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Quantitative and qualitative assessment of rainwater harvesting as an alternative water source in semi-industrial areas

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ABSTRACT

Rainwater harvesting (RWH) from the roofs of buildings can be an alternative source to meet urban water demands. Harvested rainwater could be significant in industrial buildings and factories due to their large roof areas. In this study, the quality and quantity of harvested rainwater that was stored in tanks of different storage volumes in a semi-industrial area were investigated. Mathematical modeling and an analysis showed that for roof areas between 500 and 3,000 m^2, the volume of rainwater stored in small storage tanks (less than 25,000 L) ranged from 134 to 743 m^3 and the volume of rainwater collected in large storage tanks (more than 25,000 L) was within the range of 172–956 m^3. The reliability of meeting daily water demands of storage tanks of at least 1,000 L to a maximum of 5,000 L for small roof areas (from 500 to 1,500 m^2) ranged between 25%–70% and 3%–22%, respectively. Similarly, reliability for large roof areas (2,000–3,000 m^2) varied from 38% to 78% and from 10% to 36%, respectively. For qualitative analysis of RWH systems, two pilots were made of galvanized steel and isogum. The values of chemical, physical and microbial parameters of the collected rainwater samples from isogum and galvanized steel roof covers, including Cl^-, So_4^{2-}, No_3^-, Mg^{2+}, Cd^{2+}, TDS, Cr, Ni, and total hardness, were found to be less than those of drinking water standards. Statistical analysis indicated that the galvanized steel pilot is more suitable than the isogum pilot in terms of meeting the criteria specified by the drinking water Standard No. 1053 of Iran. The microbial content of the harvested rainwater in the galvanized steel pilot was in the acceptable range and lower than those of the isogum pilot. In the galvanized steel pilot, no content of fecal coliform and fecal streptococci was observed, and the total coliform levels were negligible. The findings suggest that RWH could meet a part of industrial water demands.

Keywords: Rainwater harvesting; Reliability; Quantitative and qualitative; Water supply; Semi-industrial areas

1. Introduction

Nowadays, rainwater harvesting (RWH) in urban areas is one of the most practical water supply techniques. Harvested rainwater from roofs is one of the sources of recycled water [1] and can help in providing of potable water [2] and reduce the use of potable water for non-potable [3]. RWH may become an alternative water resource [4–7], or an alternative source to contaminated groundwater [8] and non-potable uses such as irrigation and toilet flushing [9]. Moreover, RWH is a useful measure in emergency cases [10], reducing wastewater discharges [11]. Water shortage in dry season may be partially resolved by RWH in wet season [12]. One of the problems with RWH is, however, the lack of rainfall in dry season [13]. RWH systems installed to collect water from roofs of residential buildings could facilitate the management of water crisis [14]. The use of domestic RWH for poor urban households has the potential to increase water supply [15] and has been proved to be contributed to the improvement of smallholder livelihoods [16]. In the future, due to population growth and urban development, RWH will become more important as a sustainable

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water resource [17]. Harvested rainwater from green roofs must be processed with general water treatment methods [18]. RWH from green roofs can be used for non-potable purposes [19]. RWH systems in office-scale potentially offer significant water and cost savings [20], and they can also be the best choice for non-potable purposes in commercial buildings [21]. Reliability analysis of urban RWH systems for daily water demand in Dhaka city showed that 15%–25% reliability can be achieved under the wet climatic condition. Furthermore, for catchment sizes varying from 140 to 200 m^2, the harvested rainwater can be up to 550 kL/year [22].

For Irish households, uses of RWH and greywater treatment systems have the potential to supply nearly 94% of domestic water requirement [23]. Furthermore, greywater reuse could reduce wastewater discharge [24]. It has been indicated that recycling treated greywater for use in toilet flushing is an effective method in reducing drinking water consumption [25] and that water reuse can help in solving water problems [26]. RWH serves different purposes, including water supply and runoff capture [27,28]. Moreover, this system can increase availability and quality of the groundwater [29]. Recycled stormwater can potentially be used as an alternative source of irrigation water [30]. Investigation of the potentiality of RWH systems in the South Agrabad in Chittagong city using the analytic hierarchy process (AHP) approach revealed that these systems provide a sustainable solution to urban flooding problem and city water demand [31]. RWH is also an effective method for control of stormwater runoff [32–34]. Furthermore, stormwater detention tanks have been proved to be an effective way of reducing stormwater pollution [35]. Evaluation of RWH in single-family houses in Portugal indicated that the economical viability of RWH systems is significantly influenced by water fees [36]. Economic cost and potential environmental impact of RWH systems were assessed using the software program Plugrisost. It was shown that in case that the water price was greater than 4 €/m^3, RWH system was an economic alternative on the single-house scale. Additionally, suitable tanks should be with less than 5 m^3 of storage capacity based on the analysis of the environmental impact [37]. Investigation of the potential of harvesting rainwater from the roofs of non-residential buildings showed that RWH could make the net total water saving of 3.45×10^6 m^3/year in Amman, Jordan. Moreover, it was concluded that water supply via this system is less expensive compared with the conventional water supply systems. RWH also can help reducing CO_2 emissions [38].

Today, water quality control is one of the main challenges in decentralized water supply systems [39]. The quality of collected rainwater is influenced by different factors, including particles from pollutants, microorganisms, dust [40], geometry, location and maintenance of roof [41], roof slope and roughness [42], roof material [43–45], topography and weather conditions [46], wind speed [47], rain intensity [48], number of drought days before rainfall [49] and first flush [50].

