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Case Study: Evaluation and Reuse of Rainwater in a Prison in Santa Catarina State, Brazil

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Abstract

The capture and reuse of rainwater is a viable alternative in regions where water is scarce or in places where water consumption is high. However, the economic viability of the implementation of an appropriate system is reduced by the need to install pumps, filter pipes and filters. This case study was focused on evaluating the potential for the harvesting and reuse of rainwater in a prison in Santa Catarina State, Brazil. The experiment was carried out at Tubarão prison, where three sampling points were strategically selected for the collection of rainwater. The total area of the prison is 4793.73 m² and in this research only the roof areas of the buildings used to keep inmates in closed and semi-open regimes were used. In total, 3483.53 m² were considered, which guarantees an annual capture of 4314 m^3 of water and corresponds to 17% of the water consumed in the prison, providing potential savings of US$ 5408 per year. After collection, the water was filtered through an activated carbon filter to be applied as reuse water. The results demonstrate significant reductions for all parameters analyzed. In general, the average efficiency was above 70%. The best results were obtained for the removal of suspended solids (94%), dissolved solids (94%), total solids (83) and phosphorus (81%). In addition, removal values for color, chlorides and nitrate were around 70%, verifying that the filtration system with activated carbon is efficient for harvested rainwater.

Keywords: rainwater, contamination, treatment, activated charcoal, prison system

1. Introduction

Water is an essential resource for life on earth. Around 70% of the planet surface is covered by water but only a small portion is considered suitable for human consumption (Suguio, 2008; Alim et al., 2019).

Potable water is a finite resource and is becoming increasingly scarce due to factors such as the increase in world population, increasing levels of urbanization, pollution and poor management of water resources. Thus, the trend is that the gap between the consumption needs and the supply of water is increasing, and some studies have indicated that the demand for water will increase by 50% by 2050 (Santos et al., 2020; Wurthmann, 2019; Haque et al., 2016; Gomez et al., 2017; Forrest, 2020).

The search for alternatives to collect and reuse water is therefore of utmost importance. A very interesting and promising approach is the collection and efficient use of rainwater, which has been practiced for many years. This is increasingly the object of study for the supply of water in regions lacking centralized water supply systems or to contribute to the reuse and rationing of this resource. The technique consists of collecting rainwater runoff from surfaces such as roofs, through a capture system that, in general, is composed of three main components: capture, storage and treatment (Haque et al., 2016; Stang et al., 2021).

A rainwater collection system can be applied in domestic, commercial and industrial environments. The water from this system can be used for non-potable purposes, such as the irrigation of gardens in domestic or public environments, car washing, use in bathrooms and washing in general. However, to obtain water fit for drinking, appropriate water treatment is required (Alim et al., 2019; Reyneke et al., 2020; Xu et al., 2020).

It is important to emphasize that in times of water scarcity, water management in government agencies is an important factor that can contribute to mitigating adverse effects and reducing the use of potable water. One option in this regard is the collection and reuse of rainwater in schools, public buildings and prisons (Chen et al., 2021; Santos, 2020).

The government of Santa Catarina State, Brazil, has been investing in the construction of new prisons, as well as in the renovation and expansion of old units to provide a better quality of life for the inmates. The construction of a prison must follow the Basic Guidelines for Criminal Architecture, prepared by the Ministry of Justice and Public Security (Brasil, 2011).

The penitentiary system of Santa Catarina State is renowned in Brazil for the execution of public policies aimed at resocialization through work and educational activity in prisons, with a total of 6310 inmates working and 4503 inmates studying inside and outside these establishments (Brazil, 2022). Likewise, the legal system must be responsible for mitigating the problems associated with applying the custodial sentence and preparing the inmate for the return to life outside prison, in such a way that it is possible to peacefully coexistence in society (Cruz, 2010).

