Sustainability
Science and Technology

PAPER • OPEN ACCESS

Sustainable hydroponic cultivation in Uruguay: a case study on the application of rainwater harvesting for ready-to-eat produce operations

To cite this article: Mikaela Rajchman *et al* 2025 *Sustain. Sci. Technol.* **2** 044002

IOP Publishing Sustain. Sci. Technol. 2 (2025) 044002 https://doi.org/10.1088/2977-3504/ae047f

Sustainability Science and Technology

PAPER

OPEN ACCESS

RECEIVED
19 August 2024

REVISED
8 August 2025

ACCEPTED FOR PUBLICATION
8 September 2025

PUBLISHED
14 October 2025

Sustainable hydroponic cultivation in Uruguay: a case study on the application of rainwater harvesting for ready-to-eat produce operations

Mikaela Rajchman, Inés Martínez, Ronny Pelaggio and Diana Míguez*

Latitud—LATU Foundation, Technological Laboratory of Uruguay (LATU), Av. Italia 6201, Montevideo, Uruguay
* Author to whom any correspondence should be addressed.

E-mail: dmiguez@latitud.org.uy

Keywords: rainwater harvesting, multi-barrier technologies, sustainable production, climate change adaptation

Abstract

Climate change is intensifying water stress by increasing the frequency and severity of extreme weather events and reducing the predictability of water availability. This situation is worsened by decades of water misuse, poor management, overexploitation, and contamination. Rainwater (RW) harvesting offers a sustainable strategy to mitigate these challenges by providing a buffer during dry periods, reducing dependence on public water supplies, and ensuring continuous food production. This study focused on harvesting RW from the roof of a hydroponic greenhouse (∼20,000 m^3 yr^{-1}) and validating, at a pilot scale, a treatment system to produce safe water suitable for reuse in vegetable production or disinfection processes. The treatment train included two 'Y' strainers, a 0.9 μm ceramic membrane, and ultraviolet light at 253.4 nm. The system effectively reduced microbiological indicators (total and fecal coliforms, *E. coli, P. aeruginosa*, and heterotrophic plate counts) to levels that comply with national regulations. Physicochemical parameters also showed positive outcomes: turbidity and conductivity met drinking water standards, while pH values ranged from 6.11 to 6.45 due to natural CO_2 in RW —adequate for irrigation, though adjustable for other uses. The system also avoids the release of micro and nanoplastics and the formation of disinfection by-products. Further testing is recommended to assess removal of additional pathogens. This study underscores the value of multi-barrier treatment systems to ensure safe, sustainable water reuse, reduce environmental impacts, and promote efficient resource use. The proposed system strengthens the sustainability of hydroponic food production and supports the achievement of UN Sustainable Development Goals: SDG 2 (sustainable agriculture), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 13 (climate action).

1. Introduction

Dependence on water governs all life forms [1]. In humans, lack of drinking water causes dehydration, and all that it entails. At the same time, the absence of potable water increases the risk of diarrhea diseases such as cholera, typhoid fever, dysentery, and other water-borne diseases, due to microbial contamination [2]. Moreover, water is an indispensable input in a myriad of activities including irrigation, energy, and manufacture [3]. Among the manufacturing purposes, food supply is highly water-consuming [4]. Water is an essential ingredient for agricultural activities and without it, neither crops can grow, nor can animals be fed [5]. Water is also fundamental for all processing stages during food production and preparation, including cleaning and sanitizing activities. In addition, the food supply must keep pace with the continuous population growth, making water availability vital to achieve such demands. Therefore, water shortage negatively affects humans' well-being as well as the economic and social development of the population [6].

At present, water scarcity is a problem worldwide, with 844 million people that do not have drinking water available, and 2.3 billion that lack access to different basic sanitation facilities [7]. In order to directly address this problem, the sixth objective of the UN Sustainable Development Goals (SDG) aims to 'ensure availability and sustainable management of water and sanitation for all', while the second objective promotes using water resources efficiently, among other practices, to end hunger by 2030. Despite all the efforts being made to accomplish these objectives, and the fact that the world has more advanced technology than ever before, water misuse during the last decades, poor management, overexploitation, and its contamination has exacerbated water stress [6, 8].

Latin America and the Caribbean (LAC) face some of the highest levels of water stress, and rising demand coupled with water loss in distribution systems is worsening the situation. In fact, climate change has made extreme weather events such as floods and droughts more frequent and severe [9]. Countries such as Mexico and Brazil have faced severe droughts that directly affected agriculture, hydroelectric power generation and access to drinking water. For instance, in 2023, this region experienced record-breaking temperatures due to El Niño, leading to significant human, wildlife, and economic losses [10]. As a consequence, several countries experienced long periods without water, or rain-generated floods during wetter months, which resulted in great volumes of stormwater runoff and its potential contamination, as well as soil erosion [11–15]. Between 2020 and 2023, Uruguay faced an exceptional three-year drought, influenced by La Niña and other climatic factors, leading to significant hydrological imbalances across its territory [16]. In particular, the country suffered from precipitation deficits ranging from −20% to −80% between October and December 2022, which occasioned severe water scarcity in the metropolitan area [17]. Nevertheless, although the 2022 annual accumulated rainfall was 743 mm [18], Uruguay experiences an annual average rainfall of 1,160 mm (1991–2020), indicating that a considerable amount of water could be harvested for various purposes [19]. This represents an attractive solution to alleviate water shortage, while helping to cope with drought and flood problems [13].

