Research Paper

Sisal fiber as an alternative to the construction of flexible fiber filters applied to water treatment

Alice K. M. Morita and Marco A. P. Reali

ABSTRACT

The recently developed flexible fiber filters (3Fs) are modular filtration units, which can satisfactorily remove solids at high filtration rates. Normally built with polyamide fibers, it is supposed that natural fibers can be used alternatively. This paper evaluated the performance of 3Fs using as filtering media sisal fibers in lieu of the polyamide ones. The sisal fibers were evaluated by means of scanning electronic microscopy and through solubility assays in hydrochloric acid and sodium hydroxide. Six filters with 28 mm of internal diameter were built, varying their length (25, 60, and 100 cm) and porosity (85 and 93%). The filtration system was fed with synthetic water, in-line coagulation was applied by the addition of 22.5 mg/L of aluminum sulfate, and filtration rates from 20 to 80 m/h were evaluated. Only the filter with 100 cm of length and 85% of porosity could work within the limit established (1 NTU), operating at 20 and 40 m/h. For all the studied configurations, the pressure drop was considerably low (less than 0.5 mH_2O) when compared with 3Fs built with polyamide, which shows the potential of using this kind of filter as pre-filtration units or for less restrictive uses. This study showed that 3Fs can be adapted to include different configurations and materials, reducing their cost and making them appropriate for low-income countries.

Key words | deep bed fiber filtration, flexible fiber filter, low-cost configuration, sisal fiber, water clarification

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INTRODUCTION

Flexible fiber filters (3Fs) are innovative and recently developed modules, which can be used for the clarification of some kinds of water and wastewater, not requiring the previous steps of flocculation and/or sedimentation or flotation. When used as direct filtration units of pre-coagulated water, these filters can produce satisfactory filtrates even when high filtration rates are applied (Lee *et al.* 2006; Guerra *et al.* 2014).

These filters are filtration modules whose filtering media consist of polyamide fibers with an average diameter of around 30 μm. The fibers are attached to the bottom of the filter bed, are left loose on its top, and are packed parallel to the water flow. Upflow is normally adopted, and deep filtration occurs through all filter bed. Combining large specific surface area and large porosity, this filter configuration permits high removal efficiencies and low pressure drops despite the high filtration velocities applied (Lee *et al.* 2008).

Several studies can be found in the literature that present the promising results of this technology for wastewater treatment (Ben Aim *et al.* 2004; Denieul *et al.* 2011; Mauchauffee *et al.* 2012), clarification of surface water (Lee *et al.* 2006, 2008; Gao *et al.* 2012; Guerra *et al.* 2014; Niu *et al.* 2016; Morita & Reali 2019), seawater particles

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removal (Jeanmaire *et al.* 2007; Lee *et al.* 2009, 2010; Kim *et al.* 2013), stormwater treatment (Johir *et al.* 2009), and algae removal (Cha *et al.* 2009). Different raw water conditions, coagulant dosages, and filter sizes have been studied, and the results normally show great potential for the use of 3Fs, especially as direct filtration units, for the clarification of waters with higher levels of turbidity and/or at higher filtration rates, when compared with conventional sand filters (Guerra *et al.* 2014; Niu *et al.* 2016).

Despite all the studies conducted, no research can be found in the literature that adapts this filter configuration to include natural fibers. The incorporation of natural fibers to different technologies may be advantageous due to the enhancement of the production chain – associated with the generation of economic benefits – and to the use of renewable, available, local and more suitable materials for each region.

The sisal plant is the main source of hard fiber extraction in the world, and these are used to produce ropes, carpets, and even cement reinforcement. Brazilian annual production is about 120,000 tons, which increases employment rates and generates income for about 500,000 people (Silva *et al.* 2011). Constituted by long fibers, it is supposed that the sisal fibers can suit the 3F structure and thus produce an alternative and lower cost configuration of these modules.

This paper shows the results of studies conducted using sisal fibers as filtering media in 3Fs, in lieu of the commonly used polyamide fibers. This study may contribute not only to the evaluation of sisal fibers as filtering media – their efficiency, advantages, and drawbacks – but also to the enhancement of studies assessing the use of natural fibers in 3Fs.

