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Research article

Development of a fabricated first-flush rainwater harvested technology to meet up the freshwater scarcity in a South Asian megacity, Dhaka, Bangladesh☆

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ABSTRACT

The scarcity of freshwater in most of the megacities in the world is an important concern. In this regard, scientifically harvested rainwater could provide an effective measure to this crisis. In this attempt, we developed a cost-effective sensor-based automated first-flush rainwater harvesting system (RHS) to improve the freshwater scarcity and economic development of megacities like Dhaka, Bangladesh. To investigate the performance of the developed system, a suit of representative rainwater samples was systematically collected, preserved, and assessed between the months of July–December 2021 for water quality parameters such as physicochemical (pH, EC, TDS, DO, hardness, and alkalinity), anions (F^-, Cl^-, NO_2^-, NO_3^-, Br^-, and SO_4^{2-}), elemental (Ca, Mg, Cr, As, Cd, Hg, Pb, Be, Ni, Se, and Fe), and microbial contamination analysis. A Multiparameter digital meter and a titrimetric method were employed for measuring the physicochemical properties whereas elemental concentration was detected using an inductively coupled plasma-mass spectrometer and atomic absorption spectrometer. The changes in microbial contamination in the preserved rainwater were investigated from time to time during the whole experimental period. The findings showed that the mean pH (6.90) and concentrations (mg/L) of other

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concerning parameters such as TDS (15.5), DO (7.26), hardness (14.9), Cl^- (3.59), NO_3^- (4.84), SO_4^{2-} (4.62), Fe (<0.2), Cr (0.086 μg/L), As (0.224 μg/L), Cd (0.260 μg/L), Hg (0.270 μg/L), and Pb (5.530 μg/L) in the harvested rainwater samples were below the WHO drinking water guidelines and literature data implying that the harvested rainwater derived from the developed RHS is completely safe for drinking and other uses even in respect to the microbial contamination (total bacterial counts: 0–15 CFU/mL, and total and fecal coliform less than 1.8 MPN/100 mL) for long storage. Hence, this technology has a huge opportunity to mitigate safe freshwater scarcity and groundwater depletion issues, especially in megacities such as Dhaka, Bangladesh.

1. Introduction

Water, without any doubt, is the most crucial substance for surviving life on earth. Fortunately, 75% of the earth's surface is covered with water, but regrettably, the majority of this water is salty (salinity: 35 ppt) [1]. The high quantity of salt and inorganic matter in this water (TDS >35,000 mg/L) makes it unfit for human consumption [2]. Only 3% of this water body is fit for drinking and other purposes such as industrial applications and irrigation. However, the majority of freshwater (68.9%) is covered by icecaps and glaciers. The remaining 29.9 and 1.2% consist of groundwater and surface water (atmosphere, lakes, and rivers), respectively [3]. As a consequence, reliance on groundwater has been the most primitive and reliable option for humans. However, rising population and intensive groundwater use are causing ongoing groundwater depletion in megacities around the world including Cairo, Tehran, Dhaka, Delhi, Kolkata, Mumbai, Jakarta, Lagos, Manila, Ho Chi Minh City, New York, Mexico City, Karachi, Lahore, and shanghai [4–9]. The depletion of the aquifer layer has a significant impact on the geological as well as environmental equilibrium and hence, increases the danger of landslides and earthquakes, particularly in megacities [10]. Consequently, several treatment technologies such as evaporation, reverse and forward osmosis, membrane distillation, electrodialysis, and nanofiltration of surface water have been implemented to supply fresh water in industrialized and developed nations such as the United States, Italy, the United Kingdom, Japan, Canada, Germany, and France [5,6,11,12]. However, most of these technologies have high economic costs, significant energy consumption, and several constraints for long-term operation [5,12].

When it comes to solutions to these problems, the rainwater that is harvested naturally may be the most promising alternative to surface and groundwater [13–15]. Notably, to reduce the dependency on groundwater and freshwater production costs, many countries including Australia, Germany, India, and so on, now impose strict regulations on rainwater harvesting (RH) and a few of them have already operated rainwater harvesting systems (RHSs) for their city's freshwater supply [16]. In brief, RH is the collection and storage of natural rainfall water at a suitable time for its proper use later. However, the collection system for rainfall water should not be ordinary but scientific, and the importance of maintaining the potable quality of harvested rainwater for different applications must be taken into serious consideration. The initial rainwater of urban areas is usually contaminated due to the dust content of the air as well as the catchment area of ordinary rainwater harvesting systems. Moreover, this debris content can promote the growth of microbial species in the stored water. Hence, the design of the catchment area in the RHS is critical in determining the storage quality of harvested rainwater. A properly designed catchment area of an RHS can reduce the chance of augmented dust contamination and, thus enhances the stability of rainwater. So, it is one of the major challenges in RH technology to segregate the first runoff of rainfall water from the storage tank of fresh rainwater so that the quality of the harvested water can be preserved for a long time. However, the available and traditional RHSs are not equipped with a proper flushing system to separate the initial filthy water. Hence, the harvested rainwater cannot be preserved for a long time, and sometimes it loses its potable quality. Besides, none of them have any first-flush water evacuation system which is a primary requirement for the system to separate and store the next filthy water automatically. Thus, the development of RHS with the novel feature of automatic segregation of initial runoff of dust, debris, and other pollutants that contaminated rainfall water while collecting the rainwater is crucial.

Depending on the local climate, rainwater is often readily acceptable for use in gardening, vehicle washing, building, irrigation, and other purposes. Nonetheless, the rainwater gathered from any random location is not always suitable for drinking or other safety uses due to various contaminants in it from polluted atmospheric contributions [17]. The atmospheric environments of many megacities around the world including Dhaka city (Bangladesh) are being found polluted [18]. The direct consumption of rainwater harvested in polluted atmospheric environments is threatening to human health. Hence, before consumption, the treatment and measurement of the contamination level in the harvested rainwater, especially which is stored for a long time, in those areas are crucial and it deserves a complete water quality assessment before using the harvested rainwater in any city.