Rainwater harvesting (RWH) is the collection of rainwater (RW) from catchment surfaces and its storage, which can be used for different commercial, domestic and industrial purposes [11, 20]. The system consists of a catchment area, which is in general a roof, a conveyance system (*e.g.* gutters, plumbing), sanitation device(s), a sub-surface reservoir or tank and a distribution system [21–24]. RWH relieves the load and pressure on the public water supply, that is the main source of water in cities, provides water during dry seasons, which worsens due to climate change, while contributes to the management of stormwater [20], diminishing production costs.

RWH has a long history all around the world and was even carried out in ancient times [12, 13]. In fact, in many countries, and in particular in the countryside, people rely on RW as the only source of potable water [24]. However, in the last few years this practice regained attention in other areas due to its potential to reduce drinking water use [6, 11]. There is great interest in exploiting RW for applications that do not require potable water quality. According to Hugues, by doing this, it would be possible to halve the volume of potable water consumed in houses [12]. Moreover, RW can be employed for irrigation in greenhouses, vertical farms, traditional agriculture, urban agriculture and small scale commercial hydroponics production [25–28]. In particular, agriculture plays a significant role in the economy of LAC, being the world's leading region in terms of net food exports [29]. Therefore, there is a strong need to implement advanced technologies for efficient water management in key sectors such as this one.

Furthermore, RW may be used for drinking purposes, after an appropriate purification treatment [20, 30]. The last remark is of utmost importance because harvested RW is not likely to comply with drinking water standards. Regarding physicochemical parameters, RW's quality depends on the presence of atmospheric contaminants such as dust, fertilizers and pesticides used for agricultural activities near the catchment surface, and other pollutants from biomass burning, as well as the materials used to construct the roof-catchment and tanks [13, 31, 32]. Compared to water from the supply network, the main advantage of RW is the absence of chlorine and chlorine byproducts, which have adverse effects on health [6, 12, 33]. In addition, RW must be treated to remove pathogenic microorganisms which are a severe threat to human health. Different bacteria, virus and protozoa present in the faeces of animals (*e.g.* mice and birds) and in organic matter, can end up in the water if present in the catchment surface or by runoff during the rain event [6, 31, 34]. To reduce the final load of bacteria, dust and debris, some systems include first-flush diverters that wash away the initial rainfall [21, 35]. The challenges posed during RWH, system design and treatment, trends and perspectives, and viability studies are presented in two reviews [6, 36].

Once RW is properly treated, it can be employed for numerous uses that require potable quality, such as crop production and processing. Hydroponic vegetables grow in nutrient-fortified water, which is water efficient, but requires a system to supply it. Moreover, the demand for fresh ready-to-eat vegetables has increased globally, making it essential to apply a post-harvest washing and disinfection step during its production to effectively eliminate pathogens [37]. The possibility of obtaining RW from greenhouse roofs and using it for nutrient solution and vegetable sanitization is an attractive and easy-to-adopt idea to reduce dependency and pressure on public water supply, while contributing to the circularity of hydroponically grown vegetables and reducing production costs. This aligns with SDGs 12 and 13 which aim to 'ensure sustainable consumption and production patterns' and to 'take urgent action to combat climate change and its impacts', respectively [7].

However, according to the studies examined, only a few articles describe and evaluate the treatment strategies needed to get potable water, as they usually focus on the evaluation of different RWH systems and their potential uses [12, 13], its feasibility in rural and urban contexts [11, 15, 25] and the determination of microbiological and physicochemical quality of RW at storage tanks [20, 22, 30]. Nevertheless, by the time of the study, we did not find any other work on the use of RW in medium or large-scale commercial hydroponic production.

The aim of this study was to harvest RW using the roof of a hydroponic greenhouse as catchment surface and validate on pilot scale a system to remove different contaminants to obtain water suitable for later use, either for the nutrient solution used in hydroponics or as input water for vegetable or surface cleaning and disinfection processes with focus on better water quality, reducing the presence of disinfection by- products (DBPs) and microplastics.

2. Materials and methods

2.1. Sampling location, dates and harvesting system

The hydroponic greenhouse where water was collected was located in Melilla (−34.74277603668966, −56.30920160349516), Montevideo (Uruguay), in a suburban rural area, with no houses nor industries nearby, but some fruit tree plantations in the surroundings. The total catchment area is approximately 19 000 m^2. At the time of this study, the annual production of processed hydroponic vegetables was 250 tons; however, it is projected to reach 500 tons in the near future.

During the study, the company had three greenhouses, but water was harvested from the roof of only one of them. The catchment surface is made of 200-micron nylon, but once a year, at the beginning of summer (December), the roof is coated with a shading agent based on calcium carbonate to protect vegetables from light during the months of highest UV intensity. According to the supplier, the product's lifespan is 3–4 months, and it wears evenly during the season [38], so the presence of calcium was expected on RW on samples taken from December until March–April.

