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Evaluation of coconut fiber as an adsorbent for the removal of polystyrene microplastics from aquatic environments: A sustainable solution

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Abstract

Microplastics have garnered significant global attention as a newly recognized, potentially hazardous pollutant capable of causing harm to organisms and threatening aquatic environments. Therefore, efficient and low-cost techniques for removing microplastics are urgently needed. In this study, coconut fiber (CF), an agro-industrial waste, was used as an adsorbent to remove microplastics from aquatic environments. The fiber was used both in its natural state and after acid pre-treatment (CF-H). These structures were analyzed by FTIR and optical microscopy. The highest adsorbed amount was found using CF-H, which equaled 0.42 mg/g of adsorbent and demonstrated a removal efficiency greater than 10%. When applying kinetic and isothermal adsorption models, the adsorption kinetics followed the pseudo-first-order model, and the Langmuir isotherm best represented the system.

Keywords: Adsorption; Coconut fiber; polution; polystyrene microplastics.

1. Introduction

Due to the remarkable physicochemical properties and the various applications, the demand for plastics has increased rapidly, it is estimated the global yields of plastics will soar to 330 billion tons by 2050 [1,2]. The exposure of these materials to natural processes such as degradation by ultraviolet radiation and physical fragmentation, leads to the decomposition of the plastic, resulting in secondary microplastics (MPs <1 mm) and nanoplastics (NPLs <100 nm) [3,4].

Microplastics, which are toxic to both animal and human health, have been detected in raw water and drinking water, in the human placenta and in human peripheral blood lymphocytes [5,6]. Therefore, microplastics pollution has emerged as a critical global environmental issue, necessitating the development of effective, scalable, and eco-friendly removal techniques[1].

Several methods have been proposed for efficient MPs removal, including membrane filtration, magnetic separation, adsorption, among these, adsorption is a simple, affordable, energy-efficient, and reusable technology that enables precise MPs elimination, offers low cost, broad adaptability, and easy implementation [5,7].

Biomass-based adsorbents have been widely used, because are sustainable material, with large surface area, easy synthesis, significant functionalization, and strong interactions with various contaminants [6]. Coconut fiber (CF), in particular, is noteworthy due to its porous structure, high surface area, and low cost, making it a sustainable material suitable for large-scale use [8]. In light of the search for effective and sustainable solutions to combat this problem, this work aims to analyze the adsorption process involved in the removal of polystyrene (PS) microplastics using coconut coir in its natural state and after acid pretreatment.

2. Materials and methods

Material

Green coconut fibers were donated by Embrapa Agroindústria Tropical (Paraipaba, Brazil). They were milled in a knife mill (Fritsch pulverisette 19) using sieves with pores to obtain particles with sizes between 0.5 mm and 1 mm. Polystyrene (PS) microplastics were obtained as a solution from Sigma Aldrich, with diameter of 500 nm, a density equal to 1.05 g/cm³ at 15 °C.

Methods

Coconut fibers underwent a washing pre-treatment, second Rosa et al.[9], followed by drying at 60 °C for 24 hours. The acid treatment the was carried out at 121 °C for 30 min using 0.6 mol/L H_2SO_4 and 2 % w/v of CF, according the method described by [10], with modifications. The resulting material was dried again at 60 °C for 24 h and labeled CF-H.

The potential of zero charge (PZC) was performed according the method described by [11], using 0.1 M NaCl solution, adjusting the pH with 0.1 M HCl and 0.1 M to achieve a pH range of 2 to 10. The Zeta potential of the PS solution (8 mg/L) was measured using a Zetasizer Nano ZS90 over a pH range of 2 to 10.

Optical microscopy was used to obtain images of the fibers (CF and CF-H), and Fourier Transform Infrared (FTIR) analysis (Agilent Cary 630) was used to identify functional groups. Adsorption tests were conducted using CF at concentrations of 2 and 4 g/L, and CF-H at a concentration of 2 g/L, with respect to 12 mL of 8 mg/L polystyrene (PS) microplastic solution at pH = 5.0 ± 0.1 [12]. Experiments were performed in an orbital shaker at 150 rpm and 25 °C. Samples were collected at different times and analyzed using a turbidimeter (HI98703) to obtain adsorption kinetics.

