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Development and economic viability analysis of photovoltaic (PV) energy powered decentralized ultrafiltration of rainwater for potable use

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ABSTRACT

This paper approaches long-term experiments for the treatment of rainwater by ultrafiltration (UF) followed by chlorination to produce potable water The water produced met the standards of drinking water in terms of physical, chemical, and microbiological parameters (coliforms and *E. coli*). The UF (50 kDa) hollow fiber membrane achieved a high permeate flux (135 L h^{-1} m^{-2}). The use of photovoltaic (PV) energy was evaluated to energize the proposed system for small, medium, and large-scale building catchment areas for rainwater. The economic assessment shows that a water cost of 0.17 US$ m^{-3}, 0.10 US$ m^{-3}, and 0.05 US$ m^{-3} for 230 m^2, 2300 m^2, and 11,500 m^2 of rooftop areas, respectively, without a PV power source. With the installation of PV panels as the source of power, similar water costs were found, 0.13 US$ m^{-3}, 0.10 US$ m^{-3}, and 0.04 US$ m^{-3} for 230 m^2, 2300 m^2, and 11,500 m^2, respectively. The results demonstrate that treatment of rainwater using UF followed by chlorination powered by renewable energy (PV) is a technical and economical alternative to supply drinking water through decentralized systems.

1. Introduction

Access to freshwater is one of the United Nations' 17 Sustainable Development Goals (SDG), which calls for universal and equitable access to safe water for all by 2030. According to a WHO [1] report, over 2 billion people worldwide consume contaminated water of which 144 million depend on surface water causing them to suffer from various waterborne diseases like diarrhea, cholera, dysentery, typhoid, and polio. The report also estimates that globally 485,000 diarrheal deaths are caused only due to contaminated water consumption. Rainwater possesses an enormous potential to contribute significantly in solving the world's freshwater crisis and its adverse consequences as most countries and regions in the world receive moderate to high-level precipitation which can be easily collected. For example, the use of this rainwater by decentralized systems can be an alternative for water supply for a single household or a community [2–4]. Results show that a household-scale decentralized unit is able to remove pollutants from rainwater and this represents an important element in the process of achieving the Millennium Development Goals, as centralized systems are often inefficient or nonexistent in developing countries [5]. On the one hand, we need the supply of more freshwater for day-to-day human activities, on the other hand, we must seek the use of renewable and sustainable energies, such as PV energy to reduce greenhouse gas emission.

However, rainwater is not free from contaminants and as such is not readily suitable for human consumption and many other human activities. Rainwater is normally harvested from rooftops of domestic or commercial buildings and therefore possesses different types of chemical and microbiological contaminants highly hazardous to human health [3,6]. The contaminants can originate from the air that the raindrops traverse before hitting the rooftops, drainage pipes, and storage tanks [7]. Depending on the locations, time of collection, and the level of air pollution, rainwater can contain high levels of lead, aluminum, sulfate, nitrate, carbon dioxide, chromium, cobalt, nickel, vanadium, and various forms of industrial and traffic wastes. The microbiological contaminants in rainwater usually originate from the soil and leaf litter accumulated on the roof, fecal materials of squirrels, birds, possums, lizards, rats, dead animals, and insects either on the rooftops or in the storage tanks, and airborne microorganisms blown in by wind [7,8]. The fecal materials can contain hazardous bacteria, viruses, and protozoan

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pathogens. As a result, the collected rainwater in storage tanks could be a source of *Escherichia coli* (*E. coli*) and other pathogens contamination. For example, a study performed by Ahmed et al. [9] evaluated 27 seven storage tank rainwater samples in Australia of which 17 (63 %) were found *E. coli* positive. In Bermuda, L'evesque et al. [10] evaluated 102 rainwater samples collected from 102 storage tanks of which 66 % showed contamination with *E. coli.* Rainwater storage tanks also could serve as a breeding space for mosquitoes which can spread many diseases including malaria. The materials of storage tanks can also contaminate rainwater [8]. Rainwater treatment is therefore essential to make it suitable for drinking and other domestic uses. However, it should be noted here that in-situ rainwater purification is beneficial and could be made sustainable due to reduced water transport distances [11].

Different types of rainwater treatment methodologies exist in different regions of the world. In developing countries boiling, chlorination, pasteurization by solar technology are widely used for rainwater purification [12,38]. These are mostly quite rudimentary technologies and do not always guarantee a purification level to potable standard [7,8]. Alim et al. [13] tested a filtration bank to produce drinking water from rainwater in Australia, but none of the tests were carried out with respect to the water quality for drinking. Boiling is energy-intensive and mostly fossil fuels are used for boiling purposes. Some relatively advanced techniques have also been investigated.

Membrane separation processes are attractive for the treatment of rainwater since they provide a barrier for pathogens and remove turbidity, thereby increasing the palatability of the water [4]. Kim et al. [14] proposed a design for a rainwater purification system with a metal membrane submerged into a tank; filtration in combination with UV disinfection was also utilized. However, this process had a marginal impact in reducing total heterotrophic bacteria. Activated carbon treatment based on membrane filtration to remove dissolved organic solids (DOCs) demonstrated limited contaminants removal efficiency [15]. For example, the use of antimicrobial silver ions in combination with settling tanks and conventional filtration was investigated by Adler et al. [16]. The system was not able to remove all forms of contaminants to potable water standards and needed frequent cleaning of the components. Some researchers used microfiltration which was able to remove all heterotrophic bacteria but only removed 10–50 % DOCs [15].

Dobrowsky et al. [6] used nanofiber MF membrane disks to treated rainwater, but they concluded that that numerous opportunistic bacterial pathogens and viruses persisted after filtration. Du et al. [17] used a gravimetric MF filter for the treatment of rainwater, but the permeate still contains microorganisms and organic matter into permeate. It is therefore clear that none of the above treatments of rainwater was able to ensure the water quality for drinking purposes. Conversely, ultrafiltration (UF) could produce drinking water from rain as UF membranes have tight pores (0.001–0.1 μm) than MF. It can remove suspended and colloidal material, bacteria and virus from rainwater [3]. Additionally, it requires pressures between 1 and 7 bar and therefore consumes less energy compared to reverse osmosis and nanofiltration. The work of Miorando et al. [3] demonstrated that UF could treat rainwater to potable standards in terms of oxygen demand, settleable solids, coliforms, and other parameters. However, long-term testing with broader monitoring is required to assess water quality assurance and water production costs. In this investigation, long-term trials were conducted in order to respond to the current temporal problem and to evaluate the permeate quality and the flow produced by the UF membrane allowing to bring broader inferences, with regard to both technical and economic terms.

The use of renewable energy is deemed as one of the promising approaches to the sustainability of freshwater production. The International Agency of Energy predicts that the consumption of energy will rise up to 33 % in 2040. To meet this ongoing energy demand curving the environmental pollution due to greenhouse gas emission, there are intensified efforts to power water purification technology with renewable energy sources especially photovoltaic (PV) and wind energy. Hybrid systems, which combine different desalination techniques and energy sources have also emerged as promising solutions to produce clean water [18]. As reported in the literature, some studies investigated the use of PV energy to desalinate water using NF or RO membranes [19–22]. However, the intensive use of energy for both types of membranes leads to high energy consumption and consequently could result in water cost as high as US\$1.74 m^{-3} [23]. In contrast, there is limited research to show the feasibility of PV-based energy supply for UF to purify rainwater. Czarny et al. [24] have developed a virtual model for the purification of rainwater using UF in Cambodia. However, they have not demonstrated any practical approach or economic data to show the feasibility. Additionally, Miorando et al. [3] studied UF for the treatment of rainwater for drinking purposes using short-term tests, but long-term tests are necessary to ensure sustained water quality [13] and the applicability and benefit of the proposed system in terms of cost-effectiveness and low-maintenance. This work is therefore novel as there is no study carrying out long-term tests to produce potable water from rainwater. Moreover, the system is proposed to be powered by Photovoltaic energy to reduce greenhouse gas emission. In addition, for the economic feasibility of the process, complimentary information helping to choose suitable membrane technology is necessary. This work has evaluated the UF process as a technical solution for the potabilization of rainwater using photovoltaic energy and the economic feasibility of the system.

2. Materials and methods

2.1. Experimentation through long-term trials

Ultrafiltration is a membrane process whose pore sizes range from 0.05 μm and 1 nm. Ultrafiltration uses the pressure gradient as driving force and it is typically used to retain macromolecules and colloids from a solution. The rejection of UF membranes is determined by the size and shape of the solutes relative to the pore sizes in top layer of the membrane and the transport of solvent is proportional to the applied pressure. However, the permeate flux generally decreases over time because polarization phenomena and membrane fouling [41].

The ultrafiltration of rainwater has been carried out for ten months from January to October 2019. In this period, we performed 86 trials. We choose to harvest the rainwater at an urban area of low atmospheric pollution so that it could represent many locations around the world. Rainwater was collected from the rooftop of the Food Engineering building (28° 13′53.3″ S 52° 23′04.6″ W) at the University of Passo Fundo (UPF), Brazil. In this current work long-term experiments, over a period of four daily hours for ten months were conducted replicating our intended real potable water production plant, with a complete monitoring plan to ensure the potable water quality.

2.1.1. The system - components and installation

The rainwater purification process comprising the collection, filtration, and energization, units are depicted in Fig. 1. The collect area was approximately 90 m^2 of the roof made of fiber cement tiles with an inclination of 30 % (16.69°). Rainwater was collected by aluminum gutters that led the water to the polyvinyl chloride (PVC) drop pipes. The membrane used in this experiment was a hollow fiber type polyethersulfone (50 kDa of the molecular weight cut off), with an external fiber diameter of 0.9 mm and an area of 0.1 m^2. The system is operated with this membrane as Miorando et al. [3] tested other membranes and this one achieves high permeate flux and good quality of the treated water. The equipment and the membranes were supplied by PAM Membranes (Brazil). To estimate the required number of panels for the proposed system, the average energy generated by the solar panels located in the photovoltaic park of the University of Passo Fundo was measured and used as a reference.

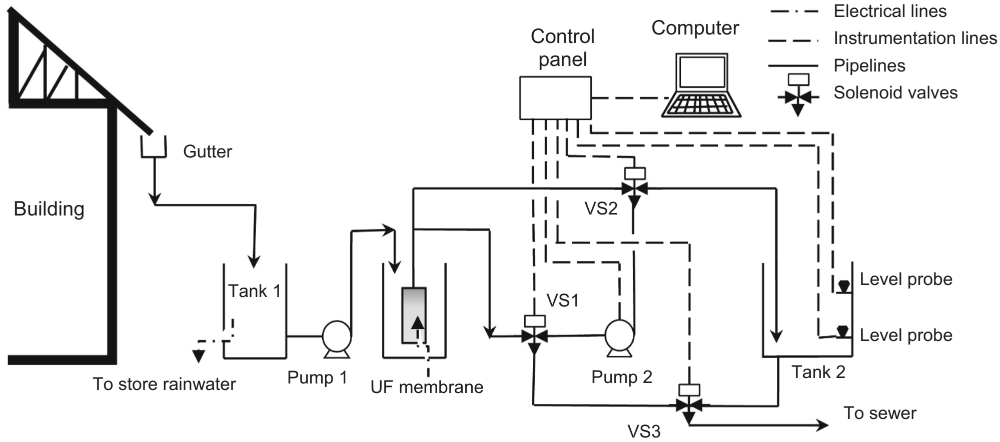

Fig. 1. The schematic facility used for long-term trials of ultrafiltration of rainwater.

Fig. 2 shows the picture of the system used for the ultrafiltration of the rainwater. Rainwater is fed to tank (1) where the UF membrane is submerged. The control system comprises the external hardware-based control component (7) which consists of the switch to power the system, connector for the electric wiring and the electric protection, and internal Scala software system supplied by the Scala Automation (Rio de Janeiro – Brazil) installed in the computer. The control of the system, on/off, time production/backflushing, pressure, pump flow, pressure, is performed using the Scala software system. When the pump (3) is turned on, the water flows through the path as indicated by the blue line, and the pressure is read on the manometer (4). The instantaneous permeate flow is read on the rotameter (5) and the treated rainwater is collected in another tank (2). When the computer puts the system on backwashing, solenoid valves (6) divert the water in the opposite direction (orange lines) and the flow is reversed.

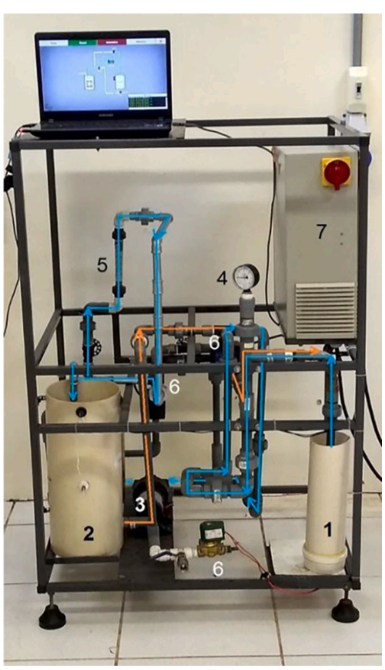

Fig. 2. The rainwater ultrafiltration system at the University of Passo Fundo: 1: Reservoir of the submerged UF membrane; 2: Reservoir of permeate; 3: Pump; 4: Manometer; 5: Rotameter; 6: Solenoid valve; 7: Control panel. Blue line: filtration; Orange line: back flushing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1.2. Operation of the system-filtration process

The reservoir of Fig. 1 was previously sanitized to collect water without the previous influence of contaminants, as well as undergoing monthly cleaning maintenance. Based on the work of Miorando et al. [3], the operation and backwash cycle was defined, which was 90 min of filtration, followed by 30 s of backwash, followed again by 90 min of filtration. The vacuum applied was 0.8 bar (80 kPa) in the operation mode and the backwashing was performed in 2 bar (200 kPa). The pipe connection between Pump 1 and Tank 1 was installed 20 cm above the bottom of the tank. This reduced the drain of sediments by the pump. The settled material was purged once a week. The software of the computer registered each event of action of level probes in Tank 2; this way we could calculate the average permeate flux by the rate of the daily filtered volume and the membrane area (0.1 m^2).

The sampling of permeate was collected at the end of the second cycle of filtration. The produced permeate was added to an equalization reservoir (capacity of 100 L) where sodium hypochlorite was dosed to keep the chlorine concentration in 1 mg L^{-1}. We monitored the permeate quality by analysis carried out daily, weekly, and monthly, as presented in Table 1. The permeate and chlorinated water underwent 25 laboratory tests, as well as the permitted water and the drill to determine its quality standard. Analyses followed the adapted protocols of APHA [25]. pH was determined using a benchtop meter (Digimed Dm-22, Brazil). Electrical conductivity was quantified using a portable conductivity meter B-Max TDS-3. Turbidity was measured with a benchtop equipment (Tecnal TB-1000, Brazil). All metals were quantified in a flame atomic absorption spectrometer (Perkin Elmer AAnalyst 200). NO_3^-, color and humic acids were measured by colorimetric/absorbance method in a spectrophotometer Shimadzu UV-1800. NO_2^- and phosphorus were measured with the colorimetric method in a spectrophotometer Merck SQ118. Ammonium and Nitrogen were measured using Kjeldahl method, and alkalinity was determined by acid titration. Sulfate was assessed using the turbidimetric method, and hardness by titration with ethylenediaminetetraacetic acid (EDTA). Organic matter was quantified by digestion with potassium permanganate. Five-day Biochemical Oxygen Demand was measured by the respirometric method after five days at 25 °C in an incubator (Tecnal BOD-TE391 –

Table 1
Monitored parameters of the water and analyzed periodicity.