The South Asian megacity, Dhaka, the capital of Bangladesh (area of 306.4 km^2), is surrounded by many rivers as well as unplanned urban infrastructures. Furthermore, the density of the population in the Dhaka metropolis is exceptionally high (44,000/km^2), and the city's population is rapidly increasing (3.56%/year), resulting in increased freshwater consumption. Currently, Dhaka City Corporation (North and South) of this metropolis is home to almost 21 million residents. A typical city resident uses around 150 L of freshwater per day, and of course, the distribution varies by neighborhood [18]. Dhaka Water Supply and Sewerage Authority (DWASA) is mainly responsible for mitigating the freshwater demand and thus heavily relies on both surface and groundwater. DWASA has a service area of 360 km^2 and a daily production capacity of 2500 million liters of water, according to the DWASA report 2017–18 [19]. DWASA is currently dependent on 78% groundwater and 22% surface water using four treatment plants, several wells, and a couple of rivers/lakes [20]. However, the overwhelming groundwater consumption is causing fatal aquifer water layer depletion with insufficient groundwater recharge facilities, thus substantially enhancing the potential risk of catastrophic geological imbalance, the possibility of landslides, and sinkhole generation. Moshfika et al. [21] presented an alarming picture of both long-term and short-term groundwater decline in Dhaka city and proposed some solutions to the existing problems including the adaptation of surface water treatment plants, RH, artificial groundwater recharge, effluent treatment plants, etc. Among these, RH is facile, feasible, and cost-effective if employed scientifically. The adopted surface water treatment plants are costly in the context of the geological and structural situation of the available rivers such as Shitolakkhya, Buriganga, and Dhaleshawri surrounding Dhaka city. The rivers around the city are already polluted owing to unplanned waste management and rapid infrastructural development near the river banks [22,23]. However, no effective measures were taken for the restoration of these surface water resources and to also think of an alternative way to meet the freshwater scarcity in the megacity, Dhaka, Bangladesh. Currently, the authorities are planning to source water from a farther river named, Meghna which will further rise the cost of treating water in the city.

In these situations, scientific rainwater harvesting could be a good alternative and a possible solution to the problem in Dhaka city. Fortunately, due to its geographical position, Dhaka city has more than 2000 mm of mean annual rainfall (2123 mm in Bangladesh according to Karim et al. [24] and BMD [25]) which is higher than in Delhi (>750 mm), Mumbai (2146.6 mm), Kolkata (1647 mm), and Karachi (250 mm) [9]. The annual rainfall of 1200 mm is recorded in Shanghai [26], 273.0 mm in Urumqi, 587.2 mm in Beijing, 919.4 mm in Chengdu [27], and 2400 mm in Malaysia [28]. Evidently, the abundant rainwater in Dhaka city could be a great natural gift as an alternative to the costly treatment plants of surface water of the municipalities and also maybe the most viable option for both surface and groundwater [29]. Further, the total area of rooftops in Dhaka city has the potential to produce approximately 126422.1 million liters of fresh rainwater utilizing an average area of roof surface of 1440 sq. ft per building. In a day, the total demand for freshwater in Dhaka city is about 2250 million liters which is sometimes very difficult to achieve. In this regard, the RHS has the potential to contribute positively to mitigating this freshwater crisis in Dhaka city [24]. The rainwater quality of Dhaka city is fairly good but the government, as well as the people in the city, do not harvest the rainwater despite the safe water demand [30]. However, it is possible to collect and harvest rainwater using scientific methods to address Dhaka's freshwater scarcity.

In the present work, we have developed a cost-effective first-flush RH technology to meet the scarcity of freshwater in urban regions. The developed system is cheaper and more feasible than the RHS adopted in Malaysia [28] and Spain [31]. This is an effective alternative to the conventional RHS in which the rainwater is simply collected in common containers directly as rooftop runoff while raining, and then it is used by the local people instantly in a few days instead of being preserved for a long time. For long-term preservation, however, rainwater is sometimes stored in cool containers or tanks; but due to contamination and lack of scientific collection procedures, this long-term rainwater preservation is not sustained. In this regard, our proposed system has some advantages over the existing RHSs which include: (i) a cost-effective and readily available mechanical floating valve that blocks the entry of rainwater into the primary tank after storing filthy rainwater from the start of the rain, (ii) an advanced first-flush evacuation technique that is featured by a sensor-based solenoid valve system, and (iii) an array of purification system integrated with the harvester which eliminates any kind of heavy metals or microparticles as well as microbial contaminants. To investigate the performance of our newly developed rainwater harvester and also to check the quality of the harvested water after a long period, the rainwater samples of Dhaka city were taken into consideration as a case study. Additionally, we emphasized the economic prospect of RH in megacities by setting it in the model city of Dhaka. Furthermore, we checked the applicability of this system-earned harvested rainwater as drinking water, and for other household or industrial applications through the laboratory analysis of the harvested water quality.

This RHS will help make sure that Dhaka and other megacities around the world have a safe supply of fresh water. Furthermore, the present work will help achieve SDG (Sustainable Development Goal) 6: "Ensure availability and sustainable management of water and sanitation for all" in which Target 6.1 states that by 2030, "globally, considerably enhances recycling and safe reuse" and "provide universal and equal access to clean and economical drinking water for everyone" will be achieved [32]. Thus, increasing the emphasis placed on innovative approaches to rainwater harvesting may be the best way to reach this goal.

Table 1
Approximate material costs in the fabrication of a rainwater harvesting system with a catchment area of 1000 square feet.

Sl·No.	Item	Material and Quantity	Unit Cost ($)	Total Cost ($)
1	Rooftop/Shed	PVC (3 mm), (1000 sq. ft)	0.32	320.00
2	Collecting Pipe	PVC (110 mm), (10 m)	0.70	7.00
3	Solar Panel	12 V, 20 W, (1 pcs)	13.42	13.45
4	Sensor	Custom made (1 pcs)	20.00	20.00
5	Debris Filter	Polypropylene (1 pcs)	5.00	5.00
6	Diverter Pipe	PVC (1 pcs)	3.00	3.00
7	Floating Valve	Plastic and Steel (1 pcs)	5.00	5.00
8	Water Tap	PVC (3 pcs)	3.00	9.00
9	Solenoid Valve	Copper (1 pcs)	16.00	16.00
10	Storage Tank 1	PVC (200 L) (1 pcs)	20.40	20.40
11	Storage Tank 2	PVC (1000 L) (1 pcs)	75.15	75.15
12	Submersible Pump	24 V DC (1 pcs)	5.00	5.00
13	UV-C Filter	24 V DC (1pcs)	20.00	20.00
14	Sediment Filter	Polypropylene Fiber (1 pcs)	10.00	10.00
15	Carbon Filter	Activated Carbon (1 pcs)	10.00	10.00
Total				539.00

2. Materials and methods

2.1. Fabrication of the rainwater harvesting system (RHS) with materials and relevant costing

An effective RHS was fabricated using readily available and customizable materials and components. To do this, a total of 15 different parts were deployed in the finalized version of the RHS. Since the reduction in the fabrication cost was one of the major objectives, this study adopted low-cost but efficient fabrication methods. However, the size and quality of the components can be changed on demand just as the cost will vary depending on the fabrication scale. A brief description of the components and relevant costs to fabricate the RHS are given in Table 1. A schematic flowchart for the overall methodology of the present work is illustrated in Fig. 1.