METHOD

This study was divided into four different phases of work, which are described in the following paragraphs.

Characteristics of synthetic raw water

The synthetic water used in all the phases of this research was produced by the addition of 1.0 mg/L of humic acid (Aldrich 1675-2), 8.5 mg/L of kaolin (Fluka 60609), and 10 mg/L of sodium carbonate (for pH adjustment) to deep well water. The characteristics of the produced synthetic water are presented in Table 1. The production of synthetic water with these characteristics had the objective of simulating conditions similar to the ones found in the literature (Lee *et al.* 2006, 2008; Morita & Reali 2019), enabling a better comparison of the results.

First phase of work – fibers characterization

During the first phase of work, sisal fibers, obtained from ropes normally used for agricultural purposes, were characterized through optic microscopy and scanning electronic microscopy (SEM) and through solubility experiments, which were conducted for better understanding the filtering process and for verifying if there were any restrictions of using the sisal fibers in water treatment. For the solubility assays, fiber samples were previously washed with distilled water and dried in a drying oven at $110 \pm 5\,^{\circ}C$ for 3 h. From these samples, 30 g were weighed and immersed in hydrochloric solution (1:1) for 30 min, with intermittent mixing, and 30 g were weighed and immersed in sodium hydroxide solution (1%) for 24 h, with intermittent mixing. After the immersion periods, the samples were washed by decantation with distilled water until pH achieved 7.0, dried at $110 \pm 5\,^{\circ}C$ for 3 h, and weighed again. The difference of mass observed before and after the experiment was associated with the fiber's loss (solubility) in acidic or basic media.

For optic microscopy, one hundred pieces of the sisal fibers were cut, and their diameter and superficial characteristics were observed so that the average diameter and the filter's surface area could be calculated.

Table 1 | Parameters of the study water

Parameters	Study water
pH	7.30 ± 0.22
Turbidity (NTU)	8.19 ± 0.85
Apparent color (CU)	14.47 ± 5.25
Alkalinity (mg/L)	35.74 ± 1.60
Total suspended solids (mg/L)	7.98 ± 0.74

For SEM analysis, fiber samples were dried at 110 ± 5 °C for 24 h and prepared on metallic support with gold coating. Four different fiber samples were analyzed through SEM: (a) without any treatment or use as filtering material, (b) after solubility assays in hydrochloric acid, (c) after solubility assays in sodium hydroxide, and (d) after 3 months of operation as a filter bed.

Second phase of work – coagulation tests

During the second phase of work, coagulation tests were conducted in batch coagulation equipment (Jar test) containing six 2-L jars, aiming to obtain the best pH and coagulant dosage for the studied synthetic water. The coagulant studied was aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$) and its dosage varied from 5 to 50 mg/L. The pH was also varied from 5.5 to 7.0 by the addition of sulfuric acid or sodium carbonate. A water temperature of 24 ± 1 °C, average velocity gradient (G) of 900 s^{-1}, and detention time of 20 s during the rapid mixing step were kept constant for all the assays. After the rapid mixing step, samples from each jar were collected, filtered through Whatman 40 paper filters, and analyzed. Turbidity, color, and pH were evaluated, and a coagulation diagram was built for the selection of the best coagulation condition.

Third phase of work – filters construction and performance evaluation

During the third phase of experiments, fiber filters with different lengths (25, 60, and 100 cm) and porosities (85 and 93%) were built, using sisal fibers in lieu of polyamide fibers. The average porosity was assessed immersing the filter bed made of fibers in distilled water, measuring the dislocated water volume, and comparing it with the calculated filter volume. The filters were constructed using pipes with 28 mm of internal diameter, and the filtering media were obtained by packing the sisal fibers parallel to the vertical axis and fixing them to a stainless steel net on the bottom of the filter. The pressure drop was monitored with a piezometer, which was connected to four equally spaced points of pressure in each filter.