Daily	Weekly	Monthly
pH, free residual chlorine, turbidity, electric conductivity, permeate volume, filtration flux, filtration pressure	Alkalinity, hardness, sulfate, ammoniacal nitrogen, organic matter, total coliforms, *E. coli*, Kjeldahl nitrogen, humic acids, total match	BOD, nitrates, nitrite, metals, color

Brazil). Total coliforms and *E. coli* were quantified in Petrifilm plates (Merck – Brazil).

2.2. Photovoltaic system to power the ultrafiltration process

The PV system used as a reference in this experiment for sizing the PV panels for economic analysis of our proposed system consists of 54 solar panels. The system is located in the PV park of the UPF (28°13′36.4″S 52°23′16.4″W) with a power capacity of 17.55 kW. The panels consist of two sets of 30 and 24 modules, respectively and each panel had a dimension of 1 × 2 m. The energy produced over a period of 14 months by the system was 210 Wh, with an average of 5 h of sunshine daily. The monthly solar irradiation in the location is shown in Fig. 3.

2.3. Economic analysis

According to the Climate-date [26], the annual average precipitation is 1746 mm, the monthly average of 145.50 mm, in the region of Passo Fundo-RS (the Rio Grande do Sul State of Brazil). The economic viability is assessed for three different scales of the buildings: small, medium, and large. For each size, we considered the required energy supply with or without on-grid photovoltaic panels. Thus, we performed the economic analysis in six scenarios. In all scenarios a gable roof was considered, making up the entire perimeter of the buildings for the rainwater harvest. The water collected is driven through the drop pipes from the roof to a storage reservoir. The population and daily consumption for each scenario are presented in Table 2. The volume of produced water in each scenario was predicted using the annual rainfall of Passo Fundo region (1746 mm, or a monthly average of 145.5 mm) and the different rooftop areas of each scenario. The population and consumption of water in each building was estimated following the suggestion of Fecomercio [27].

The assumption of Table 2 shows that a single household (230 m^2) is self-sufficient for water supply by the UF system. Conversely, we have a deficit of water in other scenarios, and we have to buy water from the municipal system.

We designed a UF system for each scenario. It is assumed that the system will have a reservoir to collect rainwater even at night, but the ultrafiltration will operate only during the daylight to use the PV energy without the need of batteries. For that, membrane area was predicted by dividing the required volume of permeate and the permeate flux for each scenario. The theoretical required power for the UF was calculated using Eq. (1):

$$P = \frac{Q \times \Delta P}{\eta} \tag{1}$$

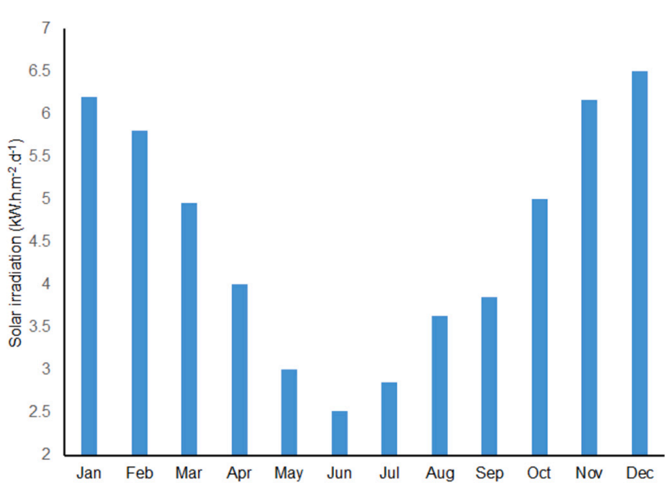

Fig. 3. Monthly solar irradiation on the location of the experiments through the year of 2019.

Table 2
Population and predicted daily consumption of water.

Scenario	Population (inhabitants)	Daily consumption liters per inhabitant per day (L/inh·d)[a]	Monthly consumption of water (m^3)	Monthly purified volume of water (m^3)
230 m^2	5[a]	150[a]	22.5	33.46
2300 m^2	330[a]	50[a]	495	334.65
11,500 m^2	2000[a]	50[a]	3000	1673.25

[a] According Fecomercio [27].

where P is the required power (W), Q is the permeate flow rate ($m^3\ s^{-1}$), ΔP is the transmembrane pressure (Pa), and η is the pump efficiency (considered 0.5).

We considered capital costs for the reservoirs for rainwater and treated water, one pump, pipes, two-level probes, and solenoid valves. A lifespan of 10 years was considered with constant annual depreciation. We also considered the PV panels as capital costs for the three scenarios with the use of photovoltaic energy.

For the capital costs, the annual depreciation is constant; this estimation is based on the straight-line method as shown in Eq. (2) [28]. The lifespan was 10 years.

$$D_t = \frac{I - H}{n} \tag{2}$$

where D_t is the annual depreciation, I is the investment, n is the lifespan and H is the residual value after the life span. We chose H to be zero (no residual value).

Fixed costs of the ultrafiltration process include maintenance, membrane replacement, electricity, and chemicals. The annual maintenance (and spare parts) cost was considered to be 2 % of the capital cost. Membrane replacement is considered to take place every two years. We considered the same membrane used in the experiments. The cost is US$ 55.00 per square meter of membrane area. The chemicals used are sodium hydroxide and nitric acid (for cleaning), sodium hypochlorite (for disinfection). These chemicals are cheap, thus, the impact on the cost will be low. The required PV panels for the small, medium, and large scales were estimated according to the power required for each one. To do so, we measured the energy generated by the photovoltaic park of the University of Passo Fundo for 14 months. The system has 54 solar panels with an area of 750 m^2 with a power of 17.55 kW. The energy produced in 14 months in the photovoltaic park was 210 Wh/month, considering a daily average of 5 h of sunshine. Thus, the monthly energy generated per panel is 31.50 kWh. The number of PV panels considered are 2, 8, and 16, for 230 m^2, 2300 m^2, and 11,500 m^2 of the catchment area, respectively.

We considered three responses for the economic assessment: the values of Internal Rate of Return (IRR) and Simple Payback (investment recovery period) as shown in Eqs. (3) and (4) [29], and the water cost (US$ m^{-3}). In the economic balance, the purified water was considered as cash inflow.

The volume of water produced was predicted by the annual average precipitation (1746 mm) multiplied by the rooftop area.

$$\text{IRR} = \frac{\textit{Cash flows}}{(1+r)^n} - \text{Initial investment} \tag{3}$$

where Cash flows is the sum of cash inflow in the time period, n and r are the discount rate.

$$\text{Payback} = \frac{\textit{Initial investment}}{\textit{annual cash flow}} \tag{4}$$

Table 3 shows a summary of the economic calculations.

Table 3
Summary of calculations for predict economic values for UF of rainwater.