Optimized dosages of CF-H were added to PS solutions at different concentrations (4 to 18 mg L^{-1}) that were also incubated at 25 °C and 150 rpm during 16 h. The removal efficiency (Re %) and the amount of PS adsorbed per gram of adsorbent (qt, mg g^{-1}) were calculated by Eqs. 1 and 2 [8]:

$$Re\ (\%) = \frac{C_0 - C_t}{C_0} x\ 100 \qquad (1)$$

$$q_{t,e} = \frac{(C_0 - C_{t,e}).V}{m} \qquad (2)$$

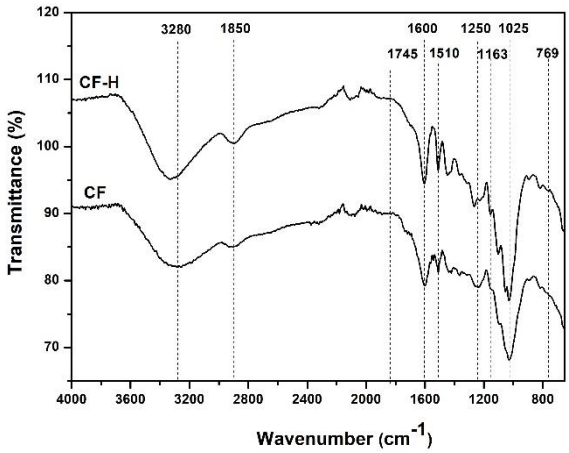
where C_0, C_t, and C_e are the initial concentration, the concentration at time t, and the equilibrium concentration, respectively; m is the mass of adsorbent and V is the volume of adsorbate.

3. Results and discussion

Characterization of coconut fiber before and after pre-treatment

Figure 1 shows the functional groups present in the coconut fiber in its natural state and after acid pretreatment.

Fig 1. FTIR spectra of fibers before and after pretreatment



The spectrum of the CF-H, compared to CF exhibited modifications, including a band at 769 cm^{-1} corresponding to the C-H deformation of lignin out of plane. The bands from 1510 to 1600 cm^{-1} that represent the C=C vibration of the aromatic skeleton of lignin, were better defined [13].These modifications indicate greater exposure of lignin in the structure, which in turn presents hydrophobic characteristics.

Figure 2 shows optical microscopy images of the coconut fiber in its natural state (Fig. 2A) and after pretreatment (Fig. 2B), both displaying a spongy and porous structure.

Fig 2. Optical microscopy image of CF (A) and CF-H (B) at 40X magnification.

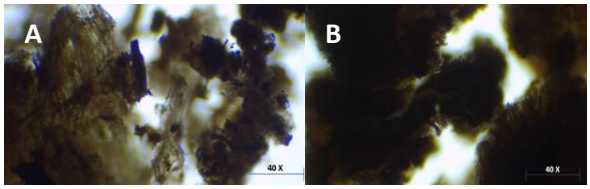
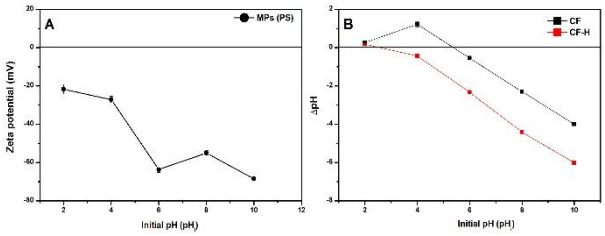


Figure 3A shows that the PS charges are all negative, according to the zeta potential, similar behavior was found reported by [14]. In Figure 3B

it is observed pH values at point of zero charge (pH $_{PZC}$) 5.5 for CF, aligning with the findings of [8].

Fig 3. Zeta potential of (A) PS (8 mg L^{-1}) and pH values at point of zero charge (B) CF and CF-H.