With regard to the supply of water to the inmates of prison units, as described in the publication Basic Guidelines for Penal Architecture, the buildings must be designed, preferably, considering the installations necessary for the storage and distribution of drinking water, as well as the appropriate sanitary conditions, water and sewage pipes, drainage system, reuse of water and use of rainwater (Brazil, 2011).

In Brazil there is no standard that addresses water consumption in prison units and few authors have determined the per capita consumption requirements per inmate. A publication by Sperling (2005) presents a per capita consumption in the prison units of 200 to 500 liters/inmate/day while the technical standard prepared by the Basic Sanitation Company of São Paulo State (SABESP - NTS 181) suggests between 100 to 190 liters/inmate/day (SABESP, 2017).

In the municipality of Tubarão, Santa Catarina, four prison units are installed, and the Male Penitentiary and the semi-open regime unit were selected to carry out this case study. This unit has a capacity of 224 and 277 inmates are currently received, respecting Resolution No. 5, of November 25, 2016, which establishes the maximum capacity in prisons in Brazil, considering overcrowding above 137.5% ideal capacity.

The average daily consumption of drinking water in this prison is 314.33 liters/day per inmate, this being distributed among all the activities carried out, such as laundry, kitchen, bathroom, car washing, consumption, washing and visits.

The factors that most influence water consumption in a penitentiary are the climatic characteristics of the region, the state of conservation of the hydraulic installations and the daily routine and activities of the inmates (Nembrini, 2005). Some penitentiary units in Brazil have tried to reduce water consumption in their buildings by using more economical and efficient hydraulic products, as well as adopting behaviors aimed at optimizing water use (Mota, 2020).

Thus, a good understanding of water consumption in penitentiary units serves as a basis for the development of strategies aimed at the economic and rational use of this resource, in addition to enabling intervention in cases of resource wastage, and with this approach considerable financial savings can also be achieved (Mota, 2020).

In this context, the collection of rainwater in prisons would be a viable alternative to minimize the costs and consumption of potable water. In addition, rainwater harvesting systems for water supply in homes or public properties are in line with the Sustainable Development Goals (SDGs), which make up the agenda established by the United Nations (UN) to be met by 2030, specifically SDG 6, which deals with water and sanitation and SDG 12, which deals with sustainable consumption and production.

It is important to note that no studies reporting the reuse of rainwater in a prison in Santa Catarina State, Brazil, could be found in the literature. Thus, the objective of this research was to perform a case study to evaluate the possibility for the reuse of rainwater in two units of the prison system in this state. The results will contribute to the development of public policies and could guide prison managers in the construction and adaptation of future facilities.

2. Materials and Methods

Samples of rainwater were obtained from points around the Tubarão prison in Santa Catarina State, southern Brazil. Sample collection was carried out according to official Brazilian methodologies NBR 9897 and NBR 9898 (ABNT, 1987).

2.1 Area of Study: Prison System

The city of Tubarão is located in the south of Santa Catarina State, 144 km from the state capital, Florianópolis. Logistically, the municipality is favored by being crossed by a major federal highway (BR-101) and it also has a rail network and regional airport and is very close to the seaports of Laguna and Imbituba. Currently, Tubarão is home to several industrial plants as well as trading and service companies, being known as a hub in the areas of health and education.

The climate in this region is characterized by well-defined seasons, with hot and humid summers and cold winters with strong winds. During the year the temperature generally ranges from 12 °C to 29 °C and is rarely below 8 °C or above 33 °C. In addition, the city of Tubarão has significant rainfall throughout the year and even in the driest months notable rainfall levels are recorded, with an annual average of 1240 mm (Climatempo, 2022).

The rainwater harvesting system used in this case study was sized specifically for the men's penitentiary in the city of Tubarão, which opened in August 2021 and has a capacity of 224. According to the design of this prison, the total roof area of the closed-regime unit is 4793.73 m^2 and the roof area of the semi-open-regime unit is 650 m^2, thus totaling 5443.73 m^2. However, for the calculation of the rainwater catchment area, roof areas of 2833.53 m^2 for the closed-regime unit and 650 m^2 for the total area of the semi-open-regime unit were used. These values were based on the architecture of this prison, aiming to facilitate the future implementation of the rainwater harvesting system on site.