2.2. Establishment of the fabricated RHS

Considering easy working access, the fabricated RHS was established on the rooftop of the Institute of National Analytical Research and Services (INARS, Google map location: 23°44'22.795''N, 90°23'0.905''E), Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka, Bangladesh. The geographical location and pictorial presentation of the fabricated RHS are depicted in Figs. 2 and 3, respectively. The institute (INARS), on the rooftop of which the RHS was established, is situated beside a heavy traffic area on New Elephant Road of Dhaka South City Corporation. The climate of Dhaka city generally ranges from semiarid to wet and is that of a tropical savanna. The city's climate is characterized by a distinct feature of the monsoonal season and is dependent on the shifting of the monsoon period. The monthly mean temperature of Dhaka varied from 19 °C (66 °F) in January to 29 °C (84 °F) in May with an average annual temperature of 26 °C (79 °F) [25]. Usually, a large portion of rainfall in Dhaka, Bangladesh occurs from May to October, and during these months, the amount of annual average rainfall usually is 2123 mm (83.6 inches) [24,25].

2.3. Collection and preservation of the rainwater in the fabricated RHS

Depending on the season, suitable time, availability, and collecting opportunity of rainfall water, the rainwater was scientifically collected and preserved in the fabricated RHS in different months *viz.,* July–December 2021 to monitor the variation in the overall rainwater quality through the variation in the seasons and associated environmental conditions. Based on the favorable circumstances, we were able to collect a total of 15 composite rainwater samples (n = 5) in the mentioned period for examination in the laboratory. For this, the samples were collected in polyethylene plastic bottles of 1 L volume purchased locally. Before collecting the samples, the bottles were washed with a 10% HNO_3 solution overnight and then, rinsed properly with deionized water (conductivity less than 0.2 µS/cm). The collected rainwater samples were then placed in cleaned bottles and immediately carried to the analytical chemistry laboratory to be stored at 4 °C until analysis.

2.4. Quality analysis of the preserved rainwater

After being collected on a regular basis, the fresh rainwater samples were analyzed in the laboratory (INARS, BCSIR) for the concentration of some physicochemical parameters, chemical elements, anions, and microbial contamination. The physicochemical properties *viz.,* pH, total dissolved solids (TDS), electrical conductivity (EC), dissolved oxygen (DO), alkalinity, and total hardness (TH) of the freshly collected samples from the harvested rainwater were measured instantly following APHA methods [33]. For the analysis of chemical elements such as Fe, Ca, Mg, Cr, As, Cd, Hg, Pb, Be, Ni, and Se, the digestion of the rainwater samples was performed with

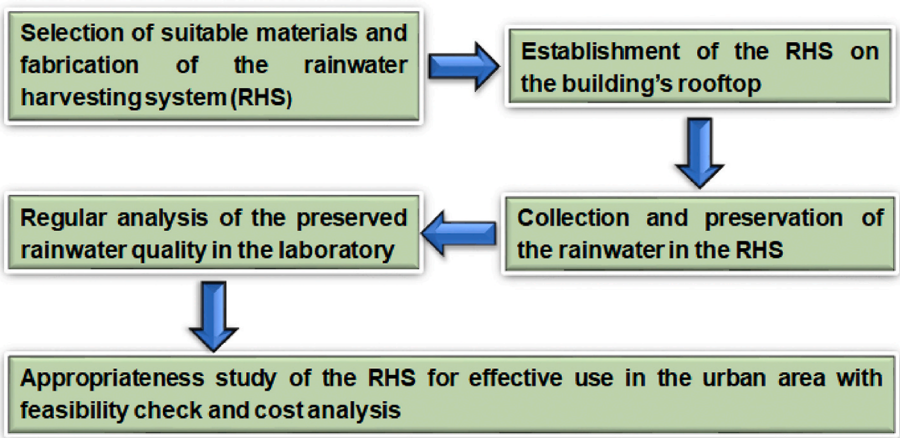

Fig. 1. Schematic flowchart for methodology.

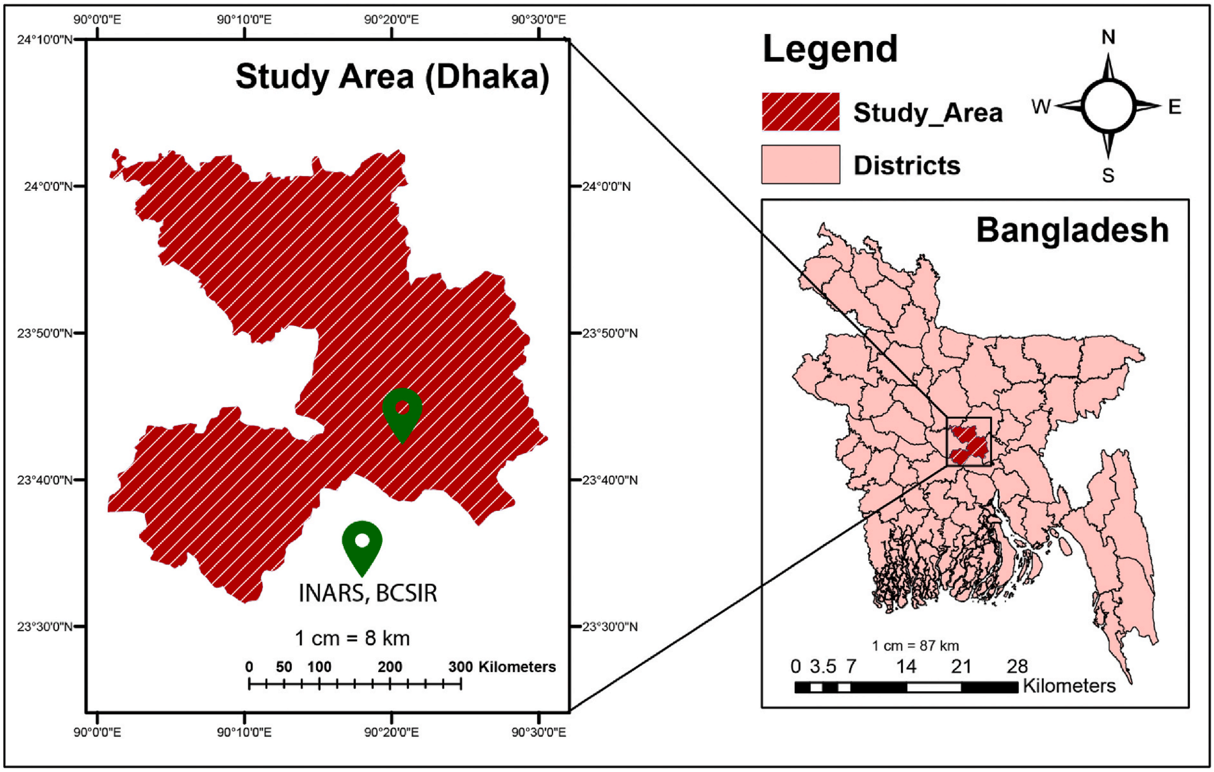

Fig. 2. Loon of the establishment of the rainwater harvesting system.

Fig. 3. Pictorial representation of the fabricated rainwater harvesting system on the rooftop of INARS, BCSIR, Dhaka, Bangladesh.

68% HNO_3. The presence of Fe, Ca, and Mg in the rainwater samples was detected by Atomic Absorption Spectrometer (AAS, Model: AA240FS, Varian, Australia) and the rest of the elements were determined using an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS, Agilent 7500). An ICP-MS equipped with several instrumental parts such as a nebulizer (Micro Mist nebulizer), onboard peristaltic pump, two pumps for evacuation, ICP argon plasma torch, octopole reaction system, quadrupole mass analyzer, and electron multiplier detector was employed for elemental analysis in the collected rainwater samples following the laboratory's internal method. The flow rate of nebulizer gas (argon), auxiliary gas (argon), plasma gas (argon), and reaction gas (helium) were 0.9 L/min, 0.3 L/min, 15 L/min, and 4 mL/min, respectively. The lens voltage and ICP RF power were 7.25 V and 1100 W, respectively. For an accurate determination of the elements in ICP-MS, the element Erbium (Er) was employed as an internal standard, in addition to performing the multi-standard calibration technique. Before analysis, those samples were diluted to 100 mL from 10 mL with a 0.5% HNO_3 solution. During operation, each standard for the quality check as well as the sample was measured in triplicate to ensure the accuracy and precision of the employed method, and all results were represented as the mean of triplicate analysis with standard deviation and relative standard deviation (less than 5%). Using working standards, the calibration curves were prepared which showed the plot of intensity versus concentration of the analyzed elements at the ppb level. The correlation coefficients (r^2) for the constructed calibration curves were found to be greater than 0.855 for most of the elements analyzed by ICP-MS. The details of the analytical methods for the analysis of Fe, Ca, and Mg using AAS along with the employed quality control approaches are described in our previous works [23,34–36]. The concentration of anions (F^-, Cl^-, NO_2^-, NO_3^-, Br^-, and SO_4^{2-}) in the rainwater samples was detected by an Ion Chromatograph (Model: SIC10AVP, Shimadzu, Japan).

The study of microbial growth such as total bacterial count (TBC) and total coliform MPN (most probable number) in the harvested rainwater was also carried out to know the feasibility of the stored rainwater for prolonged use of about one year. The TBC of the rainwater samples was determined following the method described by Reasoner and Geldreich [37]. Briefly, to recover as many viable bacteria as possible from the samples, the experiment was run using R2A agar. The bacterial count was enumerated by the standard pour plate method with serial dilutions [38]. The unit of measurement was the colony forming unit, CFU/mL. Total coliform and fecal coliform were counted through multiple-tube fermentation tests [33] employing the three-tube assay of the MPN technique. The culture media used were Lauryl Tryptose Broth (LTB) for the conjectural test, and Brilliant Green Bile Broth (BGBB) for the confirmed phase. After inoculation of the media with the samples, the LTB culture tubes were incubated at 35 ± 0.5 °C for 24 ± 2 h for estimating total coliforms and at 44.5 ± 2 °C for 24 ± 2 h for fecal coliforms determination. After the incubation period, the cultures were examined for bacterial growth, gas production, and media color changes due to acid production. Those showing no presence of growth, gas in the Durham tube, and/or changes in media color were re-incubated for an additional 24 h. If no gas or acid production was found, the test was reported as negative due to the absence of a coliform group. Contrarily, the presumptive tubes showing growth, gas, and/or color changes in LTB, would be re-inoculated in BGBB media for the confirmed phase. Quality control and quality assurance were ascertained appropriately. Then, the MPN was estimated for three tube sets from the MPN table and the coliform count was expressed as MPN/100 mL.

3. Results and discussion

A cost-effective RHS is developed and the quality of the preserved rainwater was checked by analyzing the water samples for several physicochemical parameters such as pH, TDS, EC, DO, alkalinity, and hardness; chemical elements such as Fe, Ca, Mg, Cr, As, Cd, Hg, Pb, Be, Ni, and Se; anions (F^-, Cl^-, NO_2^-, NO_3^-, Br^-, and SO_4^{2-}); and microbial contamination to study the appropriateness of the fabricated RHS for effective use in the urban area.