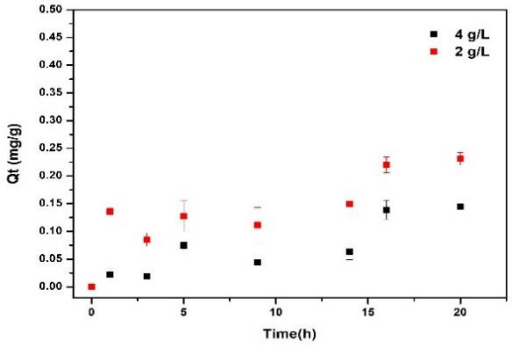


The pH PZC for the CF-H (Fig. 3B) was equal 2.5, showing a significant decrease of pH $_{PZC}$ from CF to CF-H, which can be attributed to a higher of hydroxyl groups [8], that after pretreatment were more exposed, corroborating the result obtained in Fig 1. The pH value = 5 was chosen to perform the adsorption tests.

Adsorption kinetics and isotherms

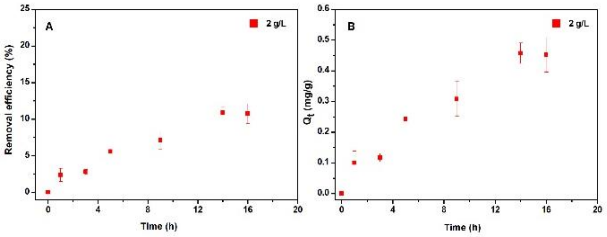
Two different concentrations were studied, namely 2 and 4 g L^{-1} for CF, using PS microplastic (8 mg/L). The adsorption capacity is shown in Figure 4.

Fig 4. adsorption capacity of Coconut fiber (CF).



The concentration of 2 g/L demonstrated a greater adsorption capacity, equal to 0.22 mg/g of CF in the equilibrium time of 16 hours, this removal may be associated with electrostatic interactions between the fiber and the PS [15]. Based on these results, CF was modified by acid pretreatment. After pretreatment, CF-H showed a removal efficiency greater than 10%, with an adsorption capacity of 0.42 mg/g, higher than that found for CF.

Fig 5. (A) Removal efficiency and (B) adsorption capacity of PS Microplastics adsorption on CF-H.



For the results obtained (Fig 5), pseudo-first (eq. 3) and pseudo-second (eq. 4) order kinetic model were applied, as shown in Table 1.

$$\ln(q_e - q_t) = \ln q_e - K_1 t \quad (3)$$

$$\frac{t}{q_t} = \frac{1}{K_2 {q_e}^2} + \frac{t}{q_e} \quad (4)$$

Table 1. Values of pseudo-first-order and pseudo second-order parameters for MPS adsorption.

Models	Parameter	2 g/L
Pseudo – first order	K_1 (h^{-1})	0.12
	R^2	0.96
	Q_e (mg/g)	0.44
Pseudo second order	K_2 (g/mg) h^{-1}	0.57
	R^2	0.88
	Q_e (mg/g)	0.52

The pseudo-first-order kinetic model provided the best fit to the experimental data, with R^2 = 0.96, indicating that physical adsorption played a dominant role in the process [15]. Following the adsorption kinetics, an adsorption isotherm study was conducted at 25 °C. The experimental results (Fig. 6) were adjusted using the Langmuir (Eq. 5) and Freundlich (Eq. 6) models, as presented in Table 2.

$$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m} \quad (5)$$

$$q_e = K_F \, C_e^{1/n} \quad (6)$$

As observed in Table 2, the Langmuir model (R^2 = 0.96) was more consistent with the experimental results, indicating that monolayer coverage was the main mechanism [15].

Table 2. Parameters of adsorption isotherms

Isoterms	Parameter	25 °C
Langmuir	K_L (L mg^{-1})	0.20
	R^2	0.96
	Q_m (mg/g)	0.40
Freundlich	K_F [(mg. g^{-1})/mg. $L^{-1})^{-1/n}$]	0.1
	R^2	0.92
	1/n	0.41

4. Conclusions

This study demonstrates the potential of coconut fiber (CF), particularly after acid pretreatment (CF-H), as an effective adsorbent for the removal of polystyrene (PS) microplastics from aquatic environments. The results showed that CF-H exhibited a higher adsorption capacity, reaