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Drinking water treatment using upflow slow sand filtration systems in high density *Cylindrospermopsis raciborskii* cyanobacteria water

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ABSTRACT

Cyanobacterium *Cylindrospermopsis raciborskii* may cause problems in drinking water treatment plants if specific attention is not focused on removing the cyanobacteria. Slow sand filtration possesses a good capacity for cyanobacteria removal and is a simple alternative to more expensive treatments. However, high cyanobacteria concentrations can correspond to an operational problem for slow sand filters by reducing the filter running time, and therefore rough filtration is necessary. In this study, two similar upflow slow sand filters were used to evaluate *C. raciborskii* removal. Water with 9.1×10^5 cells/mL was used and an average of 99% of cells were removed. Nevertheless, average concentrations of 1.4×10^4 and 2.1×10^4 cells/mL were observed after filtration, and this could continue to act as a problem for water treatment. The system also indicated good results in terms of removing total coliforms, colour and turbidity. The average turbidity was below 1.0 NTU, which is the maximum value permitted by Brazilian regulations and WHO recommendations. The major advantage of the upflow slow sand filter involved the high removal of *C. raciborskii* without compromising the running time of the filter with the filters operating for almost 80 days without the use of rough filters. However, it is necessary to use a complementary treatment process to achieve better water quality results.

Keywords: Cyanobacteria; Slow sand filtration; Upflow filtration; Water quality; Filter running time

1. Introduction

Cyanobacteria can cause problems in conventional drinking water treatment plants. This is because these plants do not remove the cyanobacteria since coagulation, flocculation, and decantation are not efficient [1]. Flotation or pre-oxidation processes are used to solve this problem [1,2]. The presence of cyanobacteria in drinking or recreation water poses a considerable risk to human health due to the ability of numerous strains to produce and secrete toxic chemical compounds [3–5].

Cylindrospermopsis raciborskii is a filamentous diazotrophic cyanobacterial species known as a producer of cylindrospermopsin (CYN) and saxitoxin (STX) [6]. The type of toxins produced can be associated with geographic distribution, and the most broadly distributed toxigenic members of the species produce CYN [7,8]. Additionally, STX-producing *C. raciborskii* strains were reported in South America [9].

A previous study indicated that *C. raciborskii* was resistant in a wide range of environmental conditions including not optimal conditions [10]. It can grow in conditions that involve nutrient deficiency, and these conditions are likely to promote the production of secondary metabolites, including CYN and STX that are toxic to human beings. Thus, the fore-mentioned adaptations allow *C. raciborskii* to spread to new environments and dominate environments that it currently inhabits. The species was initially identified mostly in tropical and subtropical latitudes although its prevalence in temperate regions has increased over the past two decades [4]. This could be related to different factors such the physiological adaptability, improved analytical

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methods, frequency analysis and environmental changes, such as global warming [8].

Furthermore, *C. raciborskii* is one of the most frequently investigated CYN-producing cyanobacteria due to its wide geographical distribution and acceptance as the first recognized CYN-producer [5]. In Brazil, *C. raciborskii* toxin production capacity is reported in different locations in which STX is the most commonly produced toxin [5,8,11–15]. In North America, *C. raciborskii* has been identified as a producer of teratogenic poly-1-methoxyalkenes [16]. Additionally, recent studies suggest that however European strains of *C. raciborskii* may be unable to produce CYN or STX although they can reveal certain toxicities through unknown and yet to be identified chemicals [5,17–19].

It is documented that the use of slow sand filters and biofilms provides a low cost solution to produce safe potable water [1]. This is due to the use of selected biodegrading bacteria that can degrade toxins [20–26]. Slow sand filtration (SSF) was tested for *C. raciborskii* removal and yielded-good results [27–29]. However, SSF without pre-filtration is typically associated with a short running time [27–30].

The use of pre-filters (or rough filters) can significantly increase filter running time and make SSF efficient with respect to the removal of the cyanobacteria [29,31]. Extant research also evaluated STX removal capacity by down flow SSF [29]. The findings indicated that the high density of *C. raciborskii* decreased STX removal efficiency, and this was attributed to a possible cell lysis in the filter. The problem was not reported with the use of a pre-filter [29].