The company's harvesting system consists of the previously described catchment area, gutters to collect water from the roof, and polyvinyl chloride pipes to transport water to a temporary high-density polyethylene 1000 l tank, without a lid. At the time of this research, the company had not constructed the reservoir yet, so sampling of RW was done directly from the tank. Therefore, the experience represented a worst-case scenario demonstrating a major challenge for the water purification system. Also, the system did not include a first flush device, that could have discarded rinsing water. As microbial variability of water samples is an important consideration, the collected units at each point were thoroughly mixed prior to subsampling, and, as liquid samples, they were assumed to be relatively homogeneous at the time of collection.

Four representative samples of approximately 120 l were stored and transported in industrial stainless-steel jugs throughout 2022. Sampling was conducted on the following dates: 26th of January (1st), 24th of February (2nd), 22nd of April (3rd) and 31st of May (4th). Samples from January and February correspond to summer, and those from April and May, to autumn season.

2.2. Procedure

Initial RW samples (RW_i) were treated at a pilot scale in the pilot plant of Latitud—LATU Foundation, as follows (figure 1):

1. RW_i was poured into tank N°1 and passed through a system containing two 'Y' strainers placed in series (750 and 149 μm),
2. After that, it went through a ceramic filter of 0.9 μm, to obtain middle treated RW (RW_m).
3. Lastly, UV light at 253.4 nm was applied.

The final RW treated samples were named RW_f. The heart of the innovative system used was a fine-filtering ceramic membrane with a high active surface, coupled with other multi-barrier technologies. This choice of filter material was designated to minimize the use of plastic material, thus reducing the input of micro and nano plastic particles in the system and, consequently, in the final product.

2.3. Microbiological parameters

The following microbiological counts were analyzed in all samples to determine the impact of each step: heterotrophic plate count (HPC) according to Method 9215A and B of the American Public Health

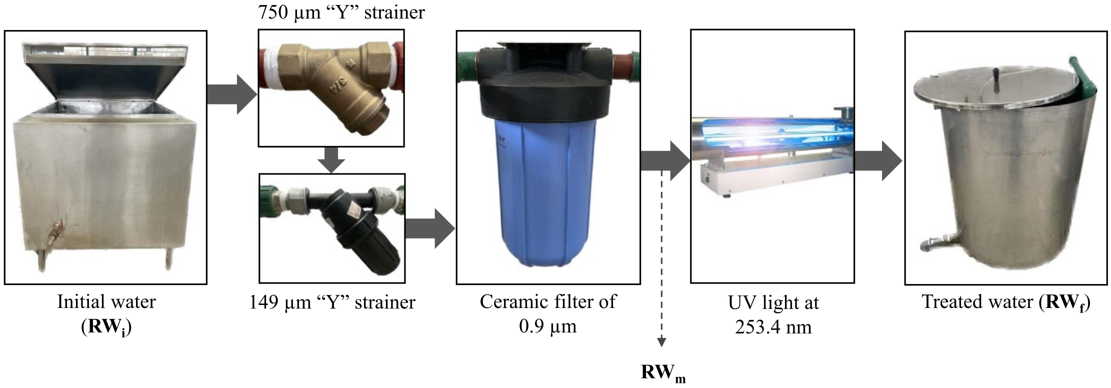

Figure 1. Rainwater treatment scheme, consisting of initial water tank N° 1, strainers, ceramic membrane, UV light and final water tank.

Association (APHA) [39], total coliforms (TC), fecal coliforms (FC), and *Escherichia coli* (*E. coli*) based on the method 9308-2:1990 of the International Organization for Standardization (ISO) [40] and *Pseudomonas aeruginosa* (*P. aeruginosa*) as described by Method 9213 E of APHA [41]. All these analyses were performed at the Microbiology Department of LATU, and are accredited to ISO/IEC 17025 standards, by United Kingdom Accreditation Services.

Furthermore, treated water from the last sampling (the 4th one) was tested for the presence of total and FC, and *E. coli* based on Method 9221 D, E and G of APHA [42] and *P. aeruginosa* according to norm 942:2008 from the Uruguayan Institute of Technical Norms (UNIT) [43] to determine whether treated water complied national regulations for drinking water quality established by UNIT 833:2008 [44]. Analyses were performed by LATU, except for *P. aeruginosa* which was analyzed by Beltran Zunino laboratory (Montevideo, Uruguay).

2.4. Physicochemical parameters

All samples (RW_i, RW_m and RW_f) were tested for turbidity (Hanna HI88703 Turbidity Benchtop Meter), pH (SevenMulti™ Mettler Toledo Dual Meter pH/Conductivity) and conductivity (Hanna HI98303 Pocket Conductivity Tester). Moreover, RW_i and RW_f from the first two sampling campaigns (1st and 2nd) were tested for calcium according to ISO 11885:2007 [45], to evaluate the mineral concentration that could be present in RW from the shading agent applied on the roof. Calcium was determined by the Water and Chemicals Department of LATU.

