present study, the following suggestions can be made for management of POU-DWTUs by citizen and health authorities for example, ministry of health:

(1) There is an increasing trend in extensive application of POU-DWTUs, especially in warm semi-arid and arid area of Iran. Therefore, it is necessary that appropriate measures should be taken by health authorities to make provision for the use of POU-DWTUs.
(2) Education of dealers and users of POU-DWTUs as an important step for minimization of possible adverse effects is strongly recommended. Informative pamphlets or brochures about POU-DWTUs process, correct maintenance options, and quality of treated water should be provided by WWC and health authorities for citizens.
(3) Considering low content of TDS of treated water by POU-DWTUs, mixing it with raw water is recommended (addition of 200–400 mL of raw water in 5 L based on quality of raw water).
(4) It was determined that POU-DWTUs are not successful and reliable in complete removal of heavy metals. Therefore in regions where raw water is contaminated with heavy metal in high concentration, application of POU-DWTUs cannot ensure safety of chemical quality of treated water. However, it should be kept in mind that high concentrations of heavy metals in treated water may be due to the passing of soft water through pipes. This in turn is an issue which requires further studies.

(5) For evaluation of POU-DWTUs application of better quality tests for example use of EC meters (electric conductivity) is recommended.
(6) Due to the fact that some of RO membrane are not chlorine resistant and could be damaged by residual chlorine in the raw water if not suitably protected by pretreatment filtration, it is recommended to consider this fact during future studies.
(7) Proper actions by users for prevention of secondary pollution of treated water in storage reservoirs should not be neglected (e.g. keeping them in clean areas of home without dust and airborne particles, avoiding the use of open mouth container, not using other containers to take water from reservoir, regular cleaning with detergents, disinfection, and etc.). These actions are more important especially in apartments and offices, which have central water purifiers in which water stored for a long time.
(8) National standards for quality of POU-DWTUs should be established by National Institute of Standard and be applied as a preparatory measure in importing these devices to the country.
(9) Requirements or guidelines should be established to treat water by POU-DWTUs quality standards.
(10) In regions where POU-DWTUs are widely used, conducting of epidemiological studies are recommended to provide knowledge about possible health effects of consumption of drinking water with low content of dissolved solids.

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