The use of up flow slow sand filters (USSF) is not common, and only a few studies use this technology although good results including turbidity, apparent colour and coliform removal were demonstrated [32,33]. In USSF, the flow occurs from the bottom to the top of the filter. This allows the water to pass through the support layer prior to the filter media. Therefore, the support layer has a pre-filter function that it does not possess in down flow systems [32]. SSF involve a simple operation. Chemical treatment prior to the filtration is not required, and low energy is expended in cleaning the filters [34]. The only problem presented by the SSF for *C. raciborskii* cells removal corresponds to the short running time, although this can be solved by using a pre-filter [29,31] which in an USSF is on the filter itself [32].

The aim of the present study involved evaluating the potential of USSF in removing *C. raciborskii* cyanobacteria cells. Water samples from a lake in which the cyanobacteria are present in high densities were used to imitate a realistic situation. The upflow is a good alternative to solve the problem of short filtration running time since the water passes through gravel media prior to the sand filter media. In the present study toxin concentrations were not measured in raw and filtered water. The efficiency of filtration system in this study was only based on the removal of *C. raciborskii* cells.

2. Materials and methods

2.1. Characteristics of the raw water

The water used in the study was obtained from a coastal tropical lake known as the Lagoa do Peri (LP). The lake is located on Santa Catarina Island, in Florianopolis, Brazil. The lake is free from the influence of ocean water and is considerably influenced by winds in the region. This leads to significant homogeneity of the water column, which can-reach a depth of 11 m [37].

In LP, the density of *C. raciborskii* almost corresponds to 10^6 cells/mL, and it is the dominant phytoplankton species in the lake [27,38]. Studies in this area revealed that this density has a short seasonal variation and that the *C. raciborskii* dominance is due to the lack of nutrients, such as nitrogen and phosphorus, in the water [37,39,40]. Hennemann and Petrucio (2011) pointed out that the dominance is a result of several intrinsic factors such as high affinity for phosphorus, high P-storage capacity, high affinity for ammonium, superior shade tolerance and wide thermal tolerance [37].

Additionally, STX, CYN and Microcystin (MYC) were reported in LP waters [11,14,36]. In a previous study by Sens et al. (2009), intracellular eq. STX were found with average concentrations of 2 μm/L in raw water. Samples were collected monthly from 2001 to 2003 [11]. STX, MYC, extracellular and intracellular CYN were observed in samples collected from September to December 2006 and the study reported that cyanotoxins were detected in a few samples and recommended that a further study should be conducted in the area. However, these are the only reports about the production of toxins ever since [14]. The fact of most toxins was detected in intracellular manner is a reason for the removal of intact cells by treatment processes.

However, the present study did not investigate any cyanobacterial metabolites in raw and purified water.

The systems used in the study were in the facilities of a drinking water treatment station. The station also uses water from LP to supply the local population. The water used is directly obtained from the lake to the station and then pumped for 24 h/d from a bypass to the raw water (RW) reservoir (Fig. 1), and thus the water is always fresh and not diluted.

2.2. Upflow slow sand filters

Two equal upflow slow sand filter columns (USSF1 and USSF2) were used in this study (Fig. 1). The filters include a 30 cm support layer of gravel underneath a 40 cm sand filter bed in cylindrical columns with a diameter of 20 cm. The filter bed depth is lower than the typical depth of USSF. Previous studies affirm that biological activity occurs in the first 35 cm of the filter bed in upflow systems [32,41], and thus a 40 cm deep layer was used to simplify the filter cleaning.

In the filter bed, sand was used with an effective grain size (d_{10}) of 0.30 mm, a uniformity coefficient of 1.6 (c_u), and a total porosity (n_t) of 0.45. The support layer was composed of three layers in which each layer involved different gravel sizes, and the gravel size decreased in the direction of flow as shown in Table 1, that provides a summary of the characteristics of the filter.

The filters include a charge chamber that assures a hydraulic-only operation of the filter with a permanent flow rate of 4 m/d (empty volume velocity). The lake water was pumped to the charge chamber from a reservoir by a peristaltic pump, and the filter run was controlled by varying the water column level in the chamber by 70 cm. That implied that a maximum head loss of 70 cm in the filter media and the support layer was established as the filter run limit.