Upflow filtration was employed, and the feed water flowed by gravity from a constant level box installed at approximately 3 m high, permitting an available hydraulic charge of around 2.0 mH_2O (see Figure S1 of the Supplementary Material).

Direct filtration was applied by the addition of aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$) solution to the feed pipe, in which a static tubular mixer was installed to promote the coagulation of the raw water. The dosage adopted in this step was equal to the best one found during the second phase and was kept constant for all filters and conditions studied. Filtration rates from 20 to 80 m/h were evaluated, and, during each condition, the filter run was stopped when filtrate turbidity achieved 1.0 NTU. Pressure drop and water flow were monitored, and filtrate samples were collected every 15 min. Turbidity, true and apparent color, pH, alkalinity, and suspended solids of the collected samples were evaluated using the methods and equipment shown in Table S1 of the Supplementary Material.

After the turbidity limit was achieved, backwashing was conducted, and the filter runs were restarted so that each condition was studied in duplicate.

Fourth phase of work – backwash assessment

The fourth and last phase of work consisted of backwashing experiments applied to filters, which showed the best performances in the previous step. The number of stages and time of air and water application were varied in each experiment. The conditions analyzed are presented in Table 2.

The applied air rate was kept in about 160 $m^3{\cdot}m^{-2}{\cdot}h^{-1}$, and the washing water flow was fixed in approximately 1,040 $m^3{\cdot}m^{-2}{\cdot}h^{-1}$. After the best combination of the number of stages and time of water and air application was found, a final study was conducted with the reduction of the water flow to 300 $m^3{\cdot}m^{-2}{\cdot}h^{-1}$, in order to make the process more efficient.

Table 2 | Studied backwash conditions

	Mode					
	1	2	3	4	5	6
Number of stages	1	1	3	3	5	5
Time of air application per stage (s)	60	15	5	10	3	6
Time of water application per stage (s)	–	30	10	10	6	6

For the evaluation of the backwashing process, the parameters considered were the recovery of pressure drop and the mass balance between solids retained in the filtration process and solids observed in the backwashing water.

RESULTS AND DISCUSSION

Results of the first phase of experimental work

Solubility assays

The solubilities of the sisal fibers in hydrochloric acid and sodium hydroxide were 2.3 and 8.9%, respectively. Although there is still no solubility standard for sisal beds, it is interesting to compare the standardization for other materials. As an example, it is possible to mention the Brazilian standard NBR 14234/1998, which recommends, for anthracite coal used in water treatment, that hydrochloric acid and sodium hydroxide solubilities are below 5 and 2%, respectively. In comparison to this standard, the sisal fibers would be adequate for acidic waters but could not be exposed to alkaline waters. This result is compatible with data found in the literature (Toledo Filho *et al.* 2000), which associates sisal fibers with faster degradation in alkaline media (pH >12). This way it seems to be important to avoid the contact of sisal media with alkaline waters or products, but it is still necessary to evaluate and establish permissible values for beds made of natural fibers.

Optic microscopy

It was observed that the sisal fibers' diameters varied considerably, from 50 μm (minimum) to 400 μm (maximum). The transversal section also varied in the same fiber, and sometimes it was verified that one fiber divided into several fibers (see Figure S3 of the Supplementary Material). The average diameter was 198.5 ± 75.2 μm, considerably wider than the polyamide fibers' diameters, which are nearly 30 μm (Lee *et al.* 2006). With the average sisal fiber diameter, it was possible to estimate the contact surface obtained for filters with different porosities and compare them with filters built with polyamide fibers. This comparison is presented in Table S2 of the Supplementary Material.

It was verified that the contact surfaces are about seven times larger for the filters made of polyamide fibers than for the ones built with sisal fibers, considering the same filter porosity. Therefore, it is supposed that filters made of polyamide fibers can produce better quality filtrates when compared with the ones built with sisal fibers. Conversely, filters made of sisal fibers may be associated with lower pressure drops.

Similarly, it was observed that the reduction of porosity from 93 to 85% of the sisal filters made the contact surface double and thus may lead to an improvement in the filtrate's quality.