Item	Prediction	Cost (US$)
Investment		
Equipment	Budgets from specialized company	
PV panels	$C_{panels} = Cost_{panel} * N_{panels}$	$Cost_{panel} = US\$380.93$
Chemicals	Predicted from extrapolation of experimental data	US$0.062/m^3 for 230 m^2 US$0.012/m^3 for 2300 m^2 US$0.006/m^3 for 11,500 m^2
Membrane	US$55/m^2 of membrane with a depreciation in 2 years $C_{membrane} = Area_{membrane} * Cost_{area}$	US$55 for 230 m^2 of rooftop (1 m^2 of membrane area) US$275 for 2300 m^2 of rooftop (5 m^2 of membrane area) US$685 for 11,500 m^2 of rooftop (25 m^2 of membrane area)
Maintenance	$C_{maintenance} = 2\ \%$ *of investment*	
Electricity	Energy required to pump filtrates the rainwater. $C_{energy} = Power_{pump} * Cost_{kWh} * working\ time$	$Cost_{kWh}$ = US$0.203/kWh Working time: 11.58 h for 230 m^2 Working time: 23.17 h for 2300 m^2 Working time: 23.18 h for 11,500 m^2
Water from municipal system	$C_{water} = US\$1.97/m3$	0 m^3 for 230 m^2 (rainwater supplies all required volume) 1924.2 m^3 for 2300 m^2 15,921 m^3 for 11,500 m^2
Water saved	$C_{water\ saved} = C_{water} * Water_{produced}$	162 m^3 per year for 230 m^2 4015 m^3 per year for 2300 m^2 20,079 m^3 per year for 11,500 m^2

3. Results and discussion

3.1. Long-term trials of ultrafiltration of rainwater

In this study, 25 important parameters concerning the quality of rainwater to be used for drinking were monitored and the results are summarized in Table 4, where the minimum, average and maximum values are presented so that it is possible to analyze the amplitude of the data for the raw, ultrafiltered and ultrafiltered plus chlorination water over the ten-month experiment period. In addition, we dosage sodium hypochlorite in the filtered water as the free chlorine was in a range between 1 mg L^{-1} and 2 mg L^{-1}.

The concentration of physicochemical and microbiological pollutants in rainwater varies widely. It is apparent that the concentration of pollutants depends on the atmosphere and spatial condition. The physicochemical parameters, organic pollutants, and microbial contamination describe how and which pollutants in the atmosphere are dissolved by rainwater. While cities for example tend to release considerable amounts of dust particles and gases from combustion processes (as CO and CO_2), pesticides are more commonly released in areas with high agricultural use [24]. We performed our experiments in a location far away from the city and industrial pollutant sources, and, thus, we did not expect higher concentrations of pollutants, as suggested by Helmreich and Horn [12]. In our experiments, UF was able to produce the rainwater of drinking quality.

We monitored the metals in the rainwater due to probable contamination from lixiviation of gutters or by the air. The UF membrane was able to reduce the metal present in the raw water like aluminum, chromium, and iron. These metals are likely to be adsorbed in colloidal and particulate material. It should be noted that all metal concentrations (including rainwater) were below the maximum value for potability.

The location of the UF facility is an important factor for the technical analysis of using rainwater for drinkable purposes. The location cannot be a site where there is high air pollution because the UF membrane is not a perfect barrier for lower contaminants such as ions and dissolved organic matter. However, we understand that many locations satisfy this criterion (lower level of ions and dissolved organic matter). These include small and medium cities or other sites with low air pollution. Figs. 4, 5, and 6 show the turbidity, color, and concentration of organic matter in the rainwater, ultrafiltered and ultrafiltered plus chlorination.

The maximum turbidity of rainwater was 4.4 NTU. This is a low concentration because we did not collect the rainwater from the bottom of the tank in Fig. 1. The UF reduced turbidity to <0.5 NTU. Turbidity is

Table 4
Minimum, maximum and average value of the monitored parameters over 10 months of experiments of ultrafiltration of rainwater.

Parameter	Rainwater			Ultrafiltrated			Ultrafiltered and chlorinated			
	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Limit
pH	6.12	7.14	8.22	6.00	7.18	8.01	6.66	7.22	8.0	6.6 < pH < 9.5
Electric conductivity (μS cm^{-1})	15.50	40.99	63.80	6.62	41.17	65.12	53.14	66.71	81.91	500.00
Turbidity (NTU)	0.10	1.08	4.40	0.00	0.07	0.52	0.00	0.08	0.37	5.00
Sulfates (mg L^{-1})	0.03	0.14	0.25	0.02	0.10	0.18	0.05	0.10	0.17	250.00
Copper (mg L^{-1})	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	0.12	0.13	2.00
Manganese (mg L^{-1})	0.03	0.075	0.12	<0.03	0.03	0.03	<0.03	<0.03	<0.03	0.10
Iron (mg L^{-1})	0.05	0.07	0.09	<0.05	<0.05	<0.05	0.05	0.065	0.08	0.30
Zinc (mg L^{-1})	<0.23	<0.23	<0.23	<0.23	<0.23	<0.23	<0.23	<0.23	<0.23	5.00
Aluminum (mg L^{-1})	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.20
Cadmium (mg L^{-1})	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.20
Lead (mg L^{-1})	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.01
Chrome (mg L^{-1})	0.07	0.07	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.05
Color (hazen)	7.5	13.33	25.00	0.00	4.00	14.00	0.00	0.00	0.00	15.00
Hardness (mg L^{-1})	2.0	7.31	12.00	0.80	4.10	12.00	2.00	3.07	4.00	500.00
Alkalinity (mg L^{-1})	6.0	13.40	20.00	5.00	12.50	20.00	6.00	9.2	12.00	NA
Phosphorus (mg L^{-1})	0.02	0.03	0.07	0.01	0.03	0.05	0.02	0.03	0.05	0.05
Kjeldahl nitrogen (mg L^{-1})	0.21	0.24	0.27	0.21	0.24	0.27	0.12	0.21	0.25	NA
Ammonia nitrogen (mg L^{-1})	0.04	0.08	0.15	0.04	0.06	0.10	0.04	0.09	0.20	1.50
Humic acids (absorbance at 254 nm)	0.00	0.01	0.05	0.00	0.01	0.03	0.01	0.01	0.02	0.10
Organic matter (mg L^{-1})	0.00	1.61	3.69	0.00	0.83	2.76	0.00	0.03	0.18	5.00
BOD (mg L^{-1})	0.50	5.75	11.00	1.00	2.32	5.25	0.75	2.2	3.00	10.00
Nitrate (mg L^{-1})	0.04	0.06	0.08	0.02	0.04	0.07	0.04	0.06	0.12	10.00
Nitrite (mg L^{-1})	0.03	0.04	0.06	0.03	0.04	0.04	0.02	0.03	0.04	1.00
Total coliforms (UFC 100 mL^{-1})	>23	>23	>23	0.00	1.00	9.2	0.00	0.00	0.00	0.00
E. coli (UFC 100 mL^{-1})	>16	>16	>16	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ND: not detected by the analytical method; NA: not applicable.

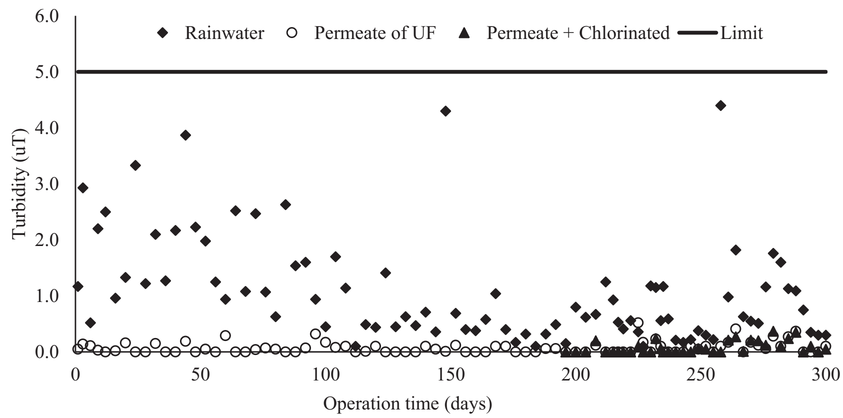

Fig. 4. Turbidity of rainwater, permeate of ultrafiltration and permeate plus chlorination along the weeks of treatment of rainwater by UF.

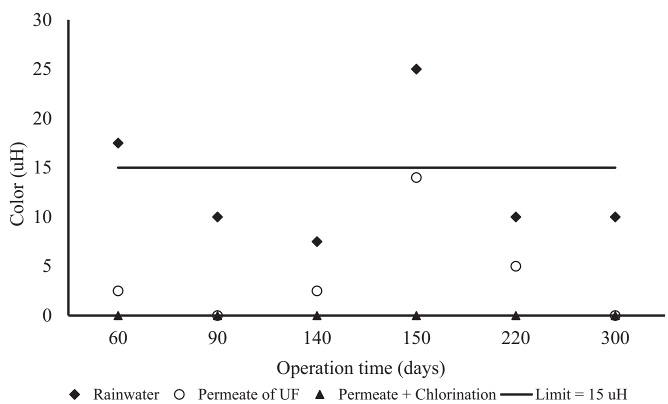

Fig. 5. Color of rainwater, permeate of ultrafiltration and permeate plus chlorination along the weeks of treatment of rainwater by UF.

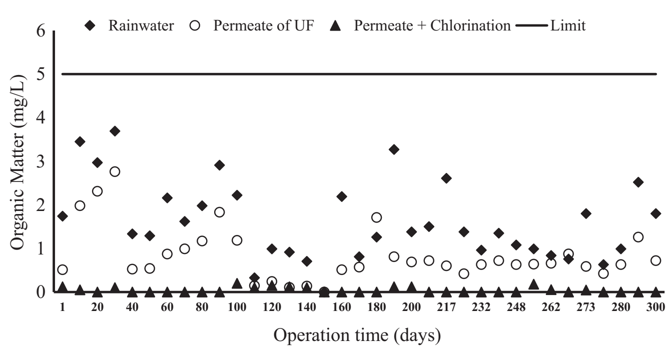

Fig. 6. The concentration of organic matter in rainwater, permeate of ultrafiltration and permeate plus chlorination along the weeks of treatment of rainwater by UF.

an indirect measure of the suspended and colloidal material present in water, and, thus, required to be removed by UF. Turbidity in water is caused by suspended particles that can act as a shield to pathogenic microorganisms and minimize the action of disinfectants [30]. In addition, the removal of colloidal (indirect measured by turbidity) and dissolved organic matter is important due to the possible formation of trihalomethane through the reaction of this species with chlorine used for disinfection [4]. From Figs. 5 and 6 we can observe that the UF is not a perfect barrier and the permeate contains an average of 25 % of the initial color and 48 % of the initial organic matter, and we observed that the chlorination helps the system to reduce color and organic matter, and the reduction of color and organic matter after chlorination is clearly visible in the latter part of the experimentation period.

The higher color values in the rainwater were observed after drought periods. In fact, the first-flush runoff (2 mm of rain) contains stronger contaminated water [24]. It should be noted that the water remained potable even after this scenario, but suspended materials washed off by the first rain may reduce membrane life.

Fig. 7 shows the concentration of ammonium and phosphorus in rainwater, permeate and permeate after chlorination over the period of monitoring. Nitrogen and phosphorus are important nutrients for microorganisms and are found in rainwater due to the deposition of particles on the roof, plant, and fecal material. We identified two periods when of the monitoring when the rainwater possessed concentration of phosphorus above 0.05 mg L^{-1} (the limit for drinking water by European Directive [31] and WHO [32] recommendation), but the ultrafiltration was able to reduce this value to approximately 0.02 mg L^{-1}. It is likely that the phosphorus present in rainwater is complexed on colloidal material and, thus, it is removed by the UF. In contrast, ammonium sources indicate the existence of organic matter in decomposition and an oxygen-poor environment. It is well known that the UF has limitations on the separation of ionic contaminants of low molar mass. However, all samples of treated water by the UF were potable after chlorination.

We also monitored the absorbance of the water at 254 nm so this can represent the concentration of humic acids in the rainwater (Fig. 8). Humic acids are one of the responsible agents for brown color change in the water. The chlorination of some waters with ammonia can lead to the creation of chlorinated by-products, such as potentially carcinogenic trihalomethanes (THM), as reported by Mahvi et al. [33]. However, we did not observe high absorbance at 254 nm, and, thus, there are no risks of the formation of THM. In fact, we also observed a low concentration of organic matter (Fig. 6) and ammonium (Fig. 7a) in all monitoring days. The European Directive for drinking water [31] points to a maximum concentration of 5 mg L^{-1} of oxygen demand to express the organic matter. The concern about organic matter lies in the hypothesis that these species can be a useful substrate for the growth of microorganisms. Concerning these parameters, there are no problems with the consumption of the rainwater treated by UF followed by chlorination.

Our monitoring plan of the process included monthly analysis of nitrate and nitrite (Fig. 9). Nitrite (NO_2^-) is not usually present in significant concentrations except in a reducing environment (very low oxygen concentration in the medium), as nitrate is the more stable oxidation state. Nitrate (NO_3^-) is found naturally in the environment and it is present at varying concentrations in all plants and it is a part of the nitrogen cycle [32]. High intake of nitrate and nitrite are most serious for infants and it can interfere with the oxygen-carrying capacity of a child's blood. The source of nitrate in the rainwater is likely the vegetal material (i.e., trees' leaves). The combination of a reducing environment favors the conversion of nitrate to nitrites (mainly by *Nitrosomonas*

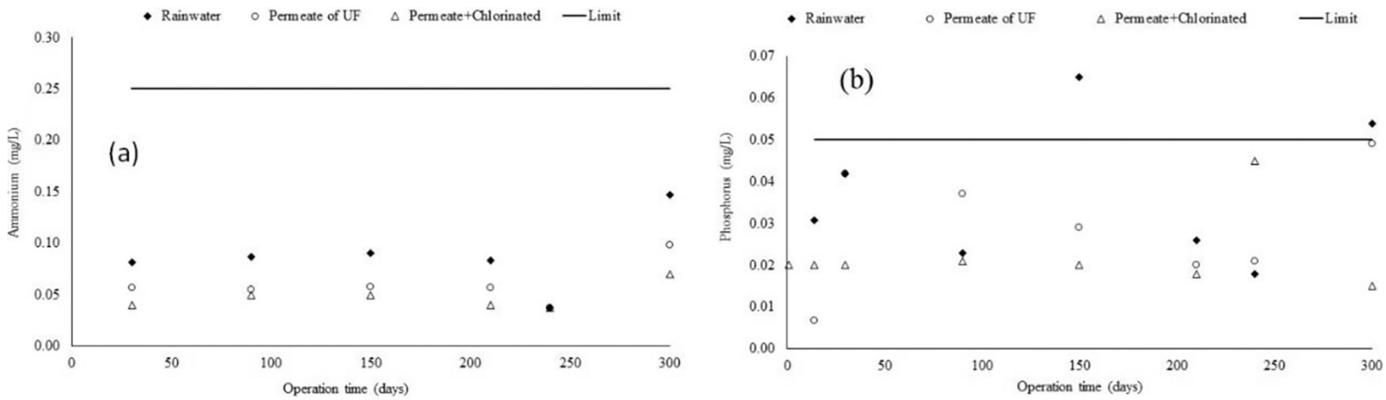

Fig. 7. The concentration of ammonium (a) and phosphorus (b) in rainwater, permeate of ultrafiltration and permeate plus chlorination against the weeks of treatment of rainwater by UF.

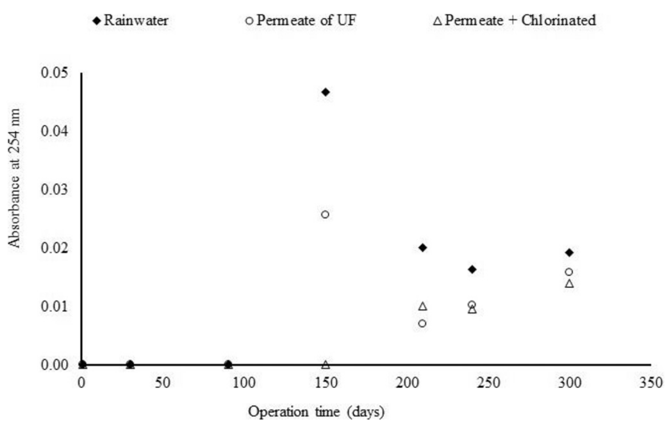

Fig. 8. Absorbance at 254 nm to estimate the humic acids in rainwater, permeate of ultrafiltration and permeate plus chlorination against the weeks of treatment of rainwater by UF.

bacteria), and the rainwater collected in our experiments has little concentration of both constituents. However, in locations of intensive urbanization and industrialization, the concentration of nitrates can be higher than 10 mg·L^{-1} [3]. Nevertheless, the place where we installed our experiments is of low urbanization and the water produced by the ultrafiltration of the rainwater did not contain high concentrations of both constituents.

We did not perform an extensive microbiological analysis of the water, but we analyzed the presence of the coliform group and *Escherichia coli* because they are specific indicators of fecal contamination and they may also indicate the contamination by pathogens microorganisms. Although Hagen et al. [34] examined the microbial removal rate of Ultrafiltration (UF) and concluded that a subsequent application of disinfection is needless. We identified the presence of coliforms in 3 samples out of 15 samples analyzed. Conversely, no chlorinated sample had coliforms. In fact, chlorination is a traditional method for disinfection, it is highly effective against nearly all waterborne pathogens and it is also relatively cheap [4,6,12], although ultraviolet (UV) irradiation with lamps has received interest in recent years. Research conducted in the USA, showed that of the potable users of rainwater, >70 % utilize ultraviolet (UV) light as their primary treatment method [35]. However, we kept chlorination as the standard method for the system as it is simple to dosage and cheap.

Long periods of drought allow the accumulation of decomposing matter in both the collecting gutters and the roof, which means that in the first rain after a dry period this material is washed to the raw water reservoir. There was a drop in rainwater quality after this phenomenon in the analyzes performed, but after ultrafiltration and chlorination, the potability standard was obtained. In this case, it is advisable to install a system to purge the first flush to improve the rainwater quality fed to the treatment.

The permeate flux was measured during all filtration trials. Fig. 10 shows the permeate flux over 62 days of experiments, performed over 10 months of tests. The maximum and minimum permeate flux was 200 L h^{-1} m^{-2} and 66 L h^{-1} m^{-2}, respectively. The average permeate flux (shown by the dotted line) was 135 L h^{-1} m^{-2}. Note that the measurement was obtained based on the daily volume of permeate divided by the membrane area. Over time, we fed rainwater with different turbidity

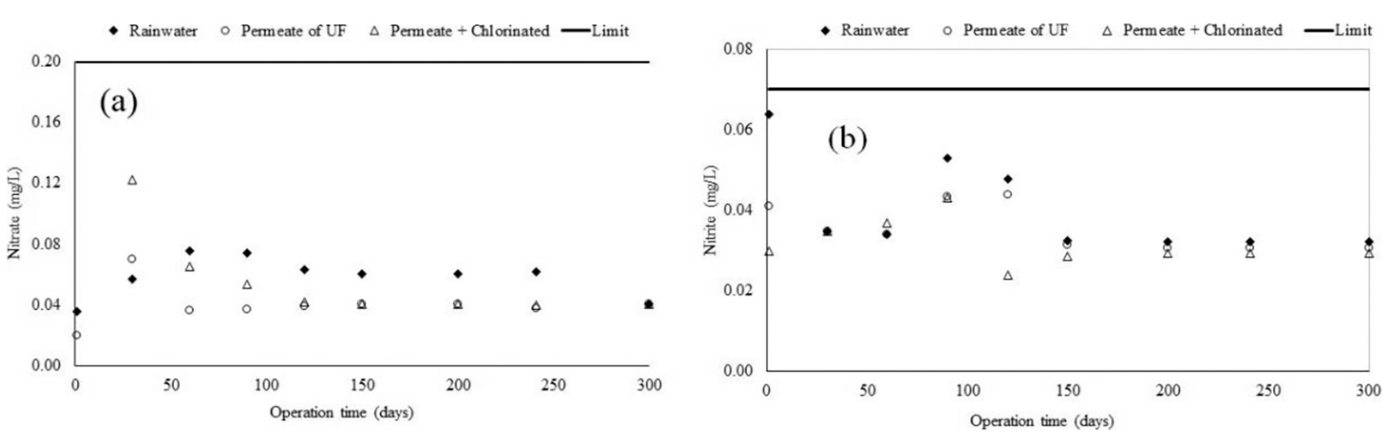

Fig. 9. The concentration of nitrate (a) and nitrite (b) in rainwater, permeate of ultrafiltration and permeate plus chlorination against the months of treatment of rainwater by UF.

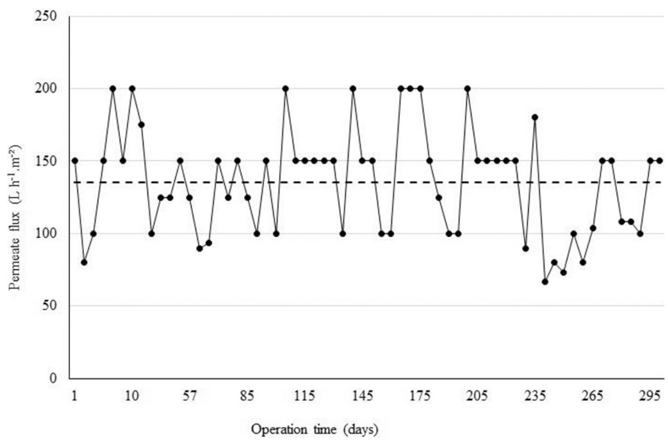

Fig. 10. Average permeate flux through days of experiments of ultrafiltration of rainwater. The bold line is just for visualization. The dotted line shows the average permeate flux.

and suspended matter to the UF equipment, and we tried to find a relationship between the turbidity and the flux. However, a poor regression was obtained. When backwashing was not enough to recover the initial flux, chemical cleaning (NaOH at pH 10 and NaOCl at 100 mg L^{-1} for 1 h) was performed on the membrane. This type of cleaning can reduce membrane life and was performed only when necessary, but the procedure was efficient for the recovery of the membrane flux.

We also measured the instantaneous flux in the experiments to evaluate the transient permeation through the membrane and to evaluate the effectiveness of the backwashing in the flux's recovery. Fig. 11 shows that with the course of filtration the flux drops due to membrane clogging. The backwashing was performed at 200 min, 400 min, and 620 min, and it can be noted that the recovery of the flux back to 200 L h^{-1} m^{-2} in 210 and 640 min. The average permeate flux was 110 L h^{-1} m^{-2} on this day.

Miorando et al. [3] ultrafiltrated rainwater with the same type of membrane that we used in our experiments and they observed a very similar flux behavior: an initial flux of approximately 200 L h^{-1} m^{-2} followed by a decay near 50 % after 100 min of filtration. The high flux recovery after the backwashings suggests that the material is deposited on the membrane surface, and the irreversible fouling is not significant.

MF membranes were used for the treatment of rainwater, however, Kim et al. [14] observed that a strong pore blockage and pore constriction reduced the flux tor approximately 20 L h^{-1} m^{-2} after 120 min of operation. Additionally, Du et al. [17] tested a gravity-driven microfiltration membrane to purify rainwater and a permeate flux of 60 L h^{-1} m^{-2} was observed using 0.6 m of hydraulic pressure. Ding et al. [36] used the UF with an added layer of powdered activated carbon to enhance the organic removal of rainwater. The flux observed was only 3 L h^{-1} m^{-2}. Therefore, the full recovery of the flux after the backwashing of our experiments indicates that the low flux was due to likely external pore blockage, and, furthermore, it was possible to keep a high flux in continuous operation in the long-term running of UF of rainwater.

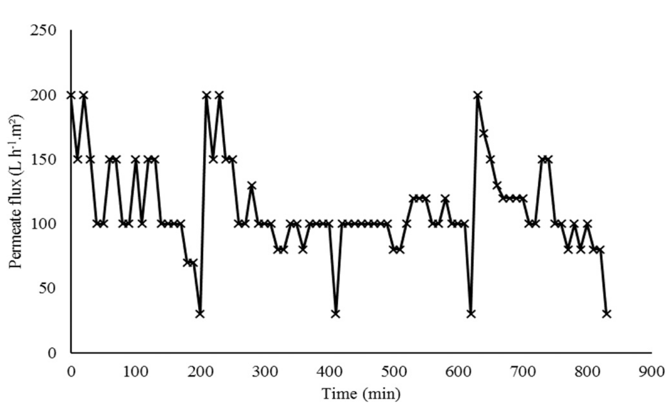

Fig. 11. Permeate flux through minutes of one trial of ultrafiltration of rainwater. The bold line is just for an easier visualization.

3.1.1. *Summary of the long-term experiment of UF of rainwater*

After 10 months of monitoring the water quality, the summary shows that the ultrafiltered and chlorinated rainwater is safe for drinking purposes. In addition, high flux is achieved by the 50 kDa UF membrane, which means that the treatment will require a low membrane area. Although Ding et al. [36] expressed their concern with regard to low removal of dissolved organics by UF when the rainwater possesses little concentration of dissolved organic matter, the UF followed by chlorination is a safe method to produce drinking water. Peter-Varbanets et al. [4] presented some examples for the use of UF membranes for "point of use" to supply water in decentralized systems. The authors claim that UF is useful to purify tap water (or any source) of low quality, especially in developing countries. We believe that the use of UF can be more than that. The catchment of rainwater as a water source and a simple method as UF plus chlorination is a sustainable technique to supply safe water at any site with enough rainfall. However, the last question must be answered: is it expensive?

3.2. *Economic analysis*

The economic analysis is presented through three scenarios based on the catchment roof area of each building. Additionally, we considered situations with and without the implementation of photovoltaic panels for each building.

The system designed is simple. It comprises two reservoirs (for storage of the rainwater and the drinking water), a centrifugal pump, two-level probes for on/off the pump, some solenoid valves, a venturi doser (for dosage of sodium hypochlorite) and pipes of PVC. All parts are cheap so the maintenance will not be expensive. We proposed to install a screen on the downfall pipe (to separate leaves, twigs, and coarse contaminants).

Table 5 (without PV panels) and Table 6 (with PV panels) show the costs for the installation of a UF system to produce drinking water in the third scenario (building with 11,500 m^2 of area). The detailed tables of others scenarios are shown as supplemental material. For this scenario, a membrane of 25 m^2 was selected (cost of US$55 m^{-2} and a total cost of US$1375). Note that we depreciated the membrane in only two years. The cost of the equipment was US$4073 and the cost of the 16 PV panels was US$6095 (Table 6). Another detail in both tables is that we have to buy water from the municipal system as the rainwater is not enough to produce all the necessary water for the building.

Table 7 shows the details of the annualized costs of three scenarios and Table 8 shows the summary of the economic assessment, and Table 8 shows the annualized economic balance. Note that in both scenarios of 2300 m^2 and 11,500 m^2 it is necessary to buy water from the municipal system in our simulation, and, thus, there is a substantially negative contribution of this part on the annual balance. The reduction of water consumption by different initiatives (i.e., reclaim of low contaminated water to flush toilets, automatized flushing in the toilets and sinks) to reduce the water consumption can turn both scenarios to be more attractive for the investment, with lower paybacks.

Table 8 also shows that the water cost is similar for both situations with or without the PV panels. The water cost in Brazil depends on the location, but it is in the range between 1.00 US$ m^{-3} and 2.00 US$ m^{-3}. We used the value of 1.97 US$ m^{-3} in our calculation based on values of Rio Grande do Sul State of Brazil. Note that the higher water cost in Table 7 is 0.17 US$ m^{-3} (only 9 % of the distributed water by the municipal system). The cost only with treatment of surface water (not included the distribution network) was predicted by Mierzwa et al. [37] as 0.10 US$ m^{-3} in Brazil. Thus, the UF of rainwater is a competitive

Table 5
Economic analysis of scenario 3 (building of 11,500 m^2) to produce drinking water from rainwater by UF without PV panels.

Description	Value (US $)	Period (years) 1	2	3	4	5	6	7	8	9	10
1.0 Investment											
Equipment	−4,073	There is no investment predicted in this period									
7 Reservoirs 1 (20,000 L)	−15,771										
Total investment	**−19,844**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2.0 Costs											
2.1 Fixed cost											
Chemicals		−74.1	−74	−74	−74	−74	−74	−74	−74	−74	−74
Membrane		−687.5	−688	−688	−688	−688	−688	−688	−688	−688	−688
Maintenance (2 % equipment)		−81.5	−81	−81	−81	−81	−81	−81	−81	−81	−81
Total		**−843**	**−843**	**−843**	**−843**	**−843**	**−843**	**−843**	**−843**	**−843**	**−843**
Electricity		−1245.7	−1246	−1246	−1246	−1246	−1246	−1246	−1246	−1246	−1246
Water from municipal system		−31,370.3	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370
Total		**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**	**−32,616**
Total cost		**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**	**−33,459**
3.0 Value saved											
Water produced		39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563
Total		**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**
Cash flow	**−19,844**	**6104**	**6104**	**6104**	**6104**	**6104**	**6104**	**6104**	**6104**	**6104**	**6104**

Table 6
Economic analysis of scenario 3 (building of 11,500 m^2) to produce drinking water from rainwater by UF with PV panels.

Description	Value (US $)	Period (years) 1	2	3	4	5	6	7	8	9	10
1.0 Investment											
Equipment	−4073	There is no investment predicted in this period									
7 Reservoirs (20,000 L)	−15,771										
Solar panels (16)	−6098										
Total investment	**−25,942**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2.0 Costs											
2.1 Fixed cost											
Chemicals		−74.1	−74	−74	−74	−74	−74	−74	−74	−74	−74
Membrane		−687.5	−688	−688	−688	−688	−688	−688	−688	−688	−688
Maintenance (2 % equipment)		−81.5	−81	−81	−81	−81	−81	−81	−81	−81	−81
Maintenance (2 % panels)		−121.9	−122	−122	−122	−122	−122	−122	−122	−122	−122
Total		**−964.9**	**−965**	**−965**	**−965**	**−965**	**−965**	**−965**	**−965**	**−965**	**−965**
2.2 Variable cost											
Electricity		0	0	0	0	0	0	0	0	0	0
Water from municipal system		−31,370.3	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370	−31,370
Total		**−31,370.3**	**−31,370**	**−31,370**	**−31,370**	**−31,370**	**−31,370**	**−31,370**	**−31,370**	**−31,370**	**−31,370**
Total cost		**−32,335.2**	**−32,335**	**−32,335**	**−32,335**	**−32,335**	**−32,335**	**−32,335**	**−32,335**	**−32,335**	**−32,335**
3.0 Value saved											
Water produced		39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563	39,563
Total		**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**	**39,563**
Cash flow	**−25,942**	**7228**	**7228**	**7228**	**7228**	**7228**	**7228**	**7228**	**7228**	**7228**	**7228**

technique to supply water through decentralized systems. Neto et al. [38] studied the treatment of rainwater by slow-sand filtration for non-potable use in a larger area (airport). The predicted water cost was 0.52 US$ m^{-3} (approximately 60 % of the water distributed by the municipal system). Thus, UF + chlorination has two advantages: better quality of water and lower cost. Moreover, the implementation of the system will result in reduced consumption of drinking water from the municipal supply and reduced greenhouse gas emission.

