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Electroflotation treatment system with down-flow granular filtration (Electroflot-filter) for cyanobacteria removal in drinking water

Thyara Campos Martins Nonato*, Tiago Burgardt, Alcione Aparecida de Almeida Alves, Maurício Luiz Sens

Federal University of Santa Catarina, Postgraduate Program in Environmental Engineering, University Campus UFSC/CTC Bairro Trindade, ZIP 88040-900 Florianópolis, Santa Catarina, Brazil, Tel. +55 (48) 99804-3505; emails: thyaranonato@outlook.com (T.C.M. Nonato), tiagoburg@me.com (T. Burgardt), ambiental.a@hotmail.com (A.A.A. Alves), mauricio.sens@ufsc.br (M.L. Sens)

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ABSTRACT

Cyanobacterial blooms are common and reported worldwide nowadays. These algae blooms change the characteristics of natural water quality, as in color, odor, and organic matter content causing a number of problems for the public supply. However, a very relevant aspect of algae blooms is that they pose a potential risk to other living beings, including humans and animals, as cyanobacteria has the ability to produce toxic compounds that compromise the quality of water resources. When the presence of cyanobacteria in a drinking water supply is identified, it is necessary to remove this contaminant. Cyanobacterial cells are difficult to eliminate in conventional treatment systems. Thus, this research aimed to study the removal of cyanobacteria in drinking water by applying the electroflotation process (DSA® electrodes) as a pre-treatment to the down-flow granular filtration process. For this purpose, the water from the Peri Lagoon source, located in the city of Florianópolis/SC, Brazil was employed. To this end, a combination of electroflotation and down-flow granular filtration processes was studied in a pilot system. The pilot system performance was determined by removing cyanobacterial cells in the treated water. According to the results obtained, the electrochemical reactor operated at a water input rate of 100.84 $m^3\ m^{-2}\ d^{-1}$ and an electric current density of 68.26 A m^{-2}. Under these conditions, along with 12 h of treatment, the average cyanobacteria removal from water was approximately 83% for the electroflotation process and approximately 58% after down-flow granular filtration. In conjunction with the studied processes, an average initial cyanobacterial removal of over 93% was attained, with an electrochemical reactor energy consumption of 1.28 kWh m^{-3}. The pilot system operated with those two processes – electroflotation and down-flow granular filtration – also presented an average removal of turbidity and apparent color of 66.14% and 62.12%, respectively. The results obtained in this research indicate that the applicability of the electroflotation process as a pre-treatment alternative to down-flow granular filtration present promising findings for cyanobacterial removal in drinking water.

Keywords: Cyanobacteria; Down-flow granular filtration; Electroflotation; Water treatment

1. Introduction

Cyanobacteria are photosynthetic microorganisms found naturally in lakes, ponds, streams, and other surface waters. Their presence, in some situations, can render a source intended for public supply unsuitable, since some species have the capacity to produce toxins harmful to human health [1].

The incidence of cyanobacteria in public water sources can sometimes lead to operational problems in water treatment plants, as it hinders coagulation, flocculation, and

* Corresponding author.

sedimentation processes, as well as reduces the filtration run time, thus having negative consequences in the efficiency and cost of the water treatment process. However, the main concern with the increased occurrence of cyanobacterial blooms is related to the ability of these microorganisms to produce and release toxins (cyanotoxins) into the liquid environment in some situations, which can affect both human and animal health.

Some genera and species of cyanobacteria blooms produce potent toxins, and there may be toxin-producing and non-toxin-producing strains within the same species. Among the genera presenting toxic species that form blooms are: *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Microcystis*, *Nodularina*, and *Oscillatoria* [2].

In Brazil, the occurrence of cyanobacterial blooms has been frequently reported in different regions of the country, including water sources used for public supply. Since Brazil is classified as a tropical country, it has characteristics favorable to the development and proliferation of these microorganisms throughout the year [3].