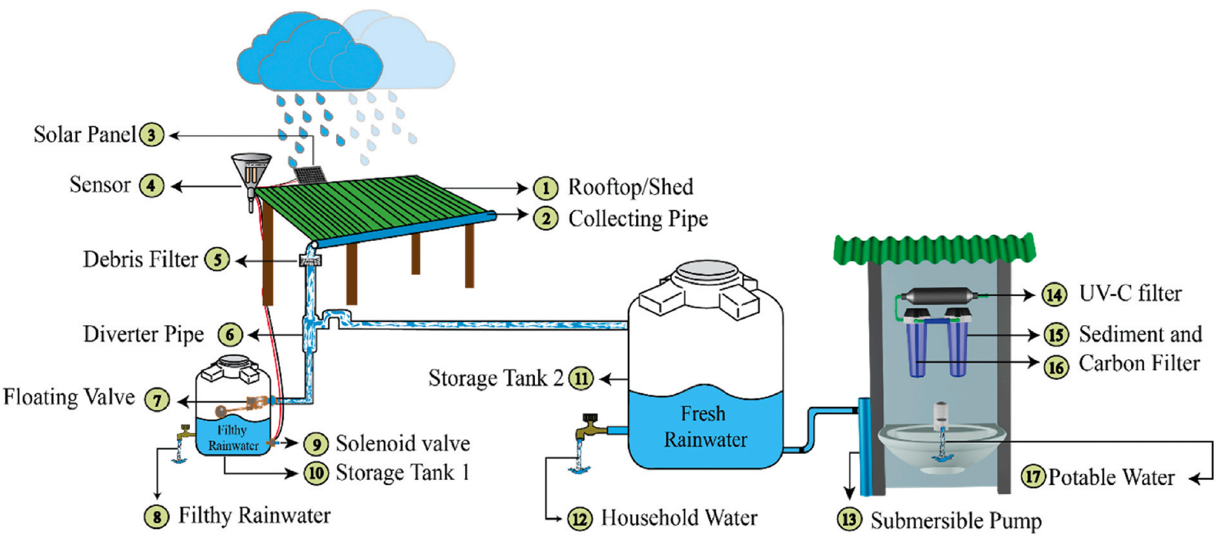

Fig. 4. Illustration of the different parts of the rainwater harvesting system installed on the rooftop of INARS, BCSIR, Dhaka, Bangladesh.

3.1. Function of the developed RHS

A clear picture of the developed RHS is depicted in Fig. 4. In this illustrated system, a properly designed catchment area (roof surface) with an integrated debris-removing filter is well-featured for the initial screening of dust from the rainwater. Furthermore, the overall system includes two separate tanks (storage Tanks 1 and 2) for collecting initial waste rainwater followed by fresh rainwater. The waste rainwater collection in storage Tank 1 is controlled by an automatic floating valve system to ensure the separation of the fresh rainwater and it is then stored in the second tank (Tank 2). This illustrates the first-flush feature of the fabricated RHS. In addition, the freshwater flow is redirected to storage Tank 2 with a bidirectional diverter. The process also offers three-stage water purification systems *viz.,* ultra-violate (UV) system, sedimentation, and activated carbon filtration. Thus, high-quality drinking water with no bacterial and elemental contamination would be achievable by adopting this process.

In addition, a solenoid valve is installed at the bottom of Tank 1, which is electrically triggered immediately after the rain stops. Thus, Tank 1 becomes empty and ready for the next rainwater collection cycle. A simple electrical sensor (illustrated in Fig. 5) is added in a cone-shaped holder which maintains the total evacuation process by signaling through a programmed microcontroller. In brief, when the rain starts, the cone-shaped container becomes full of water and hence, the copper plates of the sensor setup get connected. This action generates an electrical signal which is then sent to the microcontroller which ultimately triggers the solenoid valve to become closed. When the rain stops and the water from the cone-shape leaks from the bottom of the cone, the circuit is disconnected and hence, sends the signal to the solenoid to be open until the tank becomes partially empty. The solenoid valve is a pressure-dependent valve that gets closed upon the low pressure generated by the remaining water in Tank 1. The sensor is powered by a 2.7 V lithium-ion battery which gets its charge from a 12 V DC solar panel connected to the rooftop of the rainwater harvester. Thus, the overall process is automatic and does not require any external power supply.

3.2. Quality of the preserved rainwater in the fabricated RHS

The analytical results of the water quality parameters for the preserved rainwater samples are summarized in Table 2 along with their descriptive statistics, standard guidelines, and literature data. The pH of all collected rainwater samples was found in the range of 6.46–7.65 at 25 °C. The EC, TDS, and DO were measured to be in the range of 19.7–70.1 μS/cm, 8.70–33.1 mg/L, and 5.96–7.98 mg/L, respectively. The total hardness and alkalinity were found in the range of 9–32 and 8.98–27.3 mg/L, respectively. The concentration (mg/L) of anions were quantified to be F^- (<0.5), Cl^- (1.01–13.0), NO_2^- (<1.0), NO_3^- (3.26–6.89), Br^- (<1.0), and SO_4^{2-} (4.29–5.16). The minerals including Ca and Mg were also found in the rainfall water. The mean concentration of Ca and Mg were found as 4.40 and 0.230 mg/L, respectively while the Fe concentration was found less than 0.2 mg/L in all samples (Table 2). The concentration (μg/L) of eight heavy metal (loid)s such as Cr, As, Cd, Hg, Pb, Be, Ni, and Se range from 0.021 to 0.329, 0.008–0.432, 0.019–1.033, 0.040–0.916, 0.225–22.18, 0.002–0.003, 0.166–0.827, and 0.004–0.491, respectively (Table 2). During the microbiological assessment of 6 months

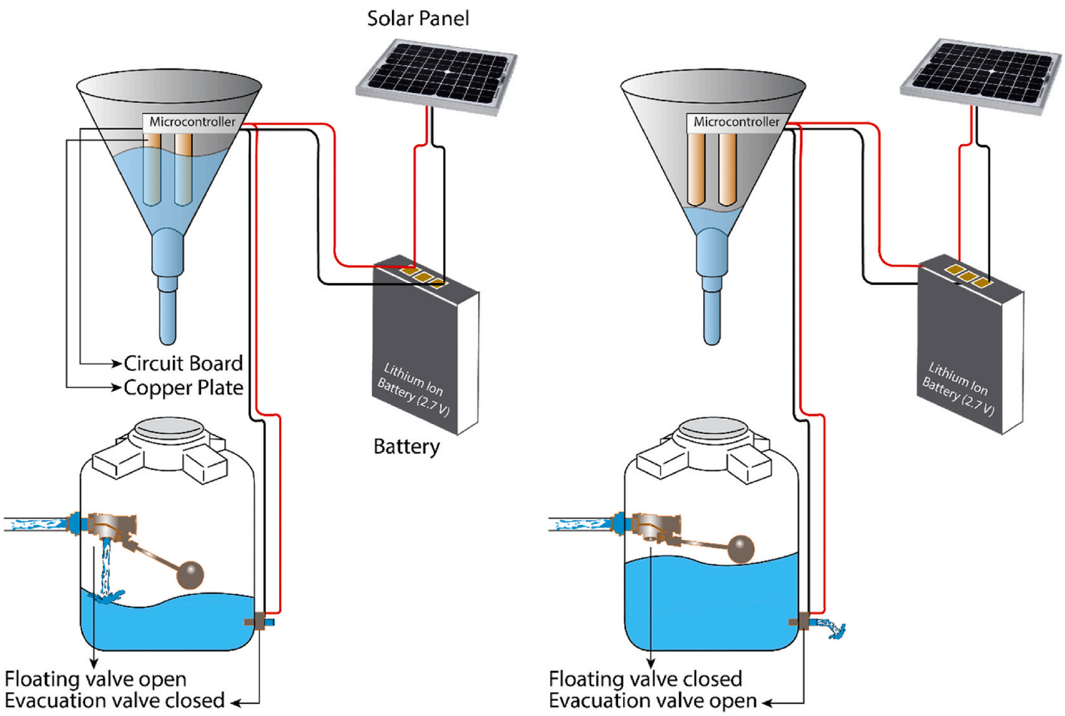

Fig. 5. Schematic presentation of separation and evacuation mechanism using the microcontroller-based sensor.

Table 2
Concentration of some physicochemical parameters, anions, heavy metals, and microbial plate count in the examined rainwater samples along with their descriptive statistics, guideline values, and literature data.

Rainwater samples	pH	EC (μS/cm)	TDS (mg/L)	DO (mg/L)	TH (mg/L)	Alkal. (mg/L)	F^- (mg/L)	Cl^- (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	Br^- (mg/L)
RS1	6.80	30.8	15.7	6.83	18	17.4	<0.5	<1.0	<1.0	<3.0	<1.0
RS2	7.02	19.7	8.70	6.68	10	9.92	<0.5	1.45	<1.0	4.30	<1.0
RS3	6.99	32.1	14.8	6.47	12	12.4	<0.5	<1.0	<1.0	5.05	<1.0
RS4	6.97	28.9	13.3	6.21	12	14.9	<0.5	1.43	<1.0	<3.0	<1.0
RS5	6.95	70.1	33.1	5.96	32	27.3	<0.5	<1.0	<1.0	6.23	<1.0
RS6	6.82	37.4	17.4	7.74	20	24.8	<0.5	1.06	<1.0	<3.0	<1.0
RS7	6.78	30.8	14.2	7.82	16	14.9	<0.5	<1.0	<1.0	<3.0	<1.0
RS8	6.93	25.6	11.7	7.81	14	19.9	<0.5	<1.0	<1.0	<3.0	<1.0
RS9	6.72	30.1	13.9	7.81	14	9.93	<0.5	13.0	<1.0	<3.0	<1.0
RS10	6.86	29.3	13.5	7.67	14	19.9	<0.5	1.01	<1.0	<3.0	<1.0
RS11	6.65	26.4	12.1	7.86	10	12.5	<0.5	<1.0	<1.0	3.26	<1.0
RS12	6.58	37.2	17.1	7.83	16	14.0	<0.5	<1.0	<1.0	6.89	<1.0
RS13	6.46	22.6	18.5	7.98	9	8.98	<0.5	<1.0	<1.0	3.32	<1.0
RS14	7.65	31.5	13.8	7.52	11	10.6	<0.5	<1.0	<1.0	<3.0	<1.0
RS15	7.38	33.8	14.6	6.66	16	11.5	<0.5	<1.0	<1.0	<3.0	<1.0
Min.	6.46	19.7	8.70	5.96	9	8.98		1.01		3.26	
Max.	7.65	70.1	33.1	7.98	32	27.3		13.0		6.89	
Mean	6.90	32.4	15.5	7.26	14.9	15.3		3.59		4.84	
SD	0.30	11.5	5.44	0.70	5.66	5.56		5.26		1.50	
RSD (%)	4.32	35.4	35.1	9.66	37.9	36.4		146.6		31.0	
Guideline values											
WHO [17]	6.5–8.5	200–800	300	8.00	200	200					
Literature data											
Rainwater, Bangladesh [14,39]	7.72	46.7	37.2		19.0	13.0		11.8		1.12	
Rainwater, outside of Bangladesh [40,41]	6.55	68.4	88.0					0.17		0.03	
Tap water, Dhaka [20,42,43]	6.50–7.75	302–764	151–407								
Groundwater, Dhaka [44]	5.98–7.50	256–868	179.2–607.6		80.0–320.1			2.50–87.5			
Surface water, Dhaka [45–48]	6.90–8.20	450–1350	225–1367	2.50–6.70				33–214		2.10–13.5	

EC = Electrical Conductivity, TDS = Total Dissolved Solids, DO = Dissolved Oxygen, TH = Total Hardness, Alkal. = Alkalinity, Max. = Maximum, Min. = Minimum, SD = Standard Deviation, RSD = Relative Standard Deviation, MPC = Microbial Plate Count.

of stored rainwater samples, total bacterial counts were recorded ranging from 1 to 215 CFU/mL. Also, both the total coliform and fecal coliform of the samples were enumerated as less than 1.8 MPN/100 mL (Table 2). But, after passing the water samples through the UV light, sedimentation, and activated carbon filtration systems, the total bacterial counts in the rainwater samples were reduced to 0–15 CFU/mL, with the same count of total and fecal coliform as before (less than 1.8 MPN/100 mL).

To know the level of the preserved rainwater quality more evidently, the analyzed data of the water quality parameters were compared with standard guidelines and literature (Table 2). The comparison revealed that the concentrations of all physicochemical parameters, chemical elements, anions, and microbial contamination were within acceptable limits. The concentrations of heavy metal (loid)s in the different rainwater samples were found very close with a little variation in the short range. All heavy metals are harmful to the environment and human health [20,49]. For instance, the toxic and harmful effect of Pb in potable water is well-known [20]. The regular and longtime consumption of Pb-contaminated water could cause malfunctions in the brain, nervous system, and kidneys. However, the level of Pb (mean: 5.530 μg/L) in our harvested rainwater was found to be insignificant as compared to the WHO guideline which can be regarded as non-lethal for human consumption [50,51]. Chromium in drinking water has also some adverse effects on human health due to massive consumption. In our experiment, no samples of rainwater were reported to be saturated with Cr contamination, even with the highest concentration of 0.329 ppm (WHO limit: 50 ppb). In addition, the concentration of Cd in the rainwater samples was also found very low in comparison to the WHO guideline as what is considered to be generally safe for human consumption. Nonetheless, the little presence of heavy metals in the harvested rainwater is presumably to be corroborated by the air pollution in Dhaka city [18]. Unregulated emissions from vehicles, dust from industrial and road sites, incineration activities of solid wastes, and so on, are considered as the main air pollution sources in the megacity of Dhaka, Bangladesh [18].