The purpose of this paper was to evaluate the potential of RWH from roofs of large industrial buildings in a semi-industrial area in the northeast of Tehran, Iran. Furthermore, the spilled rainwater from the storage tanks and the overall reliability of the system were determined under different conditions. Also, two RWH pilots involving isogum and galvanized steel roof covers were tested under several rainfall events, and the quality parameters of the collected rainwater were measured and evaluated in terms of chemical, physical and microbial aspects.

2. Methodology

2.1. Simulation procedure

RWH systems consist of three main parts: harvesting area (roof), water transmission component and water storage (tank). Tank volume should be proportional to the harvesting area (roof) [51], and the tank size is important to maximize rainwater savings [52]. Collected rainwater from roof is transferred to the storage tank by gutters and pipes. In case that the input rainwater volume is more than the remaining tank capacity, the excess rainwater may spill from the tank through a spillway (spilled water) and be directed to surface drains or sewage network (Fig. 1).

Harvested rainwater volume (H) is a function of the roof area (A), rainfall depth (R) and roof runoff coefficient (ϕ) as follows:

$$H = \phi \times R \times A \tag{1}$$

where R is in millimeters; A is in square meters; H is in L; and ϕ is dimensionless. Eq. (1) is based on a daily basis. The volume of water stored in the tank (i.e., prior to the rainfall) (V'), withdrawn from the tank (D_t) and spilled water (SP) are related as follows:

$$V = H + V' - D_t - SP \tag{2}$$

where V represents the remaining water in the tank; all parameters are in L. The volume of SP can be mathematically expressed by:

$$SP = \max(0, (H + V' - D_t) - V_{\text{Tank}}) \tag{3}$$

where V_{Tank} is the volume of the tank (tank capacity); all units are in L.

If (D_t) is less than the total water demand (D_d), the shortage supplemented by the urban water supply system (D_d) can be defined as follows:

$$D_c = \max(0, D_d - D_t) \tag{4}$$

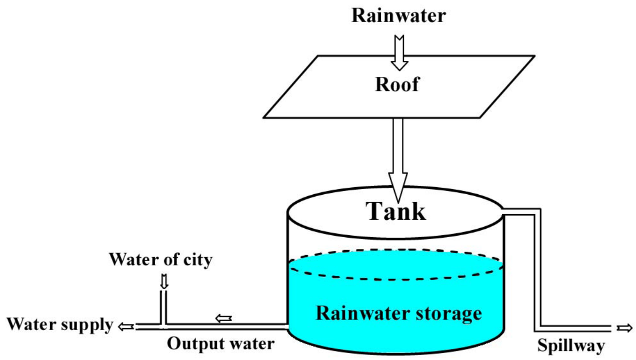

Fig. 1. Schematic view of a rainwater harvesting system.

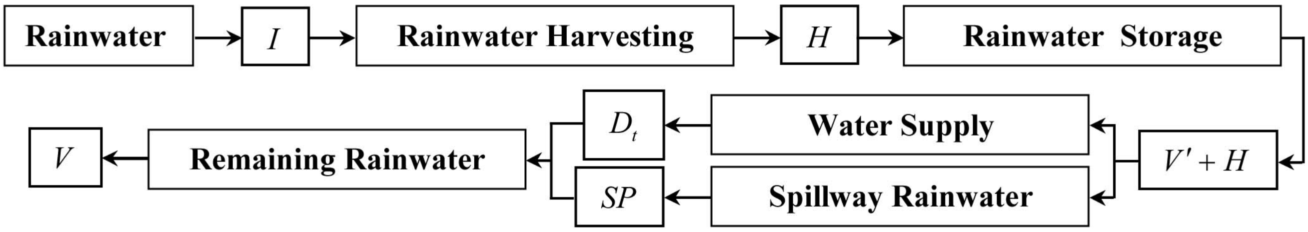

Fig. 2. Flowchart of rainwater harvesting system components.

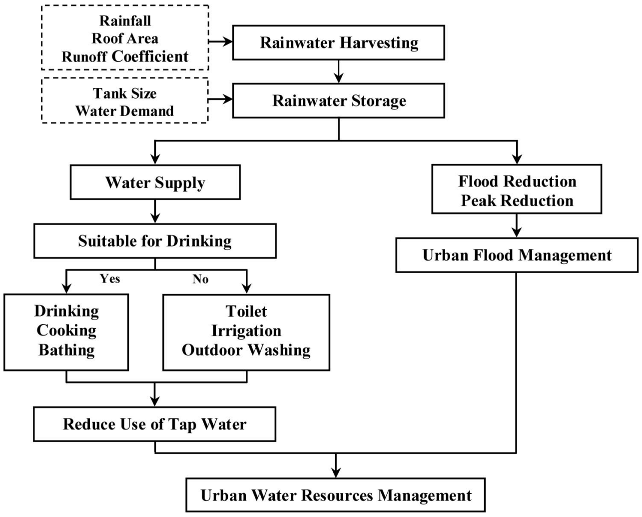

Fig. 3. Flowchart of operation RWH system from the roof of buildings.

All units are in liters. Fig. 2 shows the flowchart of interrelation of RWH system components.

The reliability of a RWH system is strongly dependent on the average annual rainfall [53]. However, the size of storage tank, the harvesting surface area and the daily water consumption also affect the reliability. The reliability can be obtained from:

$$\mathrm{Re} = \frac{D}{D'} \times 100 \tag{5}$$

where Re is the reliability (%); D is the total number of days when water demand is supplied by the RWH system alone (i.e., $D_c = 0$); and D' is the total number of days in any year.