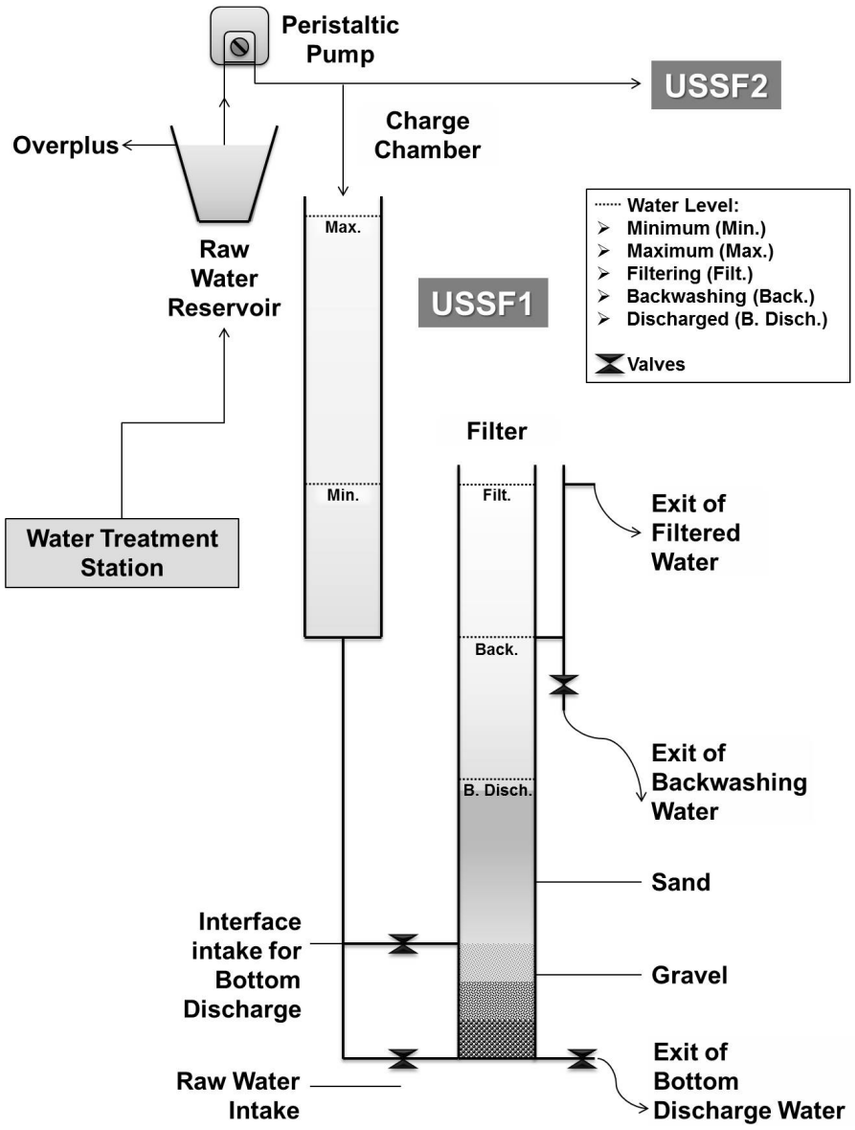

Fig. 1. The upflow slow sand filter system.

At the end of the run, the filter was cleaned and put back into operation. Different cleaning procedures were employed in the different filters based on necessity. This was the only difference between USSF1 and USSF2. Three procedures were used, namely bottom discharge, bottom discharge with water entering the interface between the support layer and filter bed, and finally backwash. The procedures were used separately or two of the procedures were used in combination with each other. Different procedures were tested in different filters each time a cleaning was needed, thus, the efficiency of cleaning could be evaluated. Bottom discharge by itself was not efficient, and a combination of two or more procedures were necessary to afford a good filter media and support layer cleaning. The filters were developed by the LAPOA with the purpose of operational improvement.

The bottom discharge was used to regenerate the headloss on the filter media and support layer. In this procedure, the flow rate was reversed, and this disturbed the filter hydraulics. The disturbance and the increase in the flow rate allowed detachment of impurities that were carried out from the filter. The bottom discharge with water entering the interface between the support layer and filter bed works in the same manner although it only disturbs the support layer, and the disturbance exceeds that of the simple bottom discharges [42].