3. Results and discussion

This study focused on the collection and further processing of RW from the roof of a hydroponic greenhouse in Melilla. According to data from the rain gauge in Melilla, the average annual rainfall (1991–2020) is 1,160 mm [30], although in 2022 the accumulated precipitation was 743 mm [18]. Based on the average value (1160 mm) and the area available for collection (19 000 m^2), the estimated amount of recoverable RW would be 22 000 m^3. However, the amount that can be collected depends on various factors. Among them, rainfall variability can be highly significant. In Melilla, records from 1991 to 2020 indicate that the average monthly rainfall varied between 85 and 113 mm during this period, meaning that although variability exists, this might not be the most significant factor causing disparities in the recovery. In broad terms, other factors that can affect the available water are system efficiency, tank size, evaporation rates, catchment surface characteristics, among others [26, 27, 46]. Although all these factors should be considered when evaluating the system's viability, including the water saving fee, the results presented below correspond to the technical evaluation of the proposed multi-barrier system for safe water recovery. This system included ceramic filtration and UV-light with a focus on avoiding or reducing the use of chemical disinfectants and plastic filters, and therefore, minimizing the presence of disinfection byproducts and micro and nanoplastics with their studied side effects [6, 33, 47].

3.1. Microbiological parameters

Figure 2 presents the results of all microbiological counts. All values were compared with the UNIT 833:2008 standard for drinking water [44].

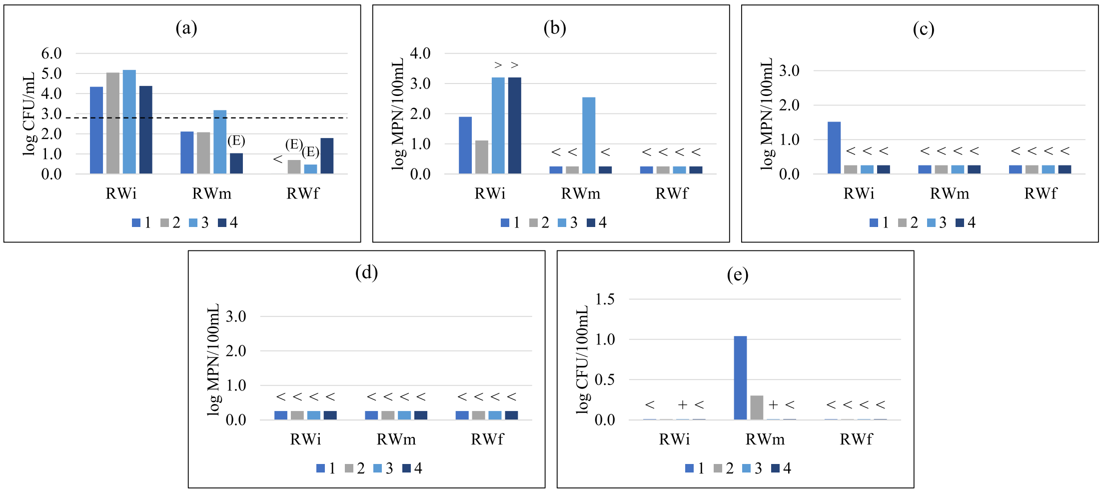

Figure 2. Microbiological counts during the four samplings (1, 2, 3 and 4) of RW_i: initial; RW_m: after 0.9 µm ceramic filter and RW_f: after UV light. (a) Heterotrophic plate count (HPC); (b) total coliforms (TC); (c) fecal coliforms (FC); (d) *E. coli;* (e) *P. aeruginosa*.
Note: CFU = colony forming units; MPN = most probable number. The symbol or letter above the bars indicate the following: '<' less than; '>' more than; '(E)' estimated count; '+' presence but not quantified. Dashed line in (a) indicates the upper limit for HPC according to national standards of drinking water [44].

The mean initial count of HPC was 4.88 log CFU ml^{-1}, considerably higher than the values reported by Daoud *et al* in its study (Palestine) and two other works in Australia (2.23, 0.85 and 1.52 log CFU ml^{-1}, respectively) cited by these previous authors, but lower than those obtained by Jordan *et al* (6.86 and 5.89 log CFU ml^{-1} in summer and winter, respectively) [22, 24]. For TC, initial contamination widely varied among samples (1.1–>3.2 log MPN/100 ml), in accordance with the observations of Jordan *et al,* who obtained more than two orders of difference between summer and winter samples (5.66 and 3.34 log MPN/100 ml, respectively) [24]. However, the latter study reports higher concentrations in summer samples, while average initial contamination here was higher in autumn samples (>3.2 log MPN/100 ml) than those harvested in summer (1.5 log MPN/100 ml). Differences between initial results obtained and those reported may be attributed to the location of collection and storage, catchment surface and facilities material, the presence or absence of a first flush device, the season, cleaning, and disinfection frequency of the system, among other factors [21]. Moreover, both HPC and TC can survive and multiply in water, which is why the quality of sampled water may differ from the one that initially entered the system, as growth can occur during storage [22]. In this study, the number of days that water was stored before sampling was not recorded, so differences in initial counts can be attributed to all factors previously described.

Regarding FC and *E. coli*, RW_i counts of almost all samples were below the limit of detection (LD) of the technique. Other studies obtained higher concentrations of FC, with results that surpassed 3 log CFU/100 ml [21, 22]. This was also observed for *E. coli* in numerous works, and the differences for both FC and *E. coli* can be attributed to the reasons previously described.

As observed in figure 2(a), HPC decreased throughout the treatment, with a total reduction that ranged from 2.59–4.70 log CFU ml^{-1}. The initial HPC of all samplings did not comply with national regulations that require less than 2.7 log CFU ml^{-1} [44]. Although strainers and ceramic filters had a great impact on HPC load, RW_m of the 3rd sampling still did not reach the established limit. Only after UV light was applied, did treated water (RW_f) from all samplings comply with current regulation for HPC.

For TC, shown in figure 2(b), the highest reduction after treatment was observed in samples with initial counts that surpassed 3.2 log MPN/100 ml, and, in such samples, reduction was greater than 2.9 log MPN/100 ml. Initially, all waters (RW_i) were above the national drinking water standard, that demands absence of TC in 100 ml. The same for HPC, TC in RW_m from the 3rd sampling were high relative to the rest, and in absolute terms. The combination of strainers, filters, and UV light (RW_f) made it possible to reach values below the LD of 0.3 log MPN/100 ml for TC. Given that national regulation states the need to achieve the absence of these bacteria in 100 ml, RW_f from the last sampling set (4th) was tested for the presence of TC, and the result was negative, indicating the absence of TC in 100 ml.

UNIT 833:2008 standard [44], also requires the absence of FC or *E. coli* for drinking water in 100 ml. In this study, figure 2(c), only FC in RW_i of the 1st sampling were above the LD, but counts were reduced after passage through strainers and the filter, with results below the LD after UV radiation. For *E. coli*, results were

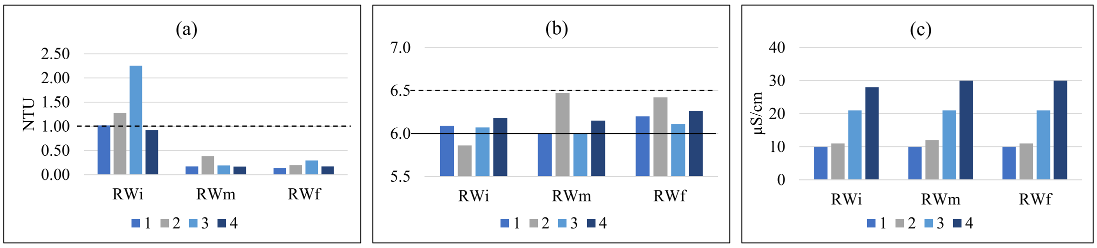

Figure 3. Physicochemical parameters during the four samplings (1, 2, 3 and 4) of RW_i: initial, RW_m: after 0.9 µm ceramic filter and RW_f: after UV light. (a) Turbidity; (b) pH; (c) conductivity.
Note: NTU = Nephelometric Turbidity Units. Dashed line in (a) indicates the upper limit for turbidity, and in (b) indicates the lower limit for pH, according to the regulation for irrigation water (solid line) [50] and the national standards of drinking water (dashed line) [44].

below the LD in all samples, including initial water (figure 2(d)). In the 4th sampling, final water was negative for FC and *E. coli*, indicating that absence in 100 ml was reached.

Regarding counts of *P. aeruginosa* in 100 ml, results revealed some inconsistencies between the treatments (figure 2(e)). Counts for RW_i and RW_m during the 1st sampling indicate that some recontamination could have occurred inside the system. The increase observed in the 2nd sampling is considered negligible, and in the 3rd one, presence was detected in RW_i and RW_m, but given that no quantification was conducted, it is not possible to compare results. Still, positive counts of *P. aeruginosa* found in RW_m of the first three samplings were reduced to levels below the LD after UV light. Considering that the current regulation in Uruguay [44] requires the absence of *P. aeruginosa* in 10 ml for drinking water, detection of *P. aeruginosa* was carried out in RW_f of the 4th sampling, with a negative result, indicating compliance with the standard.

Based on these results, the importance of using multi-barrier technologies to achieve greater reductions is demonstrated, since both filters and UV radiation contributed to the reduction of counts until acceptable values.

Finally, different pathogens present in organic matter and feces of animals that live near the catchment area can end up in RW, including *Legionella* spp., *Klebsiella* spp., *Campylobacter* spp., *Cryptosporidium* spp., *Giardia* spp. and enteric viruses [31, 48] so further studies should be conducted to determine whether the system can eliminate these pathogens. In case this system was inefficient for such purpose, other UV lamps that work with a broader range of radiation (200–415 nm) could be tested for providing a broad germicidal spectrum [49].

3.2. Physicochemical parameters

Figure 3 presents the results of all physicochemical parameters.

Values of turbidity are presented in figure 3(a). Turbidity in all the untreated waters (RW_i) was very similar, ranging from 0.92 up to 2.25 NTU, with similar values to those reported by Al-Batsh *et al* and Daoud *et al* [21, 22]. This parameter is influenced by the same factors that affect microbial counts, previously described. Turbidity of all final waters (RW_f) was below the limit established by the national drinking water standard [44]. The removal range was between 82%–87% (RW_i vs. RW_f) with the highest reduction obtained during passage through the strainers and the ceramic filter.

For pH—figure 3(b)—all results were outside the range required for drinking water (6.5–8.5) established in national and international regulations [44, 51], due to the natural CO_2 concentration in RW. However, final pH (6.11–6.45) complied with national regulation for irrigation water, that establishes a value of $pH > 6$ to prevent corrosion of the system [50]. The pH is influenced by different sources (terrigenous, agricultural, marine and biomass burning), and the initial results of this study were lower than those reported by Al-Batsh *et al* (7.0–7.6) and Daoud *et al* (6.4–10.0), but within the range observed by Schets *et al* (5.6–6.5) and by Zunckel *et al* (4.6–7.0), with the latter corresponding to a study conducted in Uruguay [21, 22, 32, 48]. Optimum pH will depend on the intended use, so further additions of alkali can be made to correct this parameter in case drinking water is required.

Regarding conductivity, the mean initial value (17.5 μS cm^{-1}) was considerably lower than that reported by Al-Batsh *et al* (389 μS cm^{-1}) and Daoud *et al* (332.5 μS cm^{-1}) [21, 22]. The treatment did not modify this parameter, and all samples complied with the national regulation of 2,000 μS cm^{-1} [44], as shown in figure 3(c). Conductivity is given by the number of dissolved ions, and there are no stages in the system that affect the ionic concentration, so no changes were expected after the treatment.

Finally, calcium was determined to quantify how much of this ion was dragged from the roof during rainfall events, and to assess the effect of treatment (results not shown). Low concentrations were obtained, either below the LD (0.5 mg ml^{-1}) or quantification (1.0 mg ml^{-1}), in RW_i and RW_f of the first two runs (January and February). These samplings were conducted during months when high calcium concentration was expected in RW_i, as the lifespan of the shading agent is 3–4 months, and it was applied during December. According to these results, no calcium was expected in the following samplings (end of April and May), so this parameter was no longer determined.

This study presents a novel approach to the treatment of harvested RW using a multi-barrier system designed to produce potable water without relying on chlorine-based disinfectants, thereby minimizing the formation of DBPs and reducing the risk of microplastic contamination through the use of a ceramic membrane. While the system demonstrated effective contaminant reduction, it is important to acknowledge certain limitations. Replicate analyses were not performed due to financial and logistical constraints, which may limit the assessment of microbial variability. Additionally, a water balance model and agronomic performance trials were beyond the scope of this work. Nevertheless, the findings offer valuable insights, particularly for hydroponic companies aiming to reduce dependence on external water sources. Future work should validate system performance at full scale and include replicate sampling for microbial parameters, and evaluate the water's agronomic suitability and long-term filter efficiency to further support the system's transferability and real-world application.

This implies that this knowledge can be transferred to other urban farms, positively impacting the country and the community by enabling access to safer and more affordable water for safe food production. It contributes to SDGs 2, 6, 12 and 13 by promoting sustainability through lower production costs [52] and improved water resource management.

4. Conclusions

The treatment system tested—comprising two 'Y' strainers, a ceramic filter, and UV radiation—effectively reduced microbiological counts in RW below regulatory limits. Further studies are recommended to assess its effectiveness against other reported pathogens.

Turbidity and conductivity values met drinking water standards, while pH was slightly outside the acceptable range due to CO_2 levels. However, pH adjustments may depend on the intended use (e.g. hydroponics or disinfection).

Moreover, installing a first-flush diverter and a closed underground reservoir is strongly recommended to improve water quality.

This work underscores the relevance of multi-barrier treatment systems using low-plastic materials, supporting water reuse, and reducing reliance on public supplies. It encourages RW harvesting in hydroponics, contributing to SDGs 2, 6, 12, and 13 through more sustainable, efficient, and climate-resilient water use.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgment

We are grateful to Verdeagua (Mapatex S.A.), for their funding and for providing rainwater samples, especially Fernanda Zunino and Sebastián Figuerón, for their commitment to the project. This work was also funded by Agencia Nacional de Investigación e Innovación (ANII) (Project No. HPI_X_2021_1_166284).

Author contributions

Mikaela Rajchman: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Writing—Original Draft. Inés Martínez: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Supervision, Writing—Review & Editing. Ronny Pelaggio: Investigation. Diana Miguez: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing—Review & Editing.

ORCID iDs

Mikaela Rajchman 0000-0002-5175-0106
Inés Martínez 0000-0002-9314-573X
Ronny Pelaggio 0000-0002-9565-9152
Diana Míguez 0000-0001-5364-5951