Among these characteristics are the low hydrodynamics of the environment, which allows the deposition of the resistant form of this microorganism (cyst and acinides); the incidence of sunlight (photosynthesis); pH between 7.8 and 8.0; the water temperature ≥20°C; the nitrogen and phosphorus ratio (N:P) between 10:1 and 16:1 and the availability of nutrients and essential metals. The process of eutrophication of water bodies increases the prevalence of these blooms [4,5].

In this context, the water from Peri Lagoon, located on the island of Florianópolis/SC – Brazil, is used to supply parts of the southern and eastern populations of this island (102,000–113,000 inhabitants), after treatment by direct filtration. A peculiar feature of the water in this lagoon is the presence of high concentrations of cyanobacteria, predominantly *Cylindrospermopsis raciborskii* and *Pseudanabaena galeata*, both hepatoxin and neurotoxin-producing filaments that cause acute and chronic poisoning, affecting the liver cells and the neuromuscular system, which can lead to the death of animals in minutes, hours, or days [6].

Studies carried out in the same supply report the occurrence of high cyanobacterial density, with a high frequency of the species *Cylindrospermopsis raciborskii* with a density from the order of 10^4–10^6 cells mL^{-1} [7,8].

As it is a filamentous cyanobacterium, its existence in the water to be treated is unfavorable to the filtration operation, especially direct filtration. As cell transfer can occur, depending on the characteristics of the filter media, it significantly reduces the filtration run [9], which is not advantageous for the filtration process. Thus, to prolong the duration of the filtration run, it is necessary to apply a pre-treatment that is capable of removing cyanobacteria without cell disruption as well as low implementation and operational costs.

Studies by Garcia et al. [10] showed that the electroflotation process is an efficient alternative for the cyanobacteria removal from the Peri Lagoon water. In this study, aluminum electrodes were used and a cyanobacteria removal of 76.3% was obtained. Conversely, the authors reported that after the electroflotation process, there was an increase of residual aluminum in the treated water. This increase in aluminum was most likely due to the stability of the electrode material.

Nevertheless, with the development of the dimensionally stable anode (DSA®), which provides wide application without electrode wear [11], this problem can be solved. DSA® possesses excellent electrochemical properties, which has encouraged studies on the application of these materials in water and wastewater treatment in general [12–16].

As an advantage, electroflotation presents the generation of small bubbles of hydrogen and chlorine gases generated from the reactions that occur in the cathodes and anodes, respectively. These small bubbles (mean diameter of approximately 20 µm) can cause flotation of the flakes and coagulated materials [17].

Thus, the electroflotation process coupled with the use of a dimensionally stable anode make it possible to expand the treatment capacity of traditional physicochemical systems, since it uses the same basic coagulation–flocculation fundamentals [18]. As a result, some research was conducted using the electroflotation process for the removal of algae [10,19,20] and microcystins [21,22] in drinking water. These studies have demonstrated noteworthy efficiency (76%–98%) of the electroflotation process in removing cyanobacteria and microcystins.

In this context, the present research aimed to evaluate the efficiency of the combination of electroflotation process (DSA® electrodes) and down-flow granular filtration in the removal of cyanobacteria from drinking water for human consumption.

2. Materials and methods

This research was developed at the Water Potabilization Laboratory (LAPOA), located at the Federal University of Santa Catarina (UFSC), Florianópolis/SC, Brazil. With the intention of developing a project similar to the one presented in Fig. 1, a pilot system was constructed, as shown in Fig. 2.

2.1. Study water

The studied source (Peri Lagoon) is located in the southeast region of the island of Florianópolis in Santa Catarina.

Peri Lagoon is used as a freshwater reservoir to supply residents located in the southern and eastern areas of Florianópolis/Brazil. The choice of the source is due to the high presence of cyanobacteria, mainly the species *Cylindrospermopsis raciborskii*.

The untreated study water, referred to as raw water was collected in the influx channel of the Peri Lagoon Water Treatment Station (WTS) and transported to LAPOA for the experiments. Water collection and preservation procedures followed the recommendations established by the American Public Health Association [23].