Although rainwater harvesting considers areas of the roofs of two prisons, closed and semi-open regime, the data referring to the consumption of drinking water only relates to the closed-regime unit. Thus, the calculations of rainwater use are based only on the closed-regime prison.

2.2 Sampling Points and Rainwater Analysis

Three sampling points were strategically selected for the collection of rainwater. The precise locations of sampling points are 28º29'37"S 49º1'9" W, 28º28'00" S 49º00'25" W and 28º28'36" S 49º1'31" W, mapped by GPS, as shown in Figure 1.

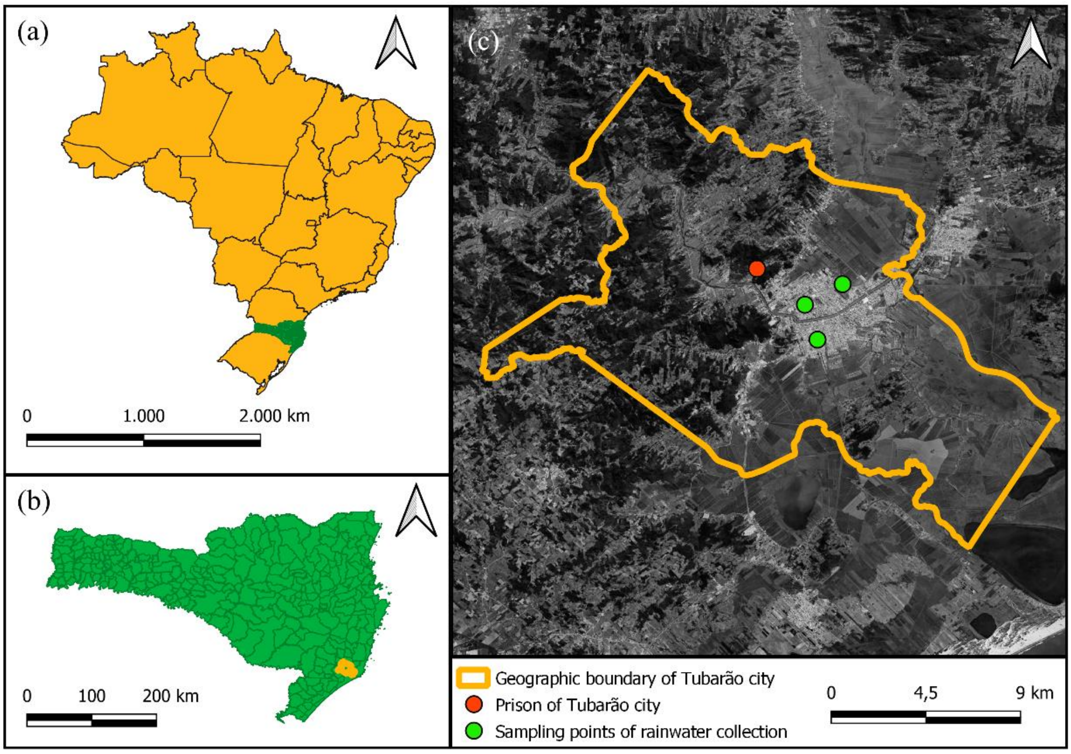

Figure 1. a) Location of Santa Catarina State (green) in Brazil; b) Location of Tubarão (yellow) in Santa Catarina State; and c) Location of the prison and sampling points of rainwater collection in Tubarão

The physicochemical analysis of the rainwater before and after filtration was performed according to the procedures of the Standard Methods for Examination of Water and Wastewater, 22nd Edition, and the specific methods are given in Table 1 (APHA, 2012). The pH of the samples was measured using a portable HANNA pH meter. All analyses were performed in triplicate and data are expressed as mean values.

2.3 Rainwater Collection

The correct sizing of a rainwater collection system requires data on the pluviometric index of the region and the roof area available for collection. The volume of water that can be collected from a roof is then calculated as the roof area (m^2) multiplied by the rainfall index of the region (mm), as represented by equation 1. In addition to this information, the average water consumption and the destination of the water collected as rain are variables that must be considered for the elaboration of the final project. In the present case study, it was not possible to obtain the average consumption of water per person associated with the different uses of water (food, personal hygiene, cleaning the environment, etc.), since the Santa Catarina prison system does not collected data on these variables.

$$V = A \times IP \tag{01}$$

where V is the collected volume of rainwater (m^3), A is the roof area (m^2) and IP is the rainfall of the region (mm).

2.4 Filtration of Water

An activated carbon filter was used for the removal of the rainwater contaminants. Commercial activated carbon, CARBOTRAT Premium, was obtained from the company Carbonífera Criciúma S.A. According to the manufacturer, activated carbon has a high hydraulic conductivity, good mechanical resistance to abrasion, low solubility in acid and basic media, high particle size uniformity with an effective diameter of 0.85 mm and a uniformity coefficient of 1.5 mm.

The adsorption of pollutants was studied in a batch system through tests using a fixed-bed column. The experiments were carried out in a glass column with an internal diameter of 1.5 cm and height of 20 cm. The flow rate evaluated was 5 mL per min. The carbon bed had a mass of 5 g, which generated a height of approximately 3 cm. The operation proceeded until column saturation was reached. For the disinfection of the water, a dosage of 2.0 mg L^{-1} of free chlorine was applied to the water from the filtration stage, with a contact time of 10 min.

3. Results and Discussion

In the past 30 years, the rainfall in the municipality of Tubarão has been consistent and relatively high. The wettest season of the year is spring, presenting an average rainfall of 116 mm per month, followed by summer (110 mm), autumn (102 mm) and winter (84 mm), as seen in Table 1.

Table 1. Mean rainfall over the past 30 years in the city of Tubarão, Santa Catarina

Month	Rainfall index
January	125
February	110
March	105
April	95
May	106
June	77
July	88
August	88

September	118
October	118
November	113
December	97

Source: Climatempo.

The consistency of high rainfall in recent years in the municipality of Tubarão shows that the municipality has great potential for the collection and use of rainwater and this could guarantee the supply of water in regions with high levels of poverty or in places where consumption is elevated.

Due to the scarcity of water around the world, other cities already use urban rainwater collection as a means of avoiding rationing and a lack of water. An example is the good results obtained in the city of Tucson, Arizona, USA, where activists developed a project to collect and reuse rainwater to establish a more sustainable community and solve environmental problems related to water shortages (Elder, Gerlak, 2019).

Another study conducted in Florida shows the feasibility of a residential rainwater harvesting system, deployed to reduce demand and complement existing centralized water supply systems, in a densely populated region of southeast Florida. The results obtained suggest that the expected costs of the water supplied by the decentralized system would be significantly lower than the expected costs of the water supplied by all alternatives of the centralized water supply system (Wurthmann, 2020).

Castonguay et al. (2018) described the development of a model to simulate the adoption of decentralized water solutions and its application and validation in the context of rainwater harvesting in Melbourne. The results provided a valuable insight into the combination of economic and regulatory instruments needed to influence household behavior and trigger the adoption of decentralized technology, in addition to acting as a guide for the water management process.

Although the rainwater collection process is well described in the literature, most research involves specific or residential installations, but the methods and technologies can be applied to any type of building. No studies reporting the application of rainwater collection and reuse in a prison system could be found in the literature.