Backwashing was used to regenerate the headloss when the bottom discharges were no longer efficient. The filter media fluidisation caused by backwashing was more efficient for filter cleaning. However, intermediate bottom discharges between backwash cleanings improved the operational time [42,43]. The combination of these cleaning methods is less labour-intensive than the usual scraping

Table 1
Upflow slow sand filters' constructive and operational characteristics

Maximum filter media headloss	70 cm
Water column above the filter media	80 cm
Support layer depth	30 cm
Material and characteristics of support bed	Gravel: L = 10 cm d = 6.65–12.7 mm L = 10 cm d = 3.18–6.65 mm L = 10 cm d = 2.00–3.18 mm
Material and characteristics of filter media	Sand: L = 40 cm d_{10} = 0.30 mm c_u = 1.56 n_t= 0.45

used in downflow SSF and only involved the operation of valves [43].

2.3. Water quality monitoring

The quality of RW and filtered water were monitored thrice a week for almost seven months from April to November 2014. Additionally, *C. raciborskii* cyanobacteria density, turbidity, colour, coliforms, organic carbon and 254 nm UV light absorbance were monitored for the analysis. Coliforms were monitored only in the last month.

Turbidity was evaluated on a *HACH* 2100N turbidimeter (Nephelometric method). The colour was evaluated using a *HACH*DR21000 Spectrophotometer (Spectrophotometric – Single-wavelength method). The total organic carbon (TOC) and dissolved organic carbon (DOC) were measured by a *Shimadzu* Toc5000A analyser using a high temperature combustion method. The 254 nm UV light absorbance was measured in a 1 cm length cell in an *OptizenPop* 3000W Spectrophotometer. All methodologies are described by the Standard Methods for the Examination of Water and Wastewater [44].

In LP, the characteristics of *C. raciborskii* individuals include a chained filament of *C. raciborskii* cells and heterocyst can occur. Thus, the counted individuals were then multiplied by the average number of cells typically found in the individuals. Therefore, the removal of cyanobacteria cells was not underestimated due to the use of results in which only the counted individuals were included.

The *C. raciborskii* filaments were counted with an *Olympus* BX40optical microscope in Sedgewick chambers. The number of filaments was multiplied by the average number of cells per filament in the examined water samples (raw or filtered).

Coliforms were measured using the defined chromogenic substrate method. An ONPG-MUG Colilert® substrate and a Quanti-Tray®/2000 apparatus were used.

3. Results and discussion

Table 2 lists the main properties of the RW used in the study and the filtered water in systems 1 and 2 (USSF1 and USSF2).

Table 2
Quality properties of the raw and filtered water in systems USSF1 and USSF2

	Unit	RW	USSF1		USSF2		WHO[a]	Brasil (2011)[a]
		M.V.	M.V.	Removal	M.V.	Removal		
		M.	M.		M.			
Turbidity	NTU	5.29	0.80	85%	0.97	82%	5, if possible 1, in small systems	1[b]
		5.31	0.67	87%	0.76	86%		
Apparent colour	Pt/Co	81	19	77%	21	74%		15[c]
		81	17	79%	17	79%		
True colour	Pt/Co	13	14		15			
		11	14		13			
C. raciborskii density	cells/mL	9.1×10^5	1.3×10^4	98%	2.1×10^4	98%		
		9.2×10^5	1.1×10^4	99%	1.1×10^4	99%		
TOC	mg/L	7.94	5.04	36%	4.95	38%		
		7.95	5.04	37%	4.89	39%		
DOC	mg/L	5.15	4.71	9%	4.58	11%		
		4.75	4.58	4%	4.46	6%		
254 nm absorbance	cm^{-1}	0.058	0.074		0.073			
		0.057	0.070		0.074			
Total coliforms	MPN/100 mL	2.3×10^4	2.8×10^3	88%	3.5×10^3	85%	Absence[b]	Absence[b]
		2.0×10^4	2.2×10^3	89%	1.4×10^3	93%		

M.V. – mean value; M. – median; [a]maximum value recommended; [b]after filtration, before disinfection; [c]after disinfection.

3.1. Turbidity and colour removal

Both filters removed turbidity satisfactorily since they removed more than 80% of turbidity on an average, and this resulted in an average turbidity below 1.0 NTU (Fig. 2), which is the maximum value permitted by Ordinance 2914 of the Brazilian Ministry of Health. A statistical analysis indicated a difference in the removal of turbidity between the two filters. There was also removal of apparent colour (Fig. 3c). A statistical analysis did not indicate any difference between the true colour of the RW and the filtered water (Fig. 3b). This indicated that there was no significant removal of true colour by the USSF. It is also considered that the colour removal is related to suspended solids since a statistical analysis did not indicate any significant difference between true and apparent colour from filtered water. SSF are known to be incapable of removing true colour [34].