References

[1] Sargen M Harvard university the graduate school of arts and sciences 2019 (available at: https://sitn.hms.harvard.edu/uncategorized/2019/biological-roles-of-water-why-is-water-necessary-for-life/#:~:text=Water%20makes%20up%2060%2D75,broadly%20governs%20all%20life%20forms) (Accessed 24 May 2023)
[2] WHO 2021 WHO: African region (available at: www.afro.who.int/health-topics/water#:~:text=A%20lack%20of%20clean%20water,blindness)%2C%20plague%20and%20typhus) (Accessed 24 May 2023)
[3] van Vliet T H, Jones E R, Flörke M, Franssen W H P, Hanasaki N, Wada Y and Yearsley J R 2021 Global water scarcity including surface water quality and expansions of clean water technologies *Environ. Res. Lett.* **16** 024020
[4] Klobucista C and Robinson K 2023 Council on foreign relations (available at: www.cfr.org/backgrounder/water-stress-global-problem-thats-getting-worse#:~:text=How%20is%20climate%20change%20affecting,stress%20in%20already%20affected%20regions) (Accessed 24 May 2024)
[5] Gruere G and Shigemitsu M 2021 Measuring progress in agricultural water management: Challenges and practical options *OECD Food, Agriculture and Fisheries Papers* **162**
[6] Alim M A, Rahman A, Tao Z, Samali B, Khan M M and Shirin S 2020a Suitability of roof harvested rainwater for potential potable water production: a scoping review *J. Clean. Prod.* **248** 119226
[7] UNICEF 2023 UNICEF and the sustainable development goals (available at: www.unicef.org/sustainable-development-goals)
[8] United Nations 2022 The sustainable development goals report 2022
[9] Caretta M A *et al* 2022 Water *Climate Change 2022: Impacts, Adaptation and Vulnerability* ed H O Pörtner, D C Roberts, M Tignor, E S Poloczanska, K Mintenbeck and A Alegría(Cambridge University Press) pp 551–712
[10] UN 2024 Another climate record: extreme heat, hurricanes, droughts ravage Latin America and Caribbean (available at: https://news.un.org/en/story/2024/05/1149516) (Accessed 12 August 2024)
[11] Alim M A, Rahman A, Tao Z, Samali B, Khan M M and Shirin S 2020b Feasibility analysis of a small-scale rainwater harvesting system for drinking water production at Werrington, New South Wales, Australia *J. Clean. Prod.* **270** 122437
[12] Hugues C R T 2019 La captación del agua de lluvia como solución en el pasado y el presente *Ing. Hidráulica y Ambiental* **40** 125–39 (available at: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S1680-03382019000200125)
[13] Jiang G *et al* 2019 Utilization status of rainwater harvesting and its improvement techniques in bare karst areas for domestic use and ecological restoration *Carbonates Evaporites* **34** 1381–90
[14] Rutledge K *et al* 2022 National geographic education (available at: https://education.nationalgeographic.org/resource/runoff/) (Accessed 24 May 2023)
[15] Stout D T, Walsh T C and Burian S J 2017 Ecosystem services from rainwater harvesting in India *Urban Water J.* **14** 561–73
[16] Montevideo Portal 2023 Análisis de Inumet de la sequía desde 2020 a 2023: ¿qué impacto tuvo el fenómeno La Niña? (available at: www.montevideo.com.uy/Ciencia-y-Tecnologia/Analisis-de-Inumet-de-la-sequia-desde-2020-a-2023–que-impacto-tuvo-el-fenomeno-La-Nina–uc845853#) (Accessed 30 May 2025)
[17] Arias P A *et al* 2024 Interplay between climate change and climate variability: the 2022 drought in Central South America *Clim. Change* **177** 6
[18] INE 2024 Anuario Estadístico Nacional 2024 Volumen N° 101 (available at: www.gub.uy/instituto-nacional-estadistica/comunicacion/publicaciones/anuario-estadistico-nacional-2024-volumen-n-101/12-clima/123-total) (Accessed 30 May 2025)
[19] INUMET 2023 INUMET (available at: www.inumet.gub.uy/clima/estadisticas-climatologicas/tablas-estadisticas)
[20] Deshmukh S 2018 Comparitive study on physico-chemical and bacteriological analysis of harvested rainwater and non harvested groundwater *Rasayan J. Chem.* **11** 331–338
[21] Al-Batsh N, Al-Khatib I A, Ghannam S, Anayah F, Jodeh S, Hanbali G, Khalaf B and van der Valk M 2019 Assessment of rainwater harvesting systems in poor rural communities: a case study from Yatta Area, Palestine *Water* **11** 585
[22] Daoud A K, Swaileh K M, Hussein R M and Matani M 2011 Quality assessment of roof-harvested rainwater in the West Bank, Palestinian Authority *J. Water Health* **9** 525–33
[23] Hicks W 2008 A cost-benefit analysis of rainwater harvesting at commercial facilities in Arlington County, Virginia
[24] Jordan F L, Seaman R, Riley J J and Yoklic M R 2008 Effective removal of microbial contamination from harvested rainwater using a simple point of use filtration and UV-disinfection device *Urban Water J.* **5** 209–18
[25] Dallman S, Chaudhry A M, Muleta M and Lee J 2021 Is rainwater harvesting worthwhile? A benefit-cost analysis *J. Water Resour.* **147** 04021011
[26] Jurga A, Pacak A, Pandelidis D and Kaźmierczak B 2021 A long-term analysis of the possibility of water recovery for hydroponic lettuce irrigation in an indoor vertical farm. Part 2: rainwater harvesting *Appl. Sci.* **11** 310
[27] Boyacı S, Atılgan A, Kocięcka J, Liberacki D and Rolbiecki R 2024 Use of rainwater harvesting from roofs for irrigation purposes in hydroponic greenhouse enterprises *Atmosphere* **15** 884
[28] Sucozhañay A, Pesántez J, Guerrero-Coronel R, Guerrero-Coronel R, Peña D and Célleri R 2024 Rainwater harvesting as a sustainable solution for the production of urban hydroponic crops *Water Reuse* **14** 177–89
[29] Soria-Ruiz J, Fernández-Ordoñez Y M, Medina-García G, Quijano-Carranza J A, Ramírez-Guzmán M E, Aguilar-Marcelino L and Vazquez-Siller L M 2021 Agriculture in Latin America: recent advances and food demands by 2050 *Information and Communication Technologies for Agriculture—Theme IV: Actions* ed D D Bochtis, S Pearson, M Lampridi, V Marinoudi and P M Pardalos (Springer) pp 139–54
[30] Ahmed W, Hamilton K A, Toze S and Haas C N 2018 Seasonal abundance of fecal indicators and opportunistic pathogens in roof-harvested rainwater tanks *J. Open Health Data* **5** 1
[31] Eslamian S and Eslamian F 2021 *Handbook of Water Harvesting and Conservation: Basic Concepts and Fundamentals* (Wiley)
[32] Zunckel M, Saizar C and Zarauz J 2006 Rainwater composition in northeast Uruguay *Atmos. Environ.* **37** 1601–11

[33] Latif S, Alim M A, Rahman A and Haque M M 2023 A review on chlorination of harvested rainwater *Water* **15** 2816
[34] Jongman M and Korsten L 2016 Microbial quality and suitability of roof-harvested rainwater in rural villages for crop irrigation and domestic use *J. Water Health* **14** 961–71
[35] Kim T, Lye D, Donohue M, Mistry J H, Pfaller S, Vesper S and Kirisits M J 2016 Harvested rainwater quality before and after treatment and distribution in residential systems *J. AWWA* **108** E571–84
[36] Raimondi A, Quinn R, Abhijith G R, Becciu G and Ostfeld A 2023 Rainwater harvesting and treatment: state of the art and perspectives *Water* **15** 1518
[37] Castro-Ibáñez I, Gil M I and Allende A 2017 Ready-to-eat vegetables: current problems and potential solutions to reduce microbial risk in the production chain *LWT* **85** 284–92
[38] Royal Brinkman 2023 Royal brinkman (available at: https://royalbrinkman.com/the-suppliers-of-royal-brinkman/hermadix/shadefix-1125-25kg-370014553) (Accessed 25 May 25 2023)
[39] APHA 2016a Method 9215 A and B heterotrophic plate count *Standard Methods for the Examination of Water and Wastewater* (APHA Press)
[40] ISO. 9308–2:1990 1990 *Water Quality—Detection and Enumeration of Coliform Organisms, Thermotolerant Coliform Organisms and Presumptive Escherichia Coli—Part 2: Multiple Tube (Most Probable Number) Method*
[41] APHA 2016b Method 9213 E recreational waters (approved 2007) *Standard Methods for the Examination of Water and Wastewater* (APHA Press)
[42] APHA 2005 Method 9221 D, E and G multiple-tube fermentation technique for members of the coliform group *Standard Methods for the Examination of Water and Wastewater* (APHA Press)
[43] UNIT 2008 Norma 942:2008. Agua potable. Análisis microbiológico. Detección de pseudomonas aeruginosa. Método de enriquecimiento en medio líquido
[44] UNIT 2010 Norma 833:2008. Agua potable—requisitos (available at: www.ose.com.uy/descargas/Clientes/Reglamentos/unit_833_2008_.pdf) (Accessed 24 May 2023)
[45] ISO. 11885:2007 2007 *Water quality—determination of selected elements by inductively coupled plasma optical emission spectrometry* (ICP-OES)
[46] de Castro Couto J S, Soares T M, Vellame L M, Nascimento Santos I L and de Almeida Souza E 2024 Simulation of hydroponic production using rainwater and brackish water *Water Resour. Irrig. Manage.* **13** 97–109
[47] Haldar S, Muralidaran Y, Míguez D, Mulla S I and Mishra P 2023 Eco-toxicity of nano-plastics and its implication on human metabolism: current and future perspective *Sci. Total Environ.* **861** 160571
[48] Schets F M, Italiaander R, van den Berg H H and de Roda Husman A M 2010 Rainwater harvesting: quality assessment and utilization in The Netherlands *J. Water Health* **8** 224–35
[49] Atlantium Technologies 2020 Atlantium (available at: https://atlantium.com/wp-content/uploads/2022/06/1B-HOD-UV-A_Technology_Overview.pdf) (Accessed 24 May 2023)
[50] Uruguay 2018 Resolución MGAP S/N *Actualizacion de las normas tecnicas sobre el uso de agua para riego* (IMPO)
[51] WHO 2022 *Guidelines for Drinking-water Quality: Fourth Edition Incorporating the First and Second Addenda* (WHO)
[52] Barbosa G L, Gadelha F D, Kublik N, Proctor A, Reichelm L, Weissinger E, Wohlleb G and Halden R 2015 Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods *Int. J. Environ. Res. Public Health* **12** 6879–91