2.2. Pilot system

The pilot system applied in this research is basically composed of the down-flow granular filter, the electrochemical reactor, a voltage stabilizing source (INSTRUTEMP – ITFA 5020) for the determination of current density, a ½ HP centrifugal pump for water recirculation, a metering pump

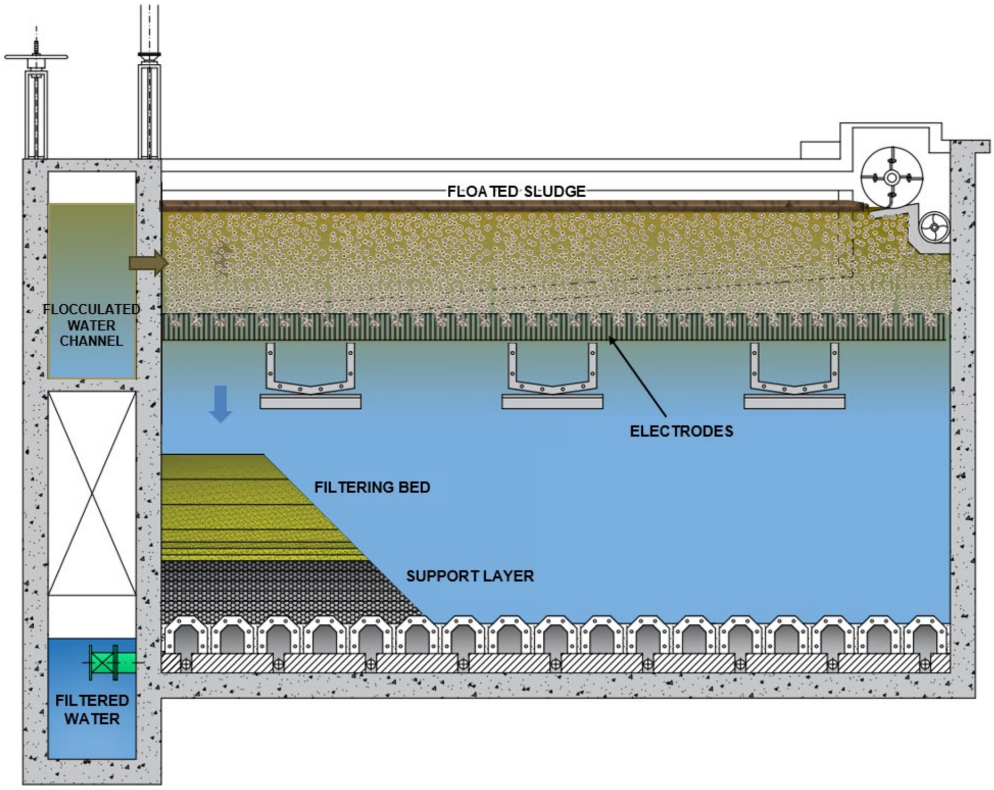

Fig. 1. Schematic section from the idea of an Electroflot-filter treatment system.

(Grabe – MDD (motorized diaphragm dosing pump) 130-07-PP/TF-1) for the control of raw water inlet flow, the hydraulic, and electrical systems and two 500 L capacity reservoirs (input/output) as shown in Fig. 2.

The down-flow granular filter consists of two 0.155 m internal diameter and 1 m long acrylic columns each. The filter medium is composed of a 0.40 m layer of sand with an effective diameter (D10) of 0.58 mm and a uniformity coefficient (UC) of 1.59 and a 0.25 m support layer of pebbles with a particle size ranging from ⅛" to ¼".

The electrochemical reactor with a 0.115 m internal diameter and a useful volume of 2.08 L was inserted between the filter columns. The implemented electrodes are composed of titanium cathodes and dimensionally stable DSA® anodes, containing $Ti/Ru_{0.34}Ti_{0.66}O_2$. An arrangement of 10 electrodes in parallel was used, being five cathodes and five anodes arranged alternately, with a total effective area of 785 cm^2 and a distance of approximately 0.8 cm between the electrodes.

2.2.1. Pilot system operationalization

After the raw water was inserted into the inlet reservoir by means of a metering pump, this water was sucked into the electrochemical reactor, where the electroflotation process occurred due to the potential difference applied to the electrodes through the electric power source. After the electroflotation process, the clarified water passed through the down-flow granular filter. Water samples were collected before electroflotation, after electroflotation and after down-flow granular filtration were performed in the raw water and treated water collection taps, as shown in Fig. 2. After treatment, the water was directed to the outlet reservoir.

2.3. Electroflotation process followed by down-flow granular filtration (electroflot-filter)

After obtaining the operating conditions of the electroflotation process with the highest performance, described by Nonato et al. [20], experiments were carried out in which the water was treated by the pilot system operating in a joint way, thus verifying the efficiency of the combination of the studied processes in the removal of cyanobacteria present in drinking water.

In this stage, three tests were conducted with the pilot system operating in a combined manner, to verify the repeatability of the experiments. During each test performed, water samples were collected before the electroflotation process, after the electroflotation process, and after the down-flow granular filtration. These collections were achieved every 60 min of treatment for the analysis of the cyanobacterial count present in the water, as well as the complementary analyses of pH, temperature, apparent color, and turbidity.

Cyanobacterial count analyses were performed according to the procedures described in method 10,900 C of the Standard Methods for the Examination of Water and Wastewater [23]. Evaluations of pH, temperature, apparent color, and turbidity were carried out according to the procedures described in the Standard Methods for the Examination of Water and Wastewater [23].

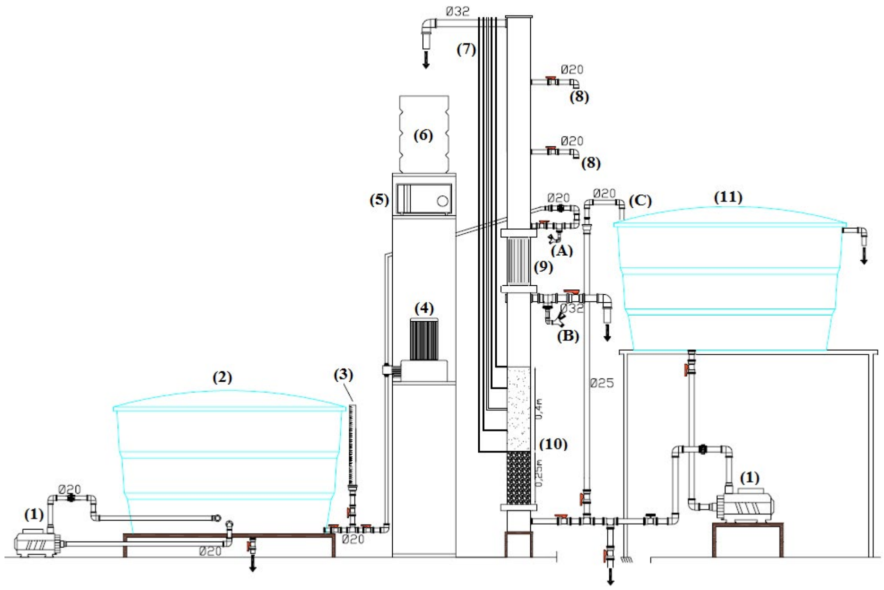

Fig. 2. Scheme of the pilot system used in the research (electroflot-filter): (1) centrifugal pump of ½ HP, (2) input reservoir, (3) flow controller, (4) dosing pump, (5) stabilizing voltage source, (6) electroflotation water reservoir, (7) piezometers, (8) discharge electroflotation water, (9) electrochemical reactor, (10) down-flow granular filter, and (11) reservoir output, (A) sample prior to electroflotation, (B) sample after electroflotation, and (C) sample after down-flow granular filtration.

The duration of each test realized with the pilot system operating in conjunction was according to the maximum loss of the filter load, which was 0.87 m, measured by piezometers.

2.4. Cleaning filter media

After each test was executed with the pilot system operating in a collective way, when the maximum loss of the filter load value of 0.87 m was reached, the treatment process was interrupted. Moreover, the filter media was cleaned by means of the backwash for 10 min at an approach speed of 1.40 m min^{-1}, which is sufficient to ensure 40% expansion of the filter medium by pumping the treated water.

To verify the efficiency of the backwash process in cleaning the filter media, samples of the wash water were collected every minute and the water turbidity analysis was accomplished.

3. Results and discussion

3.1. Results of the electroflotation process followed by down-flow granular filtration

For the electroflotation process to operate under optimal conditions [20], the water input rate was 100.84 m^3 m^{-2} d^{-1} and the electrical current density was 68.26 A m^{-2}, followed by the down-flow granular filtration process, satisfactory cyanobacterial removal results were obtained from the water.

The trials lasted 12 h each. The triplicate averages of cyanobacterial count values attained after the electroflotation process and after down-flow granular filtration can be observed in Fig. 3.

Fig. 3 shows that in the 1st hour of treatment, there was a removal of approximately 75% (380,400 cells mL^{-1}) of the total number (raw water value – 1,520,700 cells mL^{-1}) of cyanobacterial cells after the electroflotation process and more than 57% (160,500 cells mL^{-1}) after filtration, totaling a cyanobacterial cell removal percentage of more than 89% after the combination of the processes. In the first 6 h of treatment, a trend of greater variation in the removal of cyanobacteria was observed. A similar trend was noted by other authors [19,22], who mention that there was a greater variation in the reduction of cyanobacteria at the beginning of the process. According to Tumsri and Chavalparit [19], increasing the reaction time results in a higher amount of chlorine hydroxide flocs for the cyanobacteria removal.

From the first 6 h of treatment, a linear trend of the cyanobacterial removal points is observed. The average removal of cyanobacterial cells after the electroflotation process was 83.42% (252,185 cells mL^{-1}) and after filtration was 57.59% (105,323 cells mL^{-1}). The average percentage of the cyanobacterial cell removal with the pilot system operating in combination was 93.07%, with an electrochemical reactor energy consumption of 1.28 kWh m^{-3}. This energy consumption value was similar to the value obtained by Tumsri and Chavalparit [19].

Tumsri and Chavalparit [19] studied the electroflotation process for algae removal using aluminum anodes and graphite cathodes. The authors observed that for a current density of 20 A m^{-2} and 60 min of electrolysis, a removal efficiency of 96.0%–98.1% was obtained. Under these conditions, the power consumption was 1.84 kWh m^{-3}.

Garcia et al. [10] studied the cyanobacteria removal from the water supply through the electroflotation process followed by filtration, achieving an average removal of 76.3% after the electroflotation process and 100% after the filtration process. It is important to highlight that the authors used filter paper (Whatman GR 40) for filtration (in batch) in this work.

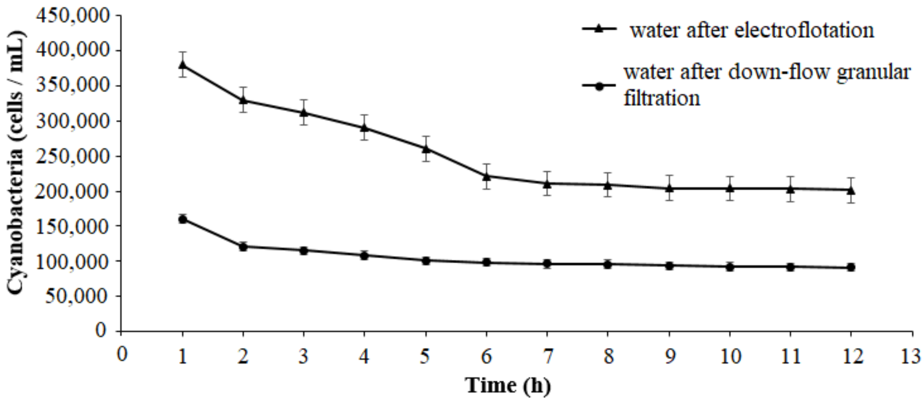

Fig. 3. Triplicate means of cyanobacterial count values obtained after the electroflotation process and after down-flow granular filtration.