Thus, upon considering all the analyzed water quality parameters and comparing their level with the standard value [17] and literature (Table 2), it has been found that the harvested rainwater quality from the newly developed first-flush technology is apt for drinking and other purposes. Further, considering an average water consumption of 150 L per capita per head, the quantity of total rainwater water gathered from our fabricated harvested system could provide water solvency noticeably at least for 6 months period. Economically, the value of this harvested rainwater is approximately not less than multi-billions. So, it can be said that Dhaka City Corporation's rainwater could be the best alternative solution for a high-quality and low-cost water supply that also helps Bangladesh

SO_4^{2-} (mg/L)	Ca (mg/L)	Mg (mg/L)	Cr (μg/L)	As (μg/L)	Cd (μg/L)	Hg (μg/L)	Pb (μg/L)	Be (μg/L)	Ni (μg/L)	Se (μg/L)	Fe (mg/L)	MPC, CFU
<4.0	5.03	0.213	0.041	0.008	0.019	0.040	0.655	0.003	0.116	0.004	<0.02	18
<4.0	2.82	0.277	0.329	0.188	0.058	0.114	0.225	0.002	0.610	0.245	<0.02	23
5.16	4.30	0.288	0.029	0.241	0.335	0.121	2.245	0.002	0.688	0.351	<0.02	7
<4.0	4.20	0.129	0.036	0.383	0.117	0.168	2.890	0.003	0.470	0.281	<0.02	3
4.41	7.89	0.269	0.156	0.210	1.033	0.127	22.18	0.002	0.782	0.318	<0.02	10
<4.0	5.48	0.194	0.238	0.145	0.754	0.187	8.361	0.003	0.613	0.246	<0.02	13
<4.0	6.15	0.490	0.072	0.115	0.066	0.337	7.952	0.003	0.028	0.176	<0.02	17
<4.0	3.72	0.098	0.072	0.162	0.062	0.572	4.518	0.003	0.603	0.211	<0.02	12
4.29	3.92	0.153	0.047	0.367	0.082	0.166	4.468	0.003	0.775	0.400	<0.02	54
<4.0	4.05	0.185	0.052	0.218	0.090	0.916	3.087	0.003	0.611	0.491	<0.02	215
<4.0	2.47	0.078	0.042	0.168	0.062	0.270	7.041	0.003	0.693	0.384	<0.02	8
<4.0	0.15	0.043	0.103	0.432	0.811	0.251	6.310	0.002	0.816	0.174	<0.02	12
<4.0	6.25	0.312	0.024	0.321	0.123	0.125	5.321	0.002	0.235	0.005	<0.02	16
<4.0	4.25	0.215	0.031	0.164	0.048	0.297	3.157	0.001	0.351	0.578	<0.02	21
<4.0	5.31	0.510	0.021	0.241	0.247	0.324	4.597	0.003	0.150	0.780	<0.02	6
4.29	0.15	0.043	0.021	0.008	0.019	0.040	0.225	0.002	0.166	0.004		3
5.16	7.89	0.510	0.329	0.432	1.033	0.916	22.18	0.003	0.827	0.491		215
4.62	4.40	0.230	0.086	0.224	0.260	0.270	5.530	0.002	0.359	0.248		29
0.47	1.82	0.135	0.089	0.112	0.328	0.221	5.198	0.001	0.092	0.103		52.8
10.2	41.3	58.64	103.4	49.99	126.1	82.70	93.94	50.00	2.070	40.32		182.2
Guideline values												
			50.00	10.00	3.00	10.00	10.00	4.00	100.0	10.00		500
Literature data												
1.50	6.77	0.490					80.00					5.74
99.0			5.62	6.85	5.70		76.68			21.89		70
	0.09	0.044	8–156	0.03–9.75	1–5	0.22–1.30	8–118		12–110		0.02–0.40	150–1100
3.06–28.4	20.0–72.1	2.43–36.5	1–2	0.30–21.5			10–240				0.004–0.320	150–1250
14–151												1100–8700,000

reach the SDG-6 goals.

3.3. Appropriateness of the fabricated RHS

The purpose of this work was to develop an appropriate RHS for the preservation of rainfall water in an urban region such as the megacity, Dhaka, Bangladesh, and to check the overall quality and feasibility of this water as an alternative source of freshwater. The water of the central supply line of Dhaka allegedly has an odor and excessive TDS compared to WHO standards [52]. The cause behind the high TDS and poor odor might be correlated to both the user's reservoir and DWASA's pipeline. But, DWASA has nothing to do with it since it is largely dependent on ground and surface water treatment facilities. Thus, in addition to the existing facilities for the production of water, individual or mass rainwater gathering is advised by the practitioners [53,54]. But, the main problem regarding rainwater is its collection and long-term storage process. Thus, an RHS was fabricated to collect the rudimentary filthy rainwater in storage Tank 1 and by the tricky mechanical floating valve as shown in Fig. 4. The fresh water is allowed to pass to storage Tank 2 just right after the fulfillment of storage Tank 1. This developed system allows the users to segregate the filthy rainwater without any kind of hassle. However, this separated filthy non-potable water can be utilized directly for several purposes such as washing, toilet, or any other simple purpose. But, the fresh rainwater diverted to the storage Tank 2 can be directly utilized for regular purposes, except for drinking.

The investigation of the water quality showed that our rainwater harvested at this urban location (INARS, BCSIR, Dhaka, Bangladesh) has no heavy metals threatening loads and this rainwater of Dhaka city is almost feasible with the WHO standards. Thus, the drinking of this harvested rainwater is generally safe from heavy metals contamination perspective. The rainwater in the megacity Dhaka is hardly found contaminated with organic pollutants in any report. However, considering the other probable or unknown contaminations, it is highly suggestive to use this fresh rainwater for drinking purposes after filtration through activated charcoal, which in turn is also reported as good adsorbent material for the removal of organic pollutants [55]. Further for drinking after long storage, the rainwater should be effectively treated under UV-light exposure to remove any microbiological contamination. Since in stagnant water, particularly where the sun rays are unable to reach, microbial growth is plausible. Thus, it is also recommended for rainwater collection that the water should be collected in an apt scientific way such that the water collection system can get rid of the rudimentary contamination from dust. Adopting those easy approaches are less expensive and feasible than the conventional reverse osmosis process or any other treatment systems employed in the industries. Nonetheless, the prior quality check is very crucial to declaring it as potable water in a specific location.