Scanning electronic microscopy

The images obtained through SEM (Figure 1) made it possible to verify the existence of small fibrils and residues on the surface of the sisal fiber. The first ones are associated with the parenchyma cells (Iozzi *et al.* 2010) and seem to increase the surface area.

From Figure 1, it was possible to observe that the surfaces of the fibers submitted to solubility assays (Figure 1(b) and 1(c)) seem to be cleaner and clearer,

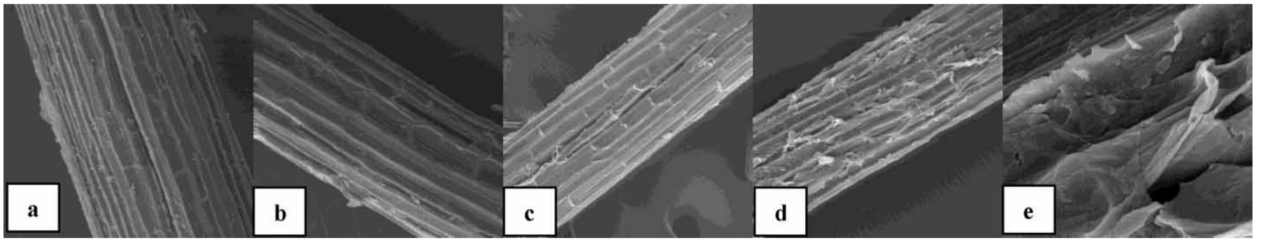

Figure 1 | Scanning electronic microscopy images of sisal fibers: (a) without any treatment (×200); (b) after solubility assays in hydrochloric acid (×200); (c) after solubility assays in sodium hydroxide (×200); (d) after 2 months of the filter's operation (×200); and (e) after 2 months of the filter's operation (×2000).

which can be associated with residues removal. Consequently, the solubility results encountered in the previous phase may be explained not only by the fiber's loss but also by the elimination of solids existing on its surface, which may be related to the handling during the fiber's production. Conversely, the fibers used as filter media presented solids on their surface, showing good filtering performance.

Results of the second phase of experimental work

After coagulation diagrams for color and turbidity were built, it was possible to verify that, for the studied water, the highest removal efficiencies were obtained for dosages from 20 to 25 mg/L and pH from 6.5 to 7.0. Therefore, the dosage of 22.5 mg/L of aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$), pH of 6.5 ± 0.2, and temperature of 25 ± 1 °C were chosen for conducting the filtration experiments.

Results of the third phase of experimental work

For all the filters built with the porosity of 93%, it was not possible to produce filtrate with less than 1 NTU, even operating at 20 m/h (see Figure S4 of the Supplementary Material). However, the longest filter could produce filtrates with turbidity of around 2 NTU, associated with very low pressure drops, of around 0.08 mH_2O after 250 min of operation at 20 m/h.

Since no filter with 93% of porosity could produce filtrates with less than 1 NTU, the filter porosities were reduced to 85% in order to evaluate whether the performance could be enhanced. The results obtained for this new porosity and for the filtration rate of 20 m/h are presented in Figure 2. As can be observed, only the 100 cm filters with 85% porosity could produce filtrates with turbidity below 1 NTU for about 200 min. Thus, the other filters were not evaluated for higher rates. Nonetheless, it was