Despite having a positive effect on removal, the remaining density in the electroflotted water was quite representative, around 252,185 cells mL^{-1}. This high density found in the electroflotted water was possibly due to the rupture of the cells, causing them to increase in the water. However, the pre-treatment electroflotation process allowed a longer duration of the filtration run (12 h of treatment) when compared to research carried out in the same source. Schöntag et al. [8] studied the direct descending double layer filtration (anthracite and sand) for cyanobacteria removal using water from the same source of the present research, without pre-treatment, and the filtration run lasted 9.6 h.

In addition to the cyanobacteria removal analysis, the variation of the pH value, temperature, and the removal of turbidity and apparent color from the water were also monitored. The results of these analyses can be seen in Figs. 4 and 5.

As observed in Fig. 4a, the pH values of the water increased after the application of the electroflotation process. The average pH value of the water before treatment was 7.55 and 8.10 after the electrochemical process (an increase of approximately 8%). According to Motheo and Pinhedo [24], this increased pH value can be explained by the products that are formed on the electrode surfaces. At the cathode, there is a water reduction with the consequent formation of hydrogen gas and an increased pH value due to the formation of hydroxyl anions (OH^-). At the anode, three reactions occur simultaneously: formation of oxygen gas, chlorine gas, and organic oxidation. In contrast to the formation of hydroxyl at the cathode, the formation of H^+ species occurs at the anode, which consequently decreases the pH value. However, this variation of the pH value to lower values does not have the same magnitude as the increased cathode pH value, because the charge balance involves chlorine gas formation and organic oxidation as well. It was also observed that after the filtration process, there was no significant change in the pH of the water, with an average pH of 8.06, slightly below the average pH after the electroflotation process (8.10).

Regarding the water temperature, it is demonstrated in Fig. 4b that there was a small variation throughout the treatment process. The average raw water temperature was approximately 25°C and the average temperature after the electroflotation process was around 27°C, an increase of 2°C after the electroflotation process. According to Larue et al. [25], the increase in water temperature after electrolysis is caused by the conversion of electric energy to heat, known as the Joule effect, which in this case can be considered insignificant. As detected, the water temperature averaged 26.73°C after the filtration process.

Fig. 5 shows the graphs with turbidity (a) and apparent color (b) values of the raw water, the water after the electroflotation process, and the water after down-flow granular filtration.

As seen in Fig. 5a, there was not a significant turbidity removal from the water after the electroflotation process. The average raw water turbidity with 12 h of treatment was 17.23 NTU and after the electroflotation process, the average water turbidity was 14.88 NTU (approximately 14% reduction). After filtration, the average value of water turbidity was 5.84 NTU (approximately 61% reduction). After combining the processes, there was an average turbidity removal of 66.14% from the water.

Regarding apparent color, there was also no significant removal after the electroflotation process (Fig. 5b). The average apparent color of raw water with 12 h of treatment was 243 μH and after the electroflotation process, the average apparent color of water was 185 μH (approximately 24% reduction). After filtration, the average apparent color of the water was 92 μH (approximately 50% reduction). After combining the processes, there was an average apparent color removal of 62.12% from the water.

This low removal of turbidity and apparent color parameters most likely occurred because the water in the Peri Lagoon has low values of color and turbidity, but also has a high concentration of cyanobacteria, which would explain this trend in the obtained results [8].

Garcia et al. [10] studied the cyanobacteria removal from the water supply through the electroflotation process followed by filtration and obtained 67.9% apparent color removal and approximately 60% turbidity removal. These results are relatively close to those observed in the present research, considering the different experimental conditions.