The Tubarão prison complex has a total roof area of 4793.73 m². However, in the present case study, only the roof areas of the units of the closed (2833.53 m²) and semi-open (650 m²) regime were considered, giving a total area of 3483.53 m² for rainwater collection, as shown in Figure 2.

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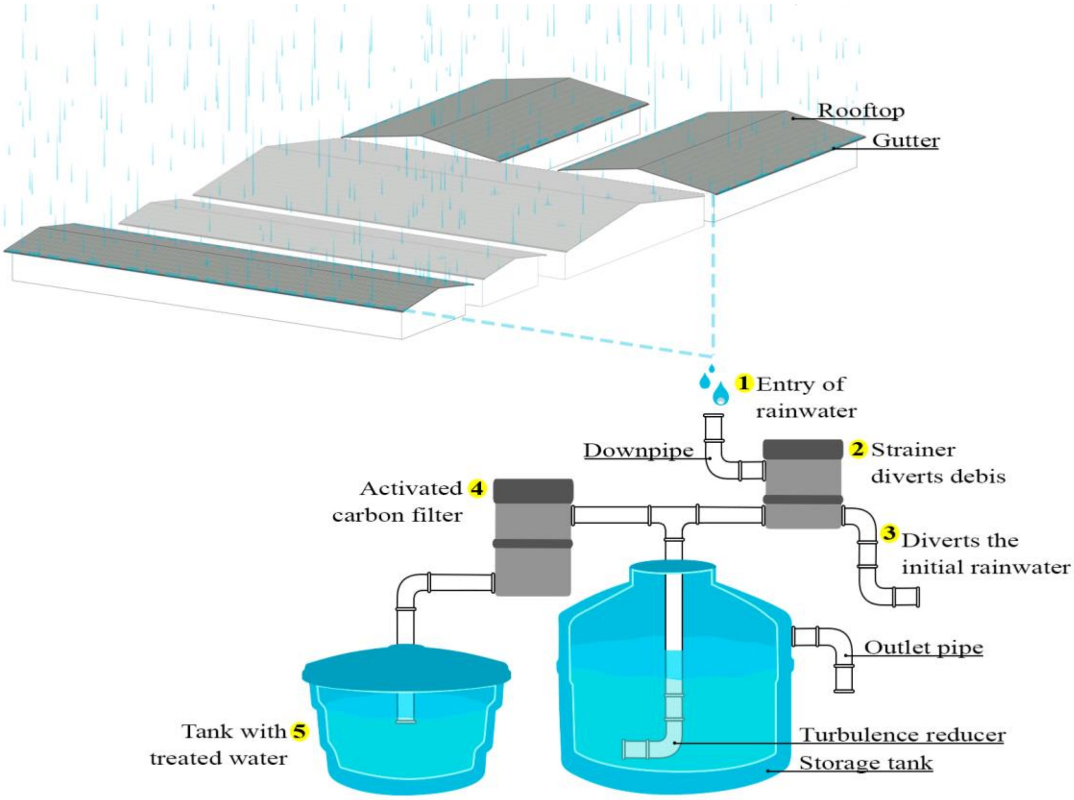

Figure 2. Schematic representation of the roof area and the rainwater collection system used for rainwater collection at the Tubarão prison complex

Based on the rainfall index of the municipality and the roof area available for rainwater collection, the average volume of rainwater that could be collected during the year was calculated, as shown in Table 2.

Table 2. Total volume of rainwater that could be collected in 2021 at the prison units in Tubarão, Santa Catarina

Month	**Total collected (m^3)**
January	435
February	383
March	365
April	330
May	369
June	268

July	306
August	306
September	411
October	411
November	393
December	337
Total	**4314**

According to Table 2, the total volume that could be collected during the year 2021 was 4314 m^3, and the lowest rainfall levels were observed in the months of June and July, with monthly averages of 268 and 306 m^3, respectively. However, the season with highest rainfall is spring (September, October and November, with average monthly volumes to be collected of 411, 411 and 393, respectively). An exception is January, with an average volume to be collected of 435 m^3, which is higher than the monthly averages observed for the spring months.