These results were expected and in keeping with those reported in a previous study of USSF by Murtha and Heller (2003) [32]. In the study, the upflow system also exhibited better results when compared to a similar downflow system.

3.2. Coliform removal

Total coliforms were adequately removed by the USSF (Fig. 4). *Escherichia coli* were only detected in a few RW samplings and in just a filtered water sample. The removal of coliforms was monitored in only a single filter run (almost 80 days). In the filter run, a decrease in water quality was observed with respect to the USSF2 as well as bad results of turbidity removal. This resulted in a difference in the total coliform removal between the two filters (Table 2).

The disinfection by SSF is related to a dirt layer above the filter media termed as the *schmutzdecke*. This is a layer composed of suspended solids trapped on the surface above the filter bed in down flow SSF. Protozoal predation on thelayer is responsible for high disinfection levels achieved by SSF [34,45,46]. It is assumed that the *schmutzdecke* does not develop in a USSF because of the flow direction. Nevertheless, it is assumed that the support layer behaves as a pre-filter, and the results of a few studies indicated supportfor coliform removal [32,33].

A study by Murtha and Heller (2003) indicated a lower removal (2.22 Log removal) of coliforms by USSF when compared to downflow conventional SSF (2.73 Log removal) in which USSF1 removed 2.31 Log average. Furthermore, the support layer was responsible for removing an average of 96% of total coliforms in the same study.

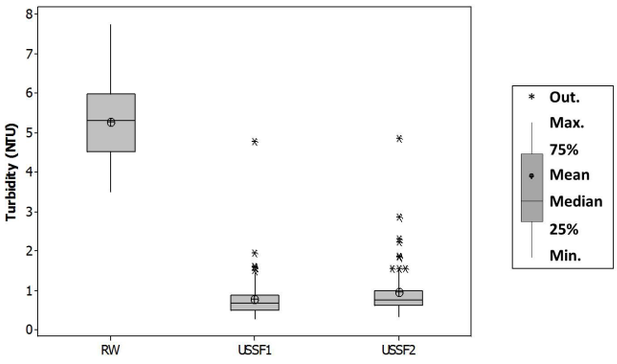

Fig. 2. Boxplot of turbidity data of raw and filtered water (n = 81).

3.3. Cylindrospermopsis raciborskii removal

The RW presented an elevated density of *C. raciborskii* cells, with a density of 9.1×10^5 cells/mL (Fig. 5). Both USSFs removed *C. raciborskii* cells, as well as 99% of RW cells with removal scor responding to 2.0 Log and 1.9 Log for each USSF as shown in Fig. 6. A significant difference was not observed between USSFs. It was also observed that only the smallest individuals passed through the filter media, and thus the number of counted individuals was multiplied by three while the number of individuals from the RW was multiplied by fifteen.

In this study, pre-filters were not used and the filter runs were not impaired. This was not the case in a study by Pereira et al. [31] in which the filter run of the downflow SSF was negatively influenced by the high density of the same cyanobacteria that were removed on the top of the filter media layer. This quickly increased the headloss and necessitated the use of pre-filters (gravel filters) since the time involved in the filter run was shorter than 24 h. Other studies with LP water also reported short filter run in downflow SSFs [27,30].