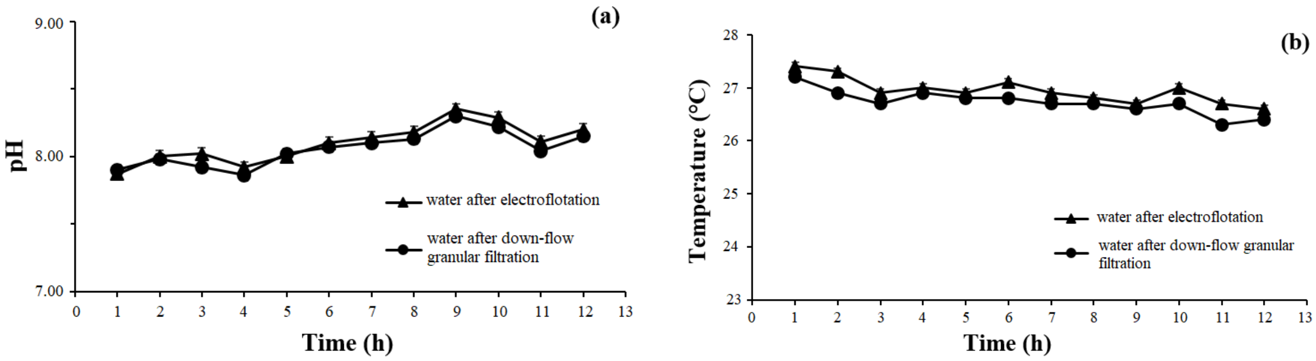

Fig. 4. Water pH (a) and temperature (b) values after the electroflotation process and after the down-flow granular filtration.

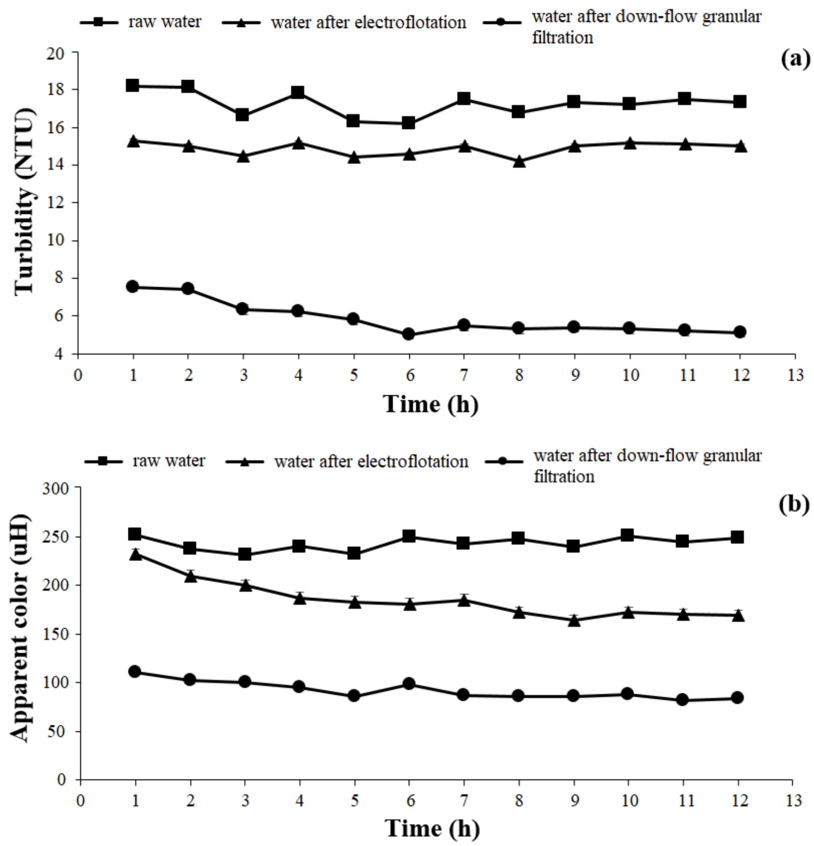

Fig. 5. Turbidity (a) and apparent color (b) of the raw water, the water after the electroflotation process, and the water after down-flow granular filtration.