The quality of collected rainwater in storage tanks determines whether it is suitable for potable or non-potable uses. The operation process of the RWH system in this study can be described by Fig. 3. According to Fig. 3, RWH depends on the rainfall characteristics, the roof area and the runoff coefficient. Furthermore, rainwater storage is a function of the tank size as well as the water demand of the inhabitants. The same figure indicates that the harvesting and storage of rainwater result in water supply and flood reduction, ultimately causing improvement in urban water resources management. The uses of the rainwater collected by RWH systems are highly dependent on the rainwater quality. The compatibility of different uses of water has to be examined by analyzing physical, chemical and biological aspects of water quality.

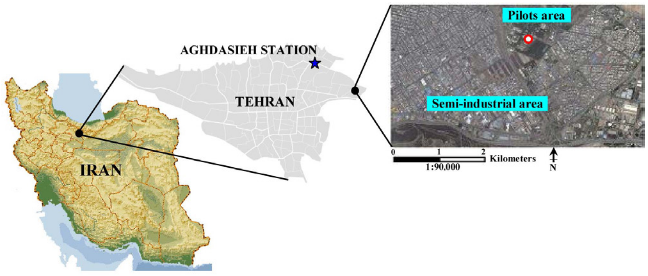

Fig. 4. Location of the pilots in the northeast of Tehran, Iran.

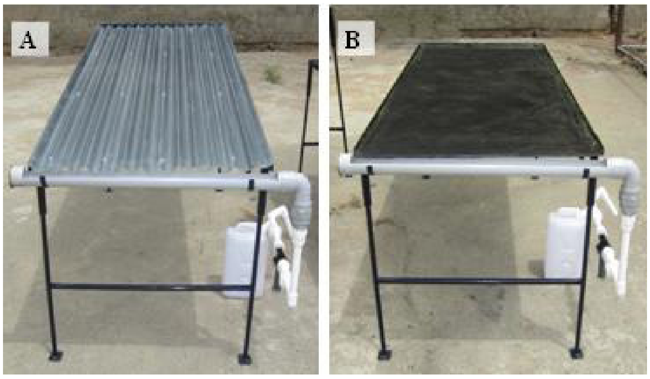

Fig. 5. (A) Galvanized steel pilot and (B) isogum pilot.

2.2. Rainfall data

In this study, rainfall data collected at a meteorological station (Aghdasiyeh station) in northeastern Tehran were used. Fig. 4 shows the location of this station in the study area. According to the daily rainfall data between 1984 and 2013 (30 years), the average annual rainfall of the area was 431 mm.

2.3. Test pilots and sampling

Two pilot-scale models to evaluate the quality of collected rainwater from two roofs of different types were developed. The roofs of the factories and industrial buildings in the study area were made of galvanized sheets and, in some cases, from isogum, which is a resistant coating of bitumen and synthetic fibers attached to the roof by heat. As a result, galvanized steel was used for one of the pilots and isogum for the other one (Fig. 5). Harvesting area of both pilots was 2 m^2. Slope of isogum pilot was 1.5% while that of galvanized sheets pilot was 12.5%. These slopes were selected based on the typical slope of the industrial

Table 1
Date and depth of rainfall and air pollution conditions on the day of sampling

	Sampling (1)	Sampling (2)	Sampling (3)	Sampling (4)	Sampling (5)
Date	2014.Apr.23	2014.Apr.27	2014.May.15	2014.May.21	2014.May.24
Rainfall depth (mm)	22.4	4.1	4.6	3.6	5.0
Air quality index (AQI)	54	44	51	68	65
Level of health concern	Moderate	Moderate	Moderate	Moderate	Moderate

buildings' roofs. In both pilots, a metal frame with a height of 3 cm surrounded three sides of the harvesting area while in the downstream side there was no frame so that the rainwater can freely flow to the gutters.

Rainwater collected from the pilot area was filtered and then transferred to the tank via a PVC tube with a semi-circular shape and a diameter of 8 cm. Drain slope was 3% so that the rainwater could easily be directed to the filter and the tank. Water flowed through a plastic tube with a diameter of 2 cm. Physical filters used in pilots perform similar to a first flush device and prevent entry of initially collected water to the storage tank. The storage tank of pilots was made of transparent plastic with a volume of 10 L. At the top of the inlet pipe to the storage tank, a 90-degree spillway was installed to let excess rainwater (i.e., SP) out of the tank when the tank became full. Fig. 5 illustrates the system components of the pilots. The pilots were placed in the northeast of Tehran in Hakimiyeh district, a semi-industrial area (Fig. 4).

After each rainfall event, samples of rainwater from storage tanks were collected, kept in sterile containers tank and transferred immediately to a laboratory for testing.

Overall, five rainfall events in the spring were studied. Table 1 presents the date and amount of rainfall in each sampling event. After each test, in order to prepare the pilots for the next test, the rainwater inside the tanks and filters was drained, and gutters, filters and tanks were washed and cleaned. During the fourth rainfall event, rainwater was collected once directly in a clean container, and chemical, physical and microbial parameters were measured.

In this research, studied roof areas of 500, 1,000, 1,500, 2,000 and 3,000 m^2 and capacity of the rainwater tanks ranged from 5,000 to 55,000 L. The water demand for industrial buildings in the study area was considered in the range of 1,000–5,000 L/d.