3.4. Feasibility check and cost analysis

The installation cost of the proposed rainwater harvester is less than that adopted in Malaysia [28] because the selected materials needed for fabricating the system are abundant, readily available, and inexpensive [53,56]. On a gross, it is possible to have a setup of this RHS for only 100 USD for a five-story building. More expense is required only for a large storage facility when it is not already available in a residential building. Usually, most of the residential buildings in Dhaka city have underground reservoir tanks which can be easily used for storing massive amounts of harvested rainwater. However, based on the precipitation, the amount of harvested rainwater from the buildings of Dhaka City Corporation can be calculated as below [57].

Mean rainwater supply for an average roof surface of one building (1440 sq. ft.) in Dhaka City Corporation

= A.R.S.A. × A.R. × R.F.

= 133.78 × 2100 × 0.9

= 252844.2 L

Mean rainwater supply for approximately 5000 Buildings in Dhaka City Corporation

= 252844.2 L × 5, 00,000

= 126422.1 million liters

Where, Average building Roof Surface Area (A.R.S.A.) = 1440 sq. ft. = 133.78 sq. m.

Average Rainfall (A.R.) = 2148 mm = 2.148 m.

Run-off Factor (R.F.) = 0.9 [Runoff factor is the amount of water that flows away from a catchment area following precipitation. The runoff factor is dependent on the type and size of the catchment area (surface features). Its value ranges from 0.6 to 1.

Cost savings analysis = 126422.1 million liters

= 126,422,100,000 L

= 126,422,100 unit [1 unit water price = 0.18 dollar per 1000 L by DWASA]

= 126,422,100 unit × 0.18

= 22,755,978 dollar

= 22.76 million dollar

The number of buildings in Dhaka City Corporation is approximated by the data provided by Dhaka North and South City Corporation [58]. It is worth mentioning that, presently, the average yearly cost of water supply at the household level is 15.18 taka or 0.18 dollars per 1000 L [59]. In a year, it is possible to save at least 22.76 million dollars, if all the residential buildings in Dhaka city adopt the RHS. Furthermore, the use of harvested rainwater would greatly improve the water stagnant issue and the lifestyle of city residents.

4. Conclusions

In this attempt, a low-cost first-flush rainwater harvesting (RH) system was successfully fabricated using easily accessible materials to meet the freshwater scarcity in a mega city like Dhaka, Bangladesh. The feasibility of the developed RHS was unveiled by collecting, preserving, and analyzing several water quality parameters (pH, EC, TDS, DO, hardness, alkalinity, F^-, Cl^-, NO_2^-, NO_3^-, Br^-, SO_4^{2-}, Ca, Mg, Cr, As, Cd, Hg, Pb, Be, Ni, Se, and Fe) including microbial contamination for the rainwater. The results of the analyzed parameters indicate that the fabricated harvesting system performed admirably to provide safe water that can be used for almost all purposes. However, to be used for drinking purposes, it is recommended that the harvested rainwater be treated with a three-stage purification system: UV-light exposure, sedimentation, and activated carbon filtration. Furthermore, the prior checking of the harvested rainwater quality is crucial for the universal declaration of the harvested rainwater produced by this RHS as potable water worldwide irrespective of geographical locations and pollution sources. Overall, considering the feasibility and cost analysis, it can be concluded that using this newly developed first-flush RH technology to collect rainwater could be a smart, useful, and cost-effective way to avoid running out of surface and groundwater in the megacity.

Although the good quality harvested rainwater achieved using this first-flush technology may be used cost-effectively as an alternative to the scarce freshwater in the megacities (e. g., Dhaka), there are some limitations in the developed harvesting technology. There is a great possibility of contamination of the fresh rainwater from the rain catchment surface area adhered with unwanted contaminants (e. g., animal excreta, debris, etc.), even after utilizing the first-flush approach. Since the rain catchment surface area is fully exposed, regular cleaning of the exposed surface is needed. In the reverse case, the harvested rainwater may be contaminated with the adhered animal excreta, debris, excessive dust, and other probable contaminants which by mixing with the water can assist the bacterial growth in the harvested water tank in the long run. This may impose a bad smell on the water and degrade the overall water quality. To avoid this issue, the rainwater harvesting system with an automatic opening and closing system of the catchment surface area may be adopted in future endeavors. In the suggested automatic system, the catchment compartment will open and close while starting and ending rain, respectively. As a result, dust, debris, and animal droppings will not get mixed with the collected rainwater. In addition, the automatic catchment surface will not require regular cleaning, and utilization of this system will make it possible to collect and store healthy and safe rainwater.

Further, the present work did not consider analyzing any organic pollutants in the harvested rainwater. Because the rainwater in Dhaka city is hardly found to be contaminated with the probable organic pollutants considering the common activities in the city.

However, in the megacities where industrial activities are most prevalent, in addition to the common urban activities, the consideration of organic pollutants in the harvested rainwater should be taken into action. Fortunately, our developed technology will also work in those situations of organic pollutants contamination since we adopted an activated carbon filtration system, a good organic pollutants adsorbent material. Furthermore, research works should be continued to meet up the freshwater crisis in the megacities through the development of more appropriate technology for harvesting this natural gift, rainwater, in a more advanced way considering the removal facilities of all kinds of probable contaminants and long-term storage with subsequent uses of the natural rainwater.

Author contribution statement

A. H. M. Shofiul Islam Molla Jamal; Yeasin Arafat Tarek: Conceived and designed the experiments; Performed the experiments; Contributed analysis tools or data; Wrote the paper.

Md. Abu Bakar Siddique: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Md. Aftab Ali Shaikh: Supervision; Contributed reagents, materials, analysis tools.

Sumon Chandra Debnath: Conceived and designed the experiments; Performed the experiments; Contributed analysis tools or data.

Md. Ripaj Uddin: Performed the experiments; Contributed analysis tools or data; Wrote the paper.

Shamim Ahmed; Md. Ahedul Akbor; Muhammad Abdullah Al-Mansur: Contributed reagents, materials, analysis tools.

Abu Reza Md. Towfiqul Islam; Rahat Khan: Analyzed and interpreted the data; Wrote the paper.

Mohammad Moniruzzaman; Shahnaz Sultana: Performed the experiments; Contributed analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

The authors declare no competing interests.

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