3.2. Filter cleaning results

After the completion of each test, the filter material was backwashed for 10 min. The average values of water turbidity during the cleaning process of the filter material can be observed in the graph shown in Fig. 6.

After 2 min of cleaning the filter medium, more than 95% of the wash water turbidity was removed (Fig. 6). After the first 2 min of cleaning, the turbidity removal from the wash water remained constant (approximately 97%), indicating that 3 min of backwash was sufficient for cleaning the filter material. This rapid backwash time suggests that the cyanobacterial cells were retained mainly within the first few centimeters of the filter medium. According to Shöntag et al. [8], the large amount of cyanobacteria present in Peri Lagoon causes low penetration (depth filtration), that is, less than 40 cm.

It was also observed that electroflotation can be an attractive option as a pre-treatment for down-flow granular filtration, because not only does it provide a wide application without electrode wear [11], it promotes a removal above 83% of the cyanobacteria present in drinking water. Pre-treatment also made it possible to increase the duration

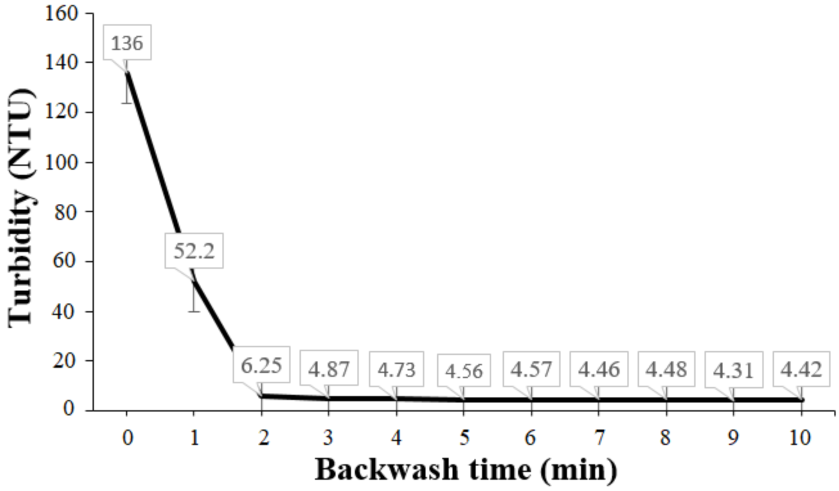

Fig. 6. Water turbidity throughout the 10 min backwash process.

of the filtration run. Electroflotation still stands out among other cyanobacterial removal methods for its economic and environmental benefits [22].

4. Conclusions

Although water from the Peri Lagoon source is difficult to treat, as it has high concentrations of cyanobacteria, the electroflotation process has proved to be an attractive option as a pre-treatment for down-flow granular filtration.

With the electrochemical reactor operating at a water input rate of 100.84 $m^3\ m^{-2}\ d^{-1}$ and an electrical current density of 68.26 A m^{-2}, with 12 h of pilot system operation, there was an average cyanobacteria removal of 83.42% and a removal of 57.59% after filtration. The average percentage of cyanobacterial cell removal with the pilot system operating in combination was 93.07%, with an electrochemical reactor energy consumption of 1.28 kWh m^{-3}. The pilot system operating in combination also presented an average turbidity and apparent color removal of 66.14% and 62.12%, respectively.

The electroflotation process as a pre-treatment enabled an increased duration of the filtration run, which makes it possible to treat larger volumes of water per day when applied to the reality of a water treatment plant.

Therefore, it is concluded that the water treatment of the Peri Lagoon source through the electroflotation process, using DSA® type electrodes, was efficient and can be used as a pre-treatment method for down-flow granular filtration for cyanobacteria removal in water for human consumption.

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