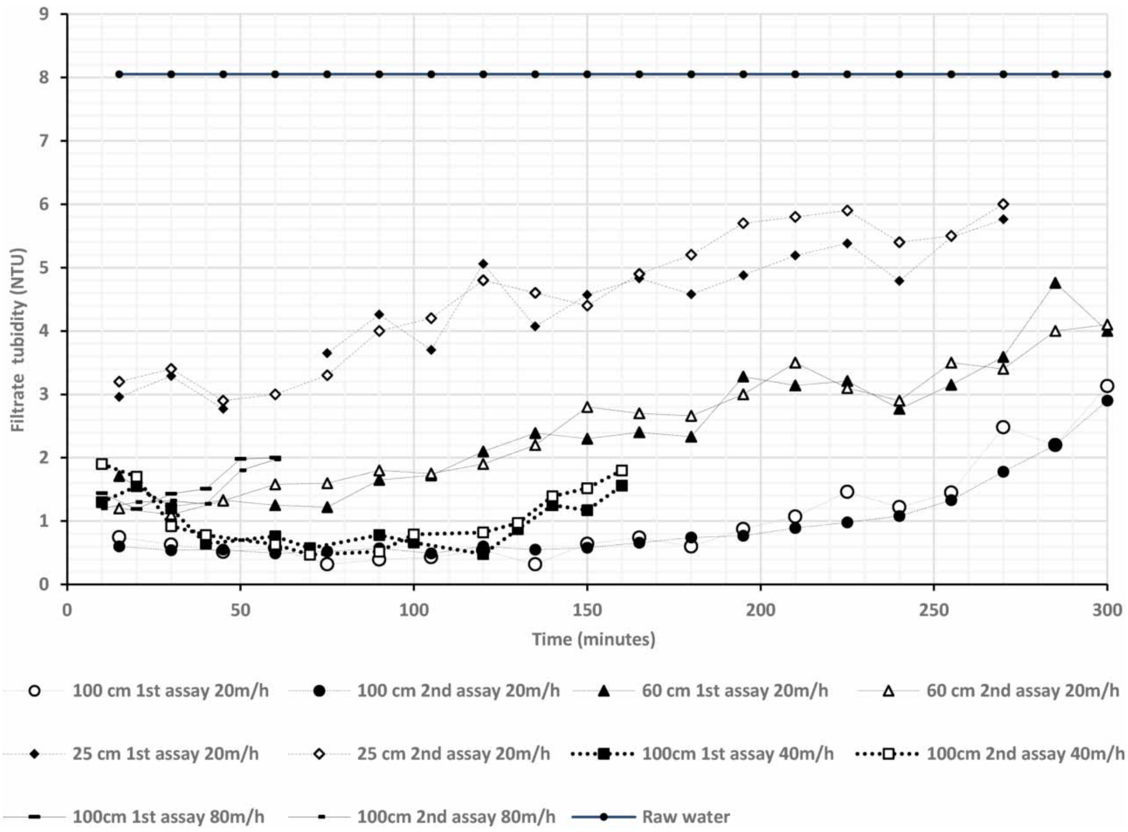

Figure 2 | Filtrate turbidity evolution for the filters studied and for filtration rates of 20, 40, and 80 m/h.

possible to verify that all lengths could proportionally reduce the filtrate turbidity, showing that depth filtration is evident in this kind of filter.

Figure 2 also shows the evolution of the filtrate turbidity for the 100 cm long filter, operating at 40 and 80 m/h. For 40 m/h, the ripening period – the time when the turbidity values tend to decrease, at the beginning of the filter run – was evident and lasted about 30 min. This is considerably high, especially for a filter run of around 100 min and considering that only after this ripening period could the filter produce filtrates within the established limit. This characteristic has already been noticed in previous studies (Lee *et al.* 2006, 2007), but it was proportionally higher for this experiment. Depth filtration was also observed, with the retention of particles through all the filter length (see Figure S5 of the Supplementary Material).

Conversely, for 80 m/h, the 100 cm long filter could not produce filtrates with turbidity below 1 NTU. Nonetheless, filtrates with turbidity below 2 NTU were produced for about 60 min, and below 1.5 NTU for about 40 min, and the ripening period was not evident for this filtration rate. Additionally, color removal was of approximately 91% during the filter run, and the pressure drop associated with this condition was around 0.4 mH_2O after 60 min of operation. This is considerably low when compared with fiber filters built with polyamide or polypropylene fibers, whose pressure drops were of around 2.0 mH_2O under similar conditions (Lee *et al.* 2008; Guerra *et al.* 2014; Morita & Reali 2019).