The monthly rainfall volumes that could be collected from the roofs and reused in the Tubarão prison units in Santa Catarina State could contribute to minimizing the costs associated with water consumption in the penitentiary.

The data available on water consumption in the Tubarão prison, from its opening in August 2021 until the last billed month (March 2022), are presented in Table 3.

The establishment is designed to receive 224 detainees. However, for security reasons, in the first month the prison housed 80 detainees and in the following months it operated at full capacity and was even overcrowded. At this prison, water consumption is relatively high, with a total average consumption for the period considered of 2129 m^3 and an average consumption per detainee of 314.33 liters/day, which is approximately 2.16 times greater than the average provided by the Basic Sanitation Company of the State of São Paulo (SABESP-NTS 181), which suggests an average value per detainee of 145 liters/day.

Table 3. Relation between the number of inmates and the volume of water consumed in the prison of Tubarão, Santa Catarina

Date	Consumption (m^3)	Number of inmates	Internal Consumption /day (L)	Rainwater collected (m^3)	% Collected in relation to consumption
August/21	1187	80	494.58	306	25

September/21	1576	214	245.48	411	26
October/21	1904	256	247.91	411	26
November/21	2180	260	279.48	393	18
December/21	2249	269	278.68	337	14
January/22	2482	265	312.20	435	17
February/22	2207	277	265.58	383	17
March/22	3247	277	390.73	365	11
Average	2129	237.25	314.33	380	17

Since its opening (i.e., from 08/2021 to 03/2022) the Tubarão prison has consumed approximately 17,032 m³ of drinking water. The water supply company for the region charges an average of US$ 1.78 per m³, which indicates that during the eight months of operation the prison unit had a charge of approximately US$ 30,294 for the service of supplying drinking water.

With the installation of a rainwater collection and reuse system, using as a reference the rainfall index in the city of Tubarão, from 08/2021 to 03/2022 it would have been possible to capture approximately 3041 m³, with a monthly average of 380 m^3, which corresponds to 17% of the total water consumed in the prison in this period (Table 3). This would mean savings of approximately US$ 5,408 per year. In addition, it should be noted that the potable water provided by the supply company is used in the prison units for cleaning the cells and other environments, the flushing of toilets and other uses that do not require potable water. Thus, the use of rainwater collected at the prison, in addition to monetary gain, can provide inmates with the most rational use of drinking water available on the planet (Gómez et al., 2017). The monthly rainfall data allow the ideal area required to meet the water needs of the prison system units to be defined.

Analysis was carried out on the as-collected rainwater and rainwater treated/filtered with activated carbon and the results are shown in Table 4.

Table 4. Results obtained for the characterization of the as-collected rainwater and rainwater treated/filtered with activated carbon

Parameters	Untreated Rainwater	Rainwater treated by filtration	Removal (%)	Method
Color (Hz)	16.1 ± 2.8	4.5 ± 1.2	72	SM 2120 C
Turbidity (FAU)	7.5 ± 1.5	3.0 ± 1.0	60	SM 2130 B
Iron (mg L^{-1})	0.28 ± 0.05	0.10 ± 0.02	64	SM 3111 AB
Sulfate (mg L^{-1})	11.2 ± 2.4	3.8 ± 1.5	66	SM 4500 SO_4^{-2} E
Chlorides (mg L^{-1})	18.5 ± 3.5	4.8 ± 1.8	74	SM 4500 Cl-B
Suspended Solids (mg L^{-1})	43 ± 12.6	2.6 ±0.5	94	SM 2540 D
Total Solids (mg L^{-1})	207 ± 8.5	34.2 ± 6.2	83	SM 2540B
Dissolved solids (mg L^{-1})	164 ± 22.4	9.8 ± 2.6	94	SM 2540 C
Phosphorus (mg L^{-1})	0.26 ± 0.02	0.05 ± 0.01	81	SM 4500-P
Nitrate (mg L^{-1})	11.6 ± 1.4	3.1 ± 1.4	73	EPA 1687

The initial characterization of the rainwater was necessary as some factors can interfere with the treatment process. Studies indicate that environmental factors such as pH, temperature, solid particles, salinity, total nitrogen and organic matter can influence the treatment process (Li et al., 2021).