3. Results and discussion

3.1. Quantitative assessment

Fig. 6 shows the average daily rainfall based on the rainfall data recorded in the Aghdasiyeh station. The most of rainfall occur in winter and spring months, and the minimum amount of rainfall occurs in summer months. Fig. 7 shows the average annual rainwater storage for different roof areas. For roof area of 500 m^2, the average rainwater storage varies from 134 to 172 m^3/year for different tank volumes from 5,000 to 55,000 L. For tank volumes over 19,000 L, the average annual storage remains 172 m^3. Mean rainwater storage values in roof area of 1,000 m^2 and storage tanks from 5,000–35,000 L are in the range of 190–342 m^3/year and remain almost constant about 344 m^3 in

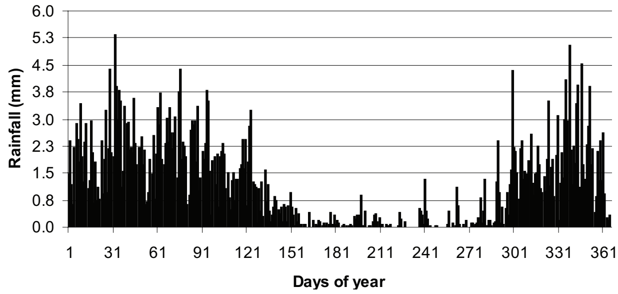

Fig. 6. Average daily rainfall depths (starting from January 1).

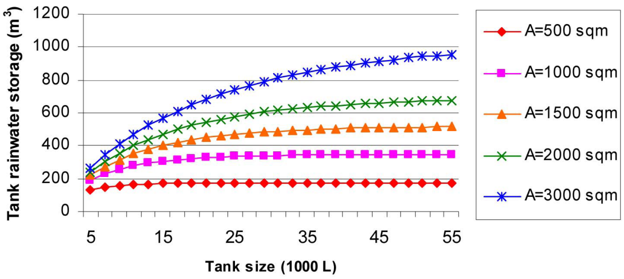

Fig. 7. Average annual rainwater storage in tank for various roof areas and tank size.

tank volumes over 36,000 L. As for roof area of about 1,500 m^2, the average rainwater storage is approximately between 222 and 514 m^3/year. In order to evaluate the effect of tank size on the rainwater storage, the average of the rainwater storage values in different roof area for any tank size was calculated. The average of rainwater storage values in 5,000–35,000 L tanks ranges from 222 to 497 m^3/year, and the minimum of the mean rainwater storage values for the tanks of more than 36,000 L capacity is 500 m^3/year. For a 2,000-m^2 roof area and a tank volume between 5,000 and 29,000 L, the rainwater storage is between 242 and 604 m^3/year, and for a tank volume from 30,000 to 55,000 L, it is almost in the range of 610–675 m^3/year. Stored rainwater volume ranges between 267 and 956 m^3 for roof areas of 3,000 m^2. According to Fig. 7, the volume of stored rainwater in case of small storage tanks has higher variation than in large tanks. Additionally, this variation is higher for larger roof areas compared with the smaller roof areas. This result concurs with that of a similar study conducted in Sidney to investigate the water savings potential of rainwater tanks installed in multi-unit buildings, Australia [54]. Another research on the RWH systems of the same city showed that water savings increase with rainwater tank size for different water uses [55]. The other factor that can be considered in RWH systems is filling frequency. This parameter specifies how many times the rainwater storage tank becomes full each year. Filling frequency depends on the average local rainfall and the storage tank capacity [56]. The studies conducted in the urban area of Jordan indicated that the minimum and maximum of this parameter are related to governmental schools with a minimum storage of 150 m^3 and universities with a minimum storage of 200 m^3, respectively [38].

The annual average volume of *SP* for various roof areas is presented in Table 2. The annual mean spilled rainwater volume for a 500-m^2 roof in the case of low and high water demands (i.e., 1,000 and 5,000 L/d) varies from 4 to 67 m^3/year and 0 to 38 m^3/year, respectively. For tank sizes over 35,000 L with a water demand of 2,500 L or more, *SP* is almost negligible. For a 1,000-m^2 roof, the mean *SP* ranges from 3 to 215 m^3/year. Generally speaking, the *SP* in case of small tanks is less than 200 m^3/year, and for large tanks, it is less than 50 m^3/year.

According to Table 2, for a 1,500-m^2 roof, the *SP* from the tanks in the case of low and high water demands roughly ranges between 255–376 m^3/year and 33–294 m^3/year, respectively. The average spilled rainwater volume from the tanks in case of 2,000 m^2 roof areas is in the range of 218–542 m^3/year, corresponding to water demands between 1,000 and 2,500 L/d and approximately in the range of 99–477 m^3/year connected with water demands between 3,000 to 5,000 L/d. For the roof area about 3,000 m^2, changes in the volume of spilled rainwater from small-size tank are more pronounced than those in large-size tanks. Whereas for tanks of 5,000–25,000 L, capacity changes in the volume of spilled rainwater are in the range of 474–878 m^3/year; for tank sizes between 26,000 and 55,000 L, this figure ranges from 313 to 781 m^3/year.

Fig. 8 shows the reliability of the RWH system for various roof areas. For water demands from 1,000 to 2,500 L/d, changes in the reliability of 500 m^2 roof area are in the range of 9%–44% (Fig. 8(a)). The reliability for water demands of 3,000, 4,000 and 5,000 L/d and tank sizes over 25,000 L remains unchanged, about 11%, 7% and 5%, respectively. For 1,000 and 1,500 m^2 roof areas (Figs. 8(b) and (c)), changes in the reliability of water demands between 1,000 and 2,500 L/d are, respectively, in the range of 14%–65% and 17–70%. The results of previous studies also indicated that the supply reliability increases with storage volume [57], and for smaller roof areas, the reliability never reach 100% even if tank size is increased [58]. The maximum reliability for water demands of 3,000, 4,000 and 5,000 L/d and 1,000 m^2 roof areas (Fig. 8(b)) are, respectively, 27%, 19% and 14%, and for 1,500 m^2 roof area (Fig. 8(c)) for the same water demands are 38%, 29% and 22%, respectively. The reliability for low water demand (i.e., 1,000 L/d) in 2,000 and 3,000 m^2 roof areas (Figs. 8(d) and (e)) is, respectively, in the range of 38%–74% and 40%–78%, and for high water demands (i.e., 5,000 L/d), the reliability ranges from 10% to 29% and 11% to 36%, respectively. Table 3 provides the reliability values under various conditions. The results of previous studies indicated that the reliability for a roof size of up to 150 m^2 having two people is almost impossible to achieve a 100% for wettest year and large tank size [59]. According to the results of other studies, an appropriate selection of rainwater tanks, reliably of total demand met, can up to 60% [60]. Another research on the RWH tanks in the coastal areas of Bangladesh reported maximum reliability of 70%–85% for average climate condition [61].

3.2. Qualitative assessment

Tables 4 and 5 present the results of measured chemical parameters of the RWH for the isogum pilot (I.P) and the galvanized steel pilot (GS.P). All samples were analyzed according to the drinking water Standard No. 1053 of Iran [62].

The small number of samples (i.e., rainfall events) did not allow water quality data to be characterized by a normal distribution. Therefore, the non-parametric Wilcoxon test was used to make comparisons among data. A significant level of $\alpha = 0.05$ was used. In addition to comparing the water quality parameters of the rainwater harvested from the galvanized and isogum pilots, the water quality parameters of the harvested rainwater of each type of pilot were compared with those of the drinking water standards and the ambient rainwater sample, which was collected for one rainfall event.

Table 2
Spilled rainwater for various tank volumes, roof areas and water demands

Roof area (m^2)	Tank volume (1,000 L)	Spilled rainwater volume (m^3) for different daily water demands						
		1,000 L	1,500 L	2,000 L	2,500 L	3,000 L	4,000 L	5,000 L
500	5–25	18–67	7–57	4–51	2–47	1–44	1–40	0–38
	26–55	4–17	1–6	0–3	0–2	0–1	~0	~0
1,000	5–25	138–215	95–198	70–186	55–177	46–170	35–161	28–154
	26–55	102–136	54–93	31–67	19–53	11–43	5–32	3–26
1,500	5–25	291–376	234–355	193–340	166–328	147–319	121–305	105–294
	26–55	255–290	181–231	131–190	96–162	73–143	48–117	33–101
2,000	5–25	452–542	387–518	337–501	299–488	273–477	237–460	213–446
	26–55	415–450	334–385	267–333	218–295	179–268	128–232	99–207
3,000	5–25	783–878	709–851	650–832	602–816	564–804	510–783	474–765
	26–55	744–781	654–706	574–646	511–597	456–558	370–502	313–466

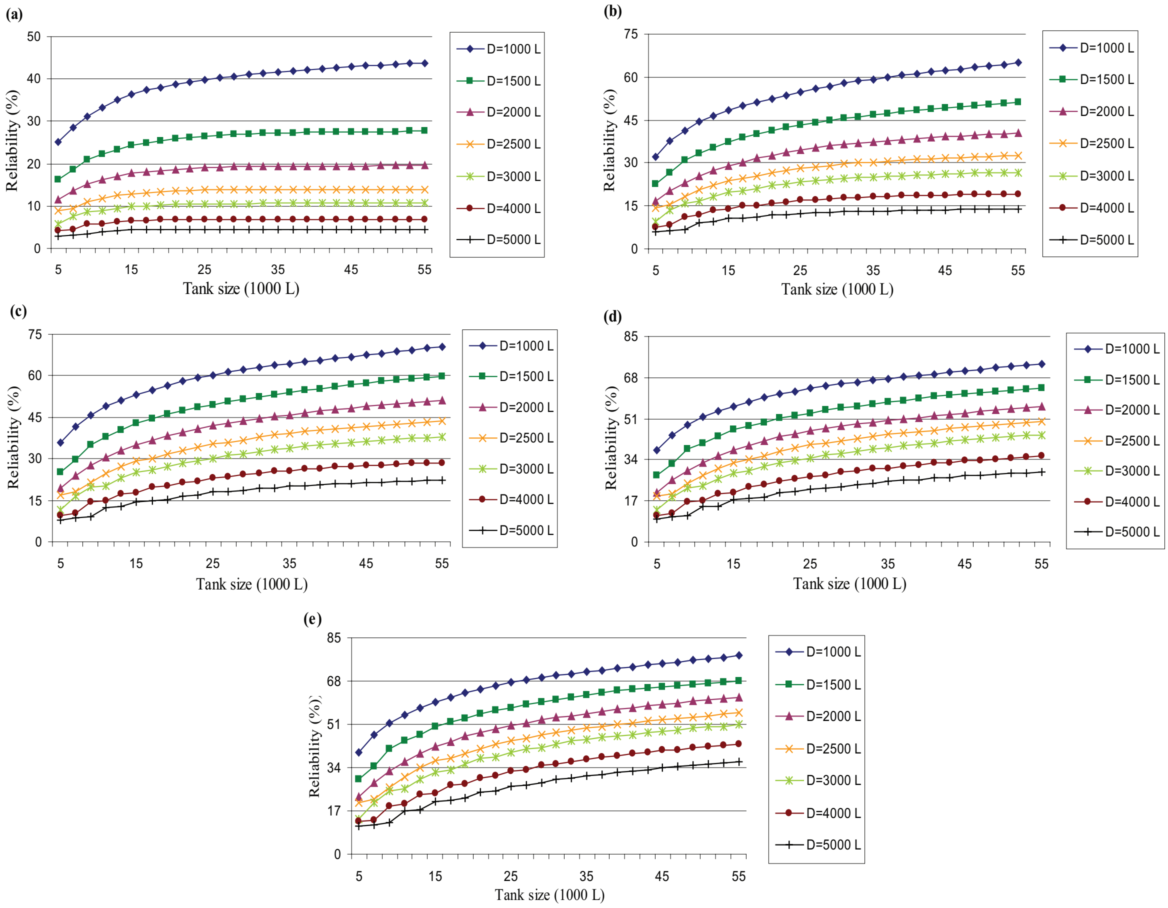

Fig. 8. Reliability for different water demands for (a) A = 500 m², (b) A = 1,000 m², (c) A = 1,500 m², (d) A = 2,000 m², and (e) A = 3,000 m².