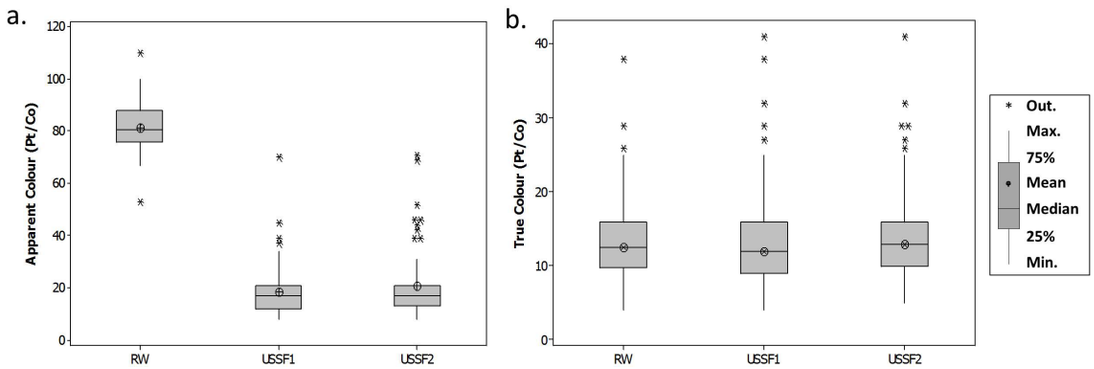

Fig. 3. Boxplot of apparent (a) and true (b) colour data of raw and filtered water (n = 81).

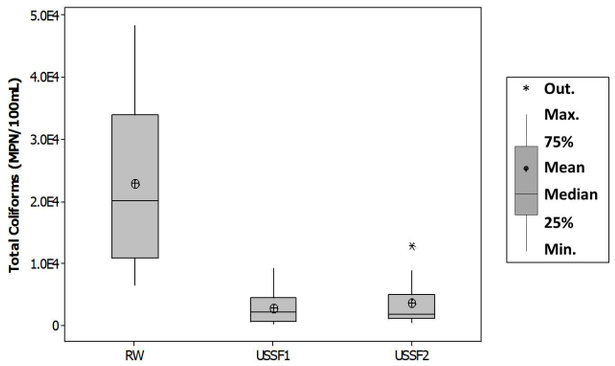

Fig. 4. Boxplot of total coliform data of raw and filtered water (n = 12).

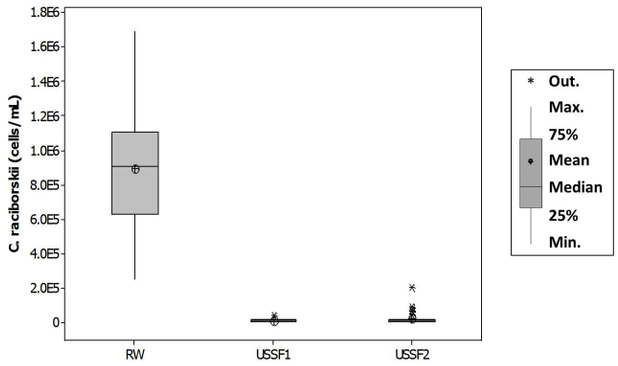

Fig. 5. Boxplot of *C. raciborskii* cell counts in raw and filtered water (n = 50).

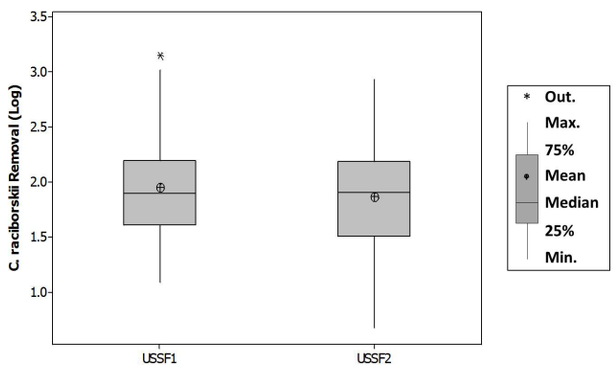

Fig. 6. Boxplot of removal of *C. raciborskii* cells (n = 50).

However, high concentrations of *C. raciborskii* cells were found even after considerable amounts of removal. This was because the USSF was not capable of removing small individuals or there was a filament break on the filter. This can pose a problem because it can cause a regrowth on the system. Additionally, there is also a possibility of cell lysis and liberation of toxins or odour compounds or the formation of disinfection by-products [47,48]. A similar problem was reported in study by Pereira et al. [31] with the use of downflow SSF.

The present study did not investigate any cyanobacterial metabolites in raw and purified water. Previous studies reported the possibility of toxic substances in the water of the LP and that the high density of cyanobacteria at the end of filtration is a cause for concern [11,36]. In the study, cyanotoxins were not evaluated, and thus it was not possible to form a conclusion about their presence. However, this could still involve a risk in the treatment involved this case.

A solution to this problem could involve the use of a pre-oxidant process [11,49]. However, these processes could elevate the costs of the technology. Another solution involves the use of a granular active carbon (GAC) column. A GAC column is a good alternative to this case since it can remove the toxins and odour compounds that can be formed on the SSF [49]. In this case a layer of GAC could be easily employed above filter media.