A study carried out by Faragò et al. [39] compared five scenarios in Denmark to use rainwater and stormwater for safe potable water. In one scenario, the authors suggested the treatment by UF plus H_2O_2, but the non-drinking use requires a second pipeline to supply the non-drinking water. The authors suggested that UF combined with UV light and UF combined with H_2O_2 are more sustainable (environmentally and economically) than Reverse Osmosis for the treatment of rainwater in a decentralized system. Additionally, the authors predicted the water cost between 1.57 US$ to 1.83 US$ per m^3 (including distribution network). In fact, the costs for the transport of water and failures of distribution networks can constitute the larger cost of tap water [40]. Alim et al. [13] performed a study to produce drinking water in a decentralized household system in Werrington, Australia. The proposed treatment was based on bank filtration/disinfection. The economic feasibility has shown that the cost of the water is AU$1.04 per liter. Thus, the decentralized UF-based system for the treatment of rainwater to produce drinking water

Table 7

Details of the economic evaluation of three scales of investment on UF of rainwater with or without photovoltaic (PV) energy. (Bold are the sum of investment, fixed, variable and total costs, inputs and cash flow).

Scenarios		Annualized Cost (US$) without PV panels	Annualized Cost (US$) with PV panels
230 m^2	**Investment**	**57.9**	**134.1**
	Fixed costs	**61.2**	**76.4**
	Chemicals	24.7	24.7
	Membrane	27.5	27.5
	Maintenance	9.0	24.2
	Variable costs	**155.7**	**0.0**
	Electricity	155.7	0.0
	Water from municipal system	0.0	0.0
	Total costs	**216.9**	**76.4**
	Inputs		
	Water saved	**532.0**	**532.0**
	Cash flow (inputs − total costs)	**315.1**	**455.6**
2300 m^2	**Investment**	**735.6**	**1345.1**
	Fixed costs	**243.9**	**365.8**
	Chemicals	49.4	49.4
	Membrane	137.5	137.5
	Maintenance	57.0	178.9
	Variable costs	**4414.2**	**3791.4**
	Electricity	622.9	0.0
	Water from municipal system	3791.4	3791.4
	Total costs	**4658.1**	**4157.2**
	Inputs		
	Water saved	**7912.6**	**7912.6**
	Cash flow (inputs − total costs)	**3254.5**	**3755.5**
11,500 m^2	**Investment**	**1984.7**	**2594.2**
	Fixed costs	**843.0**	**964.9**
	Chemicals	74.1	74.1
	Membrane	687.5	687.5
	Maintenance	81.5	203.4
	Variable costs	**32,616.0**	**31,370.3**
	Electricity	1245.7	0.0
	Water from municipal system	31,370.3	31,370,3
	Total costs	**33,459.0**	**32,335.2**
	Inputs		
	Water saved	**39,563.1**	**39,563.1**
	Cash flow (inputs − total costs)	**6104.1**	**7227,9**

Table 8

Indexes of the economic evaluation of three scales of investment on UF of rainwater with or without photovoltaic (PV) energy.

Scenarios	Without PV panels			With PV panels		
	Water cost (US $ m^{-3})	IRR[a] (%)	Payback (year)	Water cost (US $ m^{-3})	IRR (%)	Payback (year)
230 m^2	0.17	53.7	2	0.13	31.8	4
2300 m^2	0.10	43.0	3	0.10	24.9	4
11,500 m^2	0.05	28.2	4	0.04	24.8	4

[a] IRR: internal rate of return.

is beneficial because it is more sustainable, and the costs of pumping water will be lower and the possible losses of water can be controlled more accurately.

The IRR (Table 8) is lower with the use of PV panels to supply energy to the UF system in the three scenarios considered. However, this is an environmental-friendly alternative and could be an alternative where there is no other form of energy apart from PV to power the system as in rural areas or urban slums of developing countries.

From Table 9 we can observe that the electricity will comprise 49 % of costs for a household installation (230 m^2), but Faragò et al. [39] highlighted that "*alternative treatments of rainwater through ultrafiltration were the most electricity-efficient choices*" compared to rainwater treated by the stainless filter for non-potable use, RO, and groundwater abstraction. In Table 9, as expected, as the size of investment rises, the contribution of electricity is lower. In the suggested scenarios, we incorporated the PV panels only to supply the required energy to the UF system. However, different scenarios could be studied for the purpose of selling energy to the grid, but this will not impact our conclusion. Note that the addition of the PV panels increases the capital investment, but there is no variable cost for the electricity to power the UF system as the PV panels will supply the power for the UF equipment (as observed in the last column of Table 6). There is no need to purchase energy from the power dealer for all studied scenarios (230 m^2, 2300 m^2 and 11.500 m^2 of rooftop). Additionally, we amortized the investment in only 10 years, but suppliers suggest the lifespan of the PV panels is 20 years. Furthermore, there is a solar panel financing allowance in several countries (including Brazil) for the acquisition of PV panels. Thus, the cash flow could be more attractive if we used this condition and payback and Internal return rate could become more attractive.

4. Conclusions

Ultrafiltration of rainwater with chlorination can produce water for potable purposes. The technique can be implemented with economic savings even for small buildings as the water cost is lower than the traditional centralized distribution services. The long-term tests of UF of rainwater showed that the water produced has potable standards, in compliance with current regulations and WHO recommendation. The average permeate flux was as high as 135 L h^{-1} m^{-2} and, thus, a low membrane area is required for the treatment of rainwater.

The economic analysis shows that the proposed system can be installed in three scales of the rooftop catchment area of rainwater. The water costs range between 0.17 US$ m^{-3} to 0.05 US$ m^{-3} for the 230 m^2 and 11,500 m^2 of rooftop area without the installation of PV panels. In contrast, the installation of photovoltaic panels for the generation of energy to power the UF systems did not increase the water costs, and they ranged between 0.13 US$ m^{-3} to 0.04 US$ m^{-3} for 230 m^2 and 11,500 m^2 of rooftop area and the payback of the investment is 4 years. The use of PV panels reduces the IRR (see Table 4), yet all the scenarios are still attractive, with a payback of 4 years with PV panels. The value per cubic meter of water produced by the membrane, in all scenarios, was more attractive than the value of the concessionaire's water, reaching up to US$ 0.14/m^3, 14 times cheaper than the amount charged by the concessionaire.

The most expensive cubic meter of the proposed scenarios was water produced without panels in the 230 m^2 area. However, the water in this scenario costs almost half the value of the concessionaire, having a value of US$ 1.20 against US$ 1.97 of the municipal system. It is noteworthy here that for this scenario the water produced fully meets the demand of the residence, and no extra purchase is required.

The conclusion is that the implementation of photovoltaic panel energized rainwater ultrafiltration is technically and economically viable, being a reliable alternative to traditional water supply approaches, for long-term implementation. The system can be an important alternative to supply water in remote locations where there is no water distribution network. This could also be an option to help distribute clean water for all with a competitive cost.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 9
Annual financial balance of the investment for supply water by UF of rainwater for three scales using (or not) the photovoltaic energy (PV).

Scale	230 m^2		2300 m^2		11,500 m^2	
Outputs and inputs	Without PV	With PV	Without PV	With PV	Without PV	With PV
Capital per year	−58	−134	−736	−1.345	−1.985	−2.594
Fixed costs	−61	−76	−244	−366	−843	−965
Electricity	−156	0	−623	0	−1.246	0
Water from municipal system	0	0	−3.791	−3.791	−31.370	−31.370
Water saved	**532**	**532**	**7.913**	**7.913**	**39.563**	**39.563**
Annual result	**257**	**322**	**2.519**	**2.410**	**4.119**	**4.634**

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2022.103228.

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