Table 3
Reliability for various tank volumes, roof areas and water demands

Roof area (m²)	Tank volume (1,000 L)	Range of reliability (%) for different daily water demands						
		1,000 L	1,500 L	2,000 L	2,500 L	3,000 L	4,000 L	5,000 L
500	5–25	25–40	16–26	12–19	9–14	6–10	4–7	3–5
	26–55	40–44	26–28	19–20	~14	~10	~7	~5
1,000	5–25	32–55	23–43	17–35	14–28	10–23	8–17	6–12
	26–55	55–65	43–51	35–40	28–33	23–27	17–19	12–14
1,500	5–25	36–60	25–50	19–42	17–35	12–30	10–23	8–18
	26–55	60–70	50–60	42–51	35–44	30–38	23–29	18–22
2,000	5–25	38–64	28–53	20–46	19–40	13–35	11–27	10–22
	26–55	64–74	53–64	46–56	40–50	35–44	27–35	22–29
3,000	5–25	40–67	29–58	23–51	20–45	14–40	13–33	11–27
	26–55	67–78	58–68	51–62	45–55	40–51	33–43	27–36

The results of the test indicated that with the exception of total organic carbon (TOC) and NH_4^+, the differences between the all chemical parameters mean concentrations of the two pilots were not different. The mean concentrations of TOC and NH_4^+ from the isogum pilot (262.63 and 7.29 mg/l) were significantly higher than those of the galvanized steel pilot (17.47 and 2.27 mg/l). Fig. 9 shows box plot diagrams of TOC, NH_4^+, conductivity, total suspended solids (TSS), turbidity, lead, and iron for the I.P and GS.P.

The drinking water Standard No. 1053 of Iran has specified the standard values for some chemical parameters (Table 4). Among these parameters, while the mean turbidity

Table 4
Summary of the chemical parameters of rainfall and harvested rainwater samples in two pilots

Parameter	Cl^-, mg/l		So_4^{2-}, mg/l		No_3^-, mg/l		Na^+, mg/l		K^+, mg/l		Mg^{2+}, mg/l		Ca^{2+}, mg/l		Total hardness, mg/l		NH_4^+, mg/l	
Pilot type	I.P[a]	GS.P[b]	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P
Mean	6.12	3.86	54.26	19.93	15.01	12.23	8.27	4.64	1.76	1.21	2.62	1.34	51.93	18.39	140.31	51.40	7.29	2.27
Median	2.95	2.08	26.08	17.09	11.89	10.85	8.00	4.95	1.07	0.74	2.99	1.09	28.33	17.53	75.25	47.32	8.44	2.19
Maximum	20.61	11.85	190.02	36.83	28.82	20.56	19.09	8.42	5.01	3.41	5.33	2.79	156.49	33.74	412.37	95.66	9.25	2.83
Minimum	0.83	0.68	7.73	6.40	3.90	3.56	1.59	1.33	0.46	0.27	0.65	0.76	7.78	7.10	22.08	20.84	2.12	1.83
Rainwater	2.48		12.82		6.96		7.00		0.49		0.64		10.25		28.20		0.07	
1053 Standard	400[c]		400[c]		50[c]		–		–		30[d]		300[d]		500[c]		–	
p value	0.00	0.00	0.001	0.00	0.001	0.00	–		–		0.00	0.00	0.001	0.00	0.007	0.00	–	

[a]Isogum pilot.
[b]Galvanized steel pilot.
[c]Allowable maximum.
[d]Desirable maximum.

Table 4 (continued)
Summary of the chemical parameters of rainfall and harvested rainwater samples in two pilots

Parameter	TDS, mg/L		TSS, mg/L		TN, mg/L		TOC, mg/L		Turbidity, NTU		pH		EC, µs/cm	
Pilot type	I.P[a]	GS.P[b]	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P
Mean	209.00	82.00	16.38	14.27	25.52	12.11	262.63	17.47	21.59	22.51	4.90	6.37	310.00	129.00
Median	115.00	74.00	13.50	12.00	18.72	12.16	158.50	10.90	20.91	24.56	4.32	6.52	180.00	116.00
Maximum	630.00	166.00	21.15	17.13	61.36	18.80	850.00	49.28	33.26	30.31	7.00	7.63	900.00	259.00
Minimum	28.00	26.00	11.75	11.20	6.57	5.49	13.94	4.64	12.88	9.43	3.99	4.46	47.00	43.00
Rainwater	51.00		8.00		12.96		9.43		7.00		6.71		86.00	
1053 Standard	1,500[c]		–		–		–		<5[c]		6.5–9[c]		–	
p value	0.00	0.00	–		–		–		0.00	0.004	0.002	0.008	–	

[a]Isogum pilot.
[b]Galvanized steel pilot.
[c]Allowable maximum.