3.4. Organic carbon removal

The organic carbon removal was measured by monitoring TOC, DOC (Fig. 7), and the sample's absorbance of 254 nm UV light (Fig. 8).

In the RW, 70% of the TOC is represented by DOC. As shown (Fig. 7), most of the particulate organic carbon was removed by the USSF. This conclusion was possible because there is no statistical difference between the TOC and the DOC of filtered water.

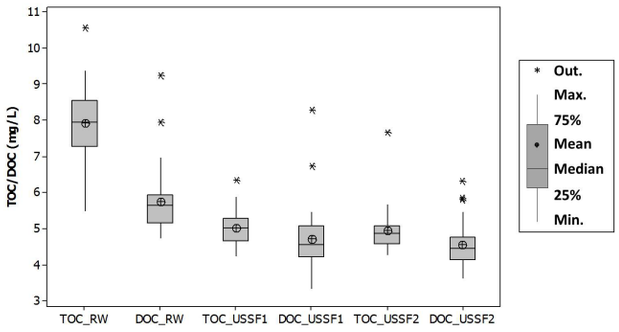

Fig. 7. Boxplot of TOC and DOC of raw and filtered water (n = 42).

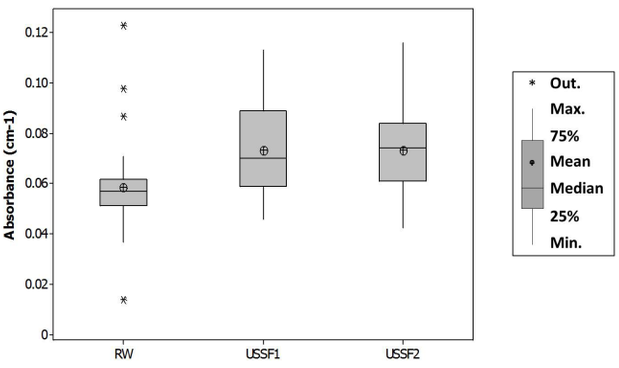

Fig. 8. Boxplot of 254 nm absorbance of raw and filtered water (n = 42).

High values of DOC were also reported by other studies that investigated the same water [12,27]. The high DOC concentration level is related to the presence and predominance of *C. raciborskii* tha represent 98% of the bacterial carbon [50]. The remaining part of the DOC is problematic due to the possibility of formation of disinfection by-products.

This concern is confirmed by the increase in the absorbance level of the filtered water when compared to that of the RW, since the absorbance level of the filtered water supposed to decrease. There was no significant difference between the two filters.

4. Conclusions

The results indicated that the proposed system was efficient in the removal of suspended materials such as turbidity and particulate organic carbon. The main advantage of the USSFs used in the study related to the significant removal of the *C. raciborskii* cells without a negative operational influence on the filters that were operated for more than 80 d without filter bed cleaning. The filters revealed significant removal of high concentrations of *C. raciborskii* with an average removal of 2 Log of cells. This is a positive result since SFF is a simple treatment and can be easily used to reduce the costs of this type of raw water treatment.

However, the remaining density of *C. raciborskii* (above 10^4 cells/mL) may still cause a problem after the disinfection processes. Multiple processing steps are recommended for the treatment of water in which high densities of cyanobacteria and USSF are not excluded and this could increase the costs of the technology. Additionally, the removal of dissolved organic substances present in the RW is also not desirable. It is considered that a transformation of the organic matter in the filter contributed to the augmentation of absorbent 254 nm UV light substances. These types of substances may cause a problem after disinfection due to the possibility of formation of disinfection by-products.

Therefore, further studies of the potential of the USSF application of the proposed technique is recommended to remove high density of *C. racibor*skii to ensure good results with respect to cyanobacteria metabolites removal and organic carbon transformation on the filter.

It is also necessary to develop a cleaning system for an improved application of the technique and to study simple techniques as a complementary treatment for the application of a simple system for *C. raciborskii* removal. It is also recommended to conduct further studies with different water sources. Nevertheless, good results with respects to operational running time were obtained with a matrix that was expected to be problematic, and this is an indication that interesting results could be obtained with water from a more appropriate source for the use of the SSF technology.

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