Concerning the filtration rates, the results obtained in this work were different from the ones found in the literature for polyamide fibers (Lee *et al.* 2006, .2008) and polypropylene fibers (Morita & Reali 2019). These authors obtained better results, mainly when using rates above 20 m/h, which can be associated with the wider diameter of the sisal fibers, leading to smaller contact surfaces, as discussed previously and shown in Table S2 of the Supplementary Material. Therefore, the retention of solids and the pressure drops are reduced for sisal filters since the particles have less contact with the fibers.

Regarding the suspended solids removal, the obtained efficiencies were of 90, 91, and 70% for the 100 cm filter with 85% of porosity, operated at 20, 40, and 80 m/h. Therefore, when operated at 20 and 40 m/h, the efficiencies were similar to the ones found in the literature, which are generally between 90 and 95% for rates as high as 80 m/h (Lee *et al.* 2008; Morita & Reali 2019). Nonetheless, a decrease in the efficiency was observed for the rate of 80 m/h.

Although the adoption of sisal fibers in lieu of polyamide fibers may show some disadvantages, related to an increase of the filtrate's turbidity and to a reduction of the filter runs, this can also bring some advantages, mainly linked to a lower cost configuration and to the lower associated pressure drops. Therefore, 3Fs made of sisal fibers may have interesting applications as pre-filtration units, considerably removing turbidity and color and generating very low pressure drops, but are not able to produce high-quality filtrates at high filtration rates. Consequently, this filter configuration may be suitable for low-income countries, where economic layouts are more appropriate and where removing color from raw water has beneficial impacts reducing the production of disinfection byproducts.

Results of the fourth phase of experimental work

Provided that the only filter which could produce a filtrate with turbidity below 1 NTU was the longer one (100 cm), with 85% of porosity, this phase of work focused only on this filter.

The fifth mode was chosen as the best one, due to the better pressure drop recovery, to the efficiency in the removal of retained solids (~100%), and to the shorter time of air application (see Table S3 of the Supplementary Material).

The first backwashing water flow (1,040 $m^3 \cdot m^{-2} \cdot h^{-1}$) led to a consumption of about 8% of the filtrate's production for the backwashing process. When the flow was reduced to 300 $m^3 \cdot m^{-2} \cdot h^{-1}$, about 3.5% of the filter's production was consumed, associated with a backwashing efficiency of 100%. This value is compatible with the ones found for conventional sand filters. It is interesting to emphasize that high water and air flows can be applied to 3Fs, as media loss does not occur in this configuration.

CONCLUSIONS

From this study, it can be concluded that:

- 3Fs built with sisal fibers could produce good quality filtrates (turbidity lower than 1 NTU) when built with 85% of porosity, 100 cm of length, and operated at 20 and 40 m/h, clarifying raw water with about 8 NTU.
- For the filtration rate of 80 m/h, no filter could produce filtrates with turbidity below 1 NTU, although the 100 cm long filter could produce filtrates with turbidity below 1.5 NTU for 40 min, associated with color removal efficiencies of about 90%.
- Considerably low pressure drops (below 0.5 mH_2O) are associated with the use of sisal fibers in 3Fs, which may contribute to their use in pre-filtration units.
- The efficiency obtained for sisal filters is below the ones found in the literature for polyamide and polypropylene fibers, which was explained by a decrease in the contact surface when the first ones are adopted.
- Sisal 3Fs consumed about 3.5% of filtered water during the backwashing, considering the best configuration studied.
- Sisal flexible fibers showed the possibility of liberation of unknown substances to water when exposed to alkaline media (pH >12), as could be observed from the solubility experiments. Further studies are required for recognizing the kind of substances liberated and the level of danger this represents to water supply. Nonetheless, neutral or acidic waters did not seem to liberate dangerous substances, and using the sisal fibers for treating water for less restrictive uses is also a possibility.
- The color removal (~90%) showed great elimination of organic compounds, which is an important step in preventing the formation of disinfection byproducts.
- The possibility of using sisal fibers in this innovative filter configuration has interesting applications in developing countries, where it is necessary to use available and cheaper materials. The results may also encourage other studies involving the use of natural fibers in water and wastewater treatments in low-income countries.

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DECLARATIONS OF INTEREST

None declared.

SUPPLEMENTARY MATERIAL

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