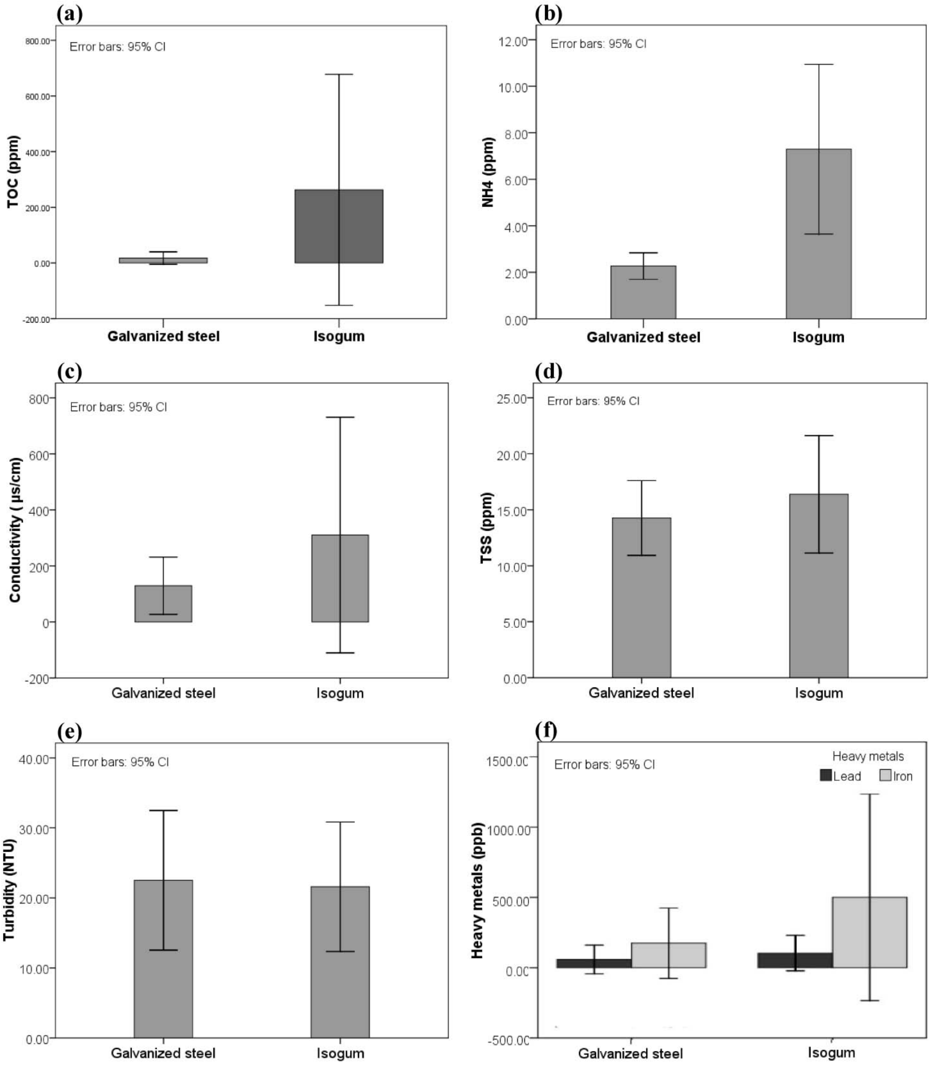

Fig. 9. Box plot diagram for the (a) TOC, (b) NH_4^+, (c) conductivity, (d) TSS, (e) turbidity, and (f) lead and iron for the isogum and galvanized steel pilots.

of the rainwater harvested from both the pilots exceeded the standard of 5 NTU, that of other chemical parameters met the standard values. For example, allowable maximum Cl^- and So_4^{2-} contents are equal to 400 mg/L, according to the drinking water Standard No. 1053; thus, the harvested water is considered potable with respect to chloride and sulfate contents in both pilots. Regarding the heavy metals, there was no case with concentration significantly higher than standard values. The average Fe, Zn, Cr and Ni concentrations of the galvanized steel pilot was significantly lower than their standard values (Table 5). For the isogum pilot, the Cr and Ni concentrations met the standards. The comparison of the water quality parameters of the ambient rainwater sample and those of the rainwater harvested from the galvanized steel pilot showed that all parameters of runoff water, with the exception of TSS, NH_4^+, Zn and Ni, exhibited no significant differences. Regarding the isogum pilot, the differences of TSS, turbidity, PH and NH_4^+ concentrations were significant.

Table 6 provides the amounts of the measured microbial parameters in the harvested tank water in the I.P and GS.P. In the GS.P, while fecal coliform for all rainwater samples was zero, the average fecal coliform in the I.P was 24 mg/1,000 L. The ratio of the mean values of total coliform in the I.P to that of the GS.P was approximately equal to 74. The amount of fecal streptococci for both pilots was zero. The values of all biological parameters in the rainfall samples were equal to zero.

During a rainfall, water flowing over the galvanized steel and the isogum pilots can dissolve some particles of both pilot surfaces. In the isogum pilot, the dissolution is higher that causes the rainwater quality be influenced more than the galvanized steel. In fact, since the surface substance of the isogum pilot is able to be dissolved in rainwater, particularly in high temperatures, and this type of pilot is made from oil and industrial material, the rainwater quality may deteriorate by flowing over the pilot surface. Due to these reasons, the rainwater collected from the galvanized pilot is better than the one collected from the isogum pilot in some water quality indicators. The result of past studies showed that a galvanized steel pilot is suitable for RWH purpose

Table 5
Summary of the heavy metals parameters of rainfall and harvested rainwater samples in two pilots

Parameter	Pb, mg/1,000 L		Hg, mg/1,000 L		Fe, mg/1,000 L		Zn, mg/1,000 L		Al, mg/1,000 L		Cr, mg/1,000 L		Ni, mg/1,000 L	
Pilot type	I.P[a]	GS.P[b]	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P	I.P	GS.P
Mean	103.00	59.00	<0.1	<0.1	500.71	173.95	5,042.31	1,558.83	503.56	190.32	18.67	18.82	6.70	4.03
Median	97.00	7.92	<0.1	<0.1	225.00	74.40	1,530.00	1,676.00	194.62	83.00	13.50	5.00	3.40	3.13
Maximum	250.00	190.00	<0.1	<0.1	1,494.00	525.21	20,004.00	2,675.00	1,522.00	557.89	39.00	45.45	20.00	8.00
Minimum	1.00	2.00	<0.1	<0.1	51.00	47.00	12.44	238.72	54.20	45.3	1.26	2.09	3.00	2.00
Rainwater	0.13		<0.1		44.00		<0.2		<0.2		8.70		<0.2	
1053 Standard	100[c]		6[c]		300[d]		3,000[d]		100–200[c]		50[c]		70[c]	
p value	0.945	0.325	NA	NA	0.49	0.003	0.617	0.026	0.334	0.925	0.017	0.03	0.00	0.00

[a]Isogum pilot.
[b]Galvanized steel pilot.
[c]Allowable maximum.
[d]Desirable maximum.
NA: Not applicable.

Table 6
Summary of the microbial parameters of rainfall and harvested rainwater samples in two pilots

Parameter	Fecal coliform, MPN/100 ml		Total coliform, MPN/100 ml		Fecal streptococci, MPN/100 ml	
Pilot type	I.P[a]	GS.P[b]	I.P	GS.P	I.P	GS.P
Mean	24	0	297	4	0	0
Median	2	0	43	0	0	0
Maximum	93	0	1,100	15	0	0
Minimum	0	0	0	0	0	0
Rainwater	0		0		0	
1053 Standard	–		–		–	
p value	–		–		–	

[a]Isogum pilot.
[b]Galvanized steel pilot.
Note: MPN – Most probable number.

[63]. Moreover, a study on the quality of water collected from the pilots of different materials indicated that metal pilots are appropriate for RWH [64]. The quality of rainwater harvested from steel roofs was indicated to be higher than that of asphalt shingle roofs [65].

4. Conclusions

In this paper, we analyzed the quality and quantity of harvested rainwater stored in tanks of different sizes from different roof surface areas and surface covers of the industrial buildings. To this aim, the rainfall data of the Hakimiyeh district in Iran were used. Furthermore, volume of stored rainwater and spilled rainwater, and the reliability of meeting water demand within industrial buildings under different conditions were investigated. In the study area, for roof areas between 500 and 1,500 m^2 with small storage tanks (from 5,000 to 25,000 L), the average annual volume of stored rainwater ranged from 134 to 469 m^3, and for large storage tanks (from 26,000 to 55,000 L), it varied between 172 and 514 m^3. In roofs area between 2,000–3,000 m^2, the average annual volume of stored rainwater for small and large tanks ranged from 242 to 743 m^3 and from 585 to 956 m^3, respectively.

The reliability in small roofs (from 500 to 1,500 m^2) for high water demands was very low and nearly stable. The reliability for low water demands, in most cases, were less than 50%, which suggested low efficiency of RWH systems for small roofs. It was shown that there is a direct relationship between tank size and reliability and reliability was significantly influenced by tank size. Maximum reliability for large roof areas (from 2,000 to 3,000 m^2) and for low water demands (1,000–2,500 L/d) was in the range of 40%–80%. Minimum reliability for high water demands (2,500–5,000 L/d) was approximately 10% while increase in the tank size improved the reliability by 20%–50%.

In this research, an experimental study was also conducted in order to compare the water quality parameters of the rainwater harvested of conventional roofing materials in the study area (i.e., isogum and galvanized roofs). The laboratory results revealed that the quality of harvested rainwater from the galvanized steel pilot was higher than that from the isogum pilot in terms of two chemical parameters of TOC and NH_4^+. Isogum surfaces are more sensitive to changes in temperature and other environmental factors than galvanized steel surfaces. Indeed, since the condition of isogum surfaces gets worse over time, the quality of harvested rainwater from isogum surfaces is low. Average amounts of Cl^-, So_4^{2-}, No_3^-, Mg^{2+}, Cd^{2+}, TH, and TDS for both pilots were less than the standard values specified by the drinking water national standards (No. 1053).

Average contents of heavy metals, namely Ni and Cr, in the harvested water from the isogum pilot were lower than the specified standard values while contents of other heavy metals were shown not to have significant differences with the acceptable values. Fe, Zn, Cr and Ni contents in the harvested water from the galvanized steel pilot were less than specified standard values.

Whereas the amounts of fecal coliform and fecal streptococcus were equal to zero in the galvanized steel pilot, the total coliform level was very low. The microbial quality of the harvested rainwater by the galvanized steel pilot was less than that of the isogum pilot.

Based on the analysis and evaluations performed in this research, harvested rainwater from galvanized steel roofs could be used for non-potable water demands including flash tank for toilet, washing the yard, irrigation, and water for chillers and cooling systems of industrial buildings. Harvested rainwater from isogum roofs has restricted use and may not be used for all water demands. Rainwater harvested from isogum surfaces must be tested for water quality prior to any consumption. Also, necessary measures must be taken in order to achieve the required water quality for desired consumptions.

Finally, a part of water requirements for industrial use could be met by installing RWH systems and choosing appropriate tank size. RWH and storage in industrial buildings and factories could cut down on the municipal water use. Furthermore, quality of rainwater harvested from roofs could be easily improved through taking some measures, such as initial roof cleaning, preventing initial flow from draining into the storage tank, using water filters, and periodic maintenance and cleaning of storage tank.

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