The water was filtered through an activated carbon filter to increase the possibilities for reuse. The results demonstrate significant reductions for all parameters analyzed. In general, the average efficiency was above 70%, and the best results were observed for the removal of suspended solids (94%), dissolved solids (94%), total solids (83) and phosphorus (81%). However, the values for color, chlorides and nitrate were above 70%. These results verify that filtration with activated carbon is efficient for rainwater treatment.

Da Costa et al. (2021) obtained similar results in the treatment of rainwater using an acrylic blanket as a filter medium in a company located in the industrial city of Itaboraí, Rio de Janeiro State, Brazil. The water characteristics before and after contact with the roof and after undergoing treatment with the filter medium were monitored. The authors reported lower average removals for color (58.84%) and turbidity (59.55%), however, without the disposal of the initial rainwater collected and with lower installation and operation costs.

Although rainwater harvesting has been extensively studied in recent years, most authors have evaluated the efficiency of harvesting with treatment based on bioretention. Bioretention requires the selection of plants, fillers and structures. The original concept of bioretention areas was based on the comprehensive effects of soil, plants and microorganisms, where the soil and plants are the main factors affecting the efficiency of the treatment achieved (Li et al., 2021). However, the application of membrane filtration technology (Liu et al., 2021) and electrocoagulation coupled to a membrane bioreactor is gaining ground. This technology shows excellent performance in the purification of rainwater based on results for the turbidity (<0.1 NTU), NH_3–N (<0.1 mg L^{-1}), total phosphorus (<0.05 mg L^{-1}), heavy metals (e.g., Cr, Zn and Cu) and organic matter (1.0 ± 0.4 mg L^{-1}), regardless of the water load applied. In addition, electrocoagulation can effectively coagulate bacteria and facilitate membrane bioreactor bioactivity, as demonstrated in rainwater treatment (Xu et al., 2021).

In guidelines for the direct reuse of rainwater, the Unites States Environmental Protection Agency (US-EPA, 1993) recommends its application for recreational fields and golf course irrigation, landscape irrigation, fire protection and toilet flushing, among other uses, and these are important components of the reclaimed water portfolio of many urban reuse programs. Also, treated rainwater can be used for some agriculture, environmental and industrial purposes.

It is important to highlight that the greatest advantage of the water reuse process is the preservation of drinking water on the planet. By reusing water for different functions, we can preserve natural sources, saving these reserves for the future. In addition, reuse water helps to lower water and electricity bills and reduces the volume of wastewater discharged.

4. Conclusions

After analyzing the results obtained, it can be concluded that with the installation of a rainwater collection and reuse system in the Tubarão prison, using the roof areas of the units of the closed and semi-open regimes (3483.53 m^2) and taking as a reference the rainfall in the city of Tubarão, in the period of 08/2021 to 03/2022 it would have been possible to capture approximately 3041 m^3 of rainwater, with a monthly average of 380 m^3. This corresponds to 17% of the total water consumed in the prison during this period, which could represent savings of approximately US$ 5,408 per year.

In addition, the results indicate that activated carbon filtration is appropriate for rainwater treatment, with an average efficiency, considering the parameters evaluated, of > 70%. The best results were obtained for the removal of suspended solids (94%), dissolved solids (94%), total solids (83) and phosphorus (81%). In addition, the color, chloride and nitrate values were above 70%. Thus, the rainwater harvested could be considered suitable for reuse for non-potable purposes, after passing through an activated carbon filter and a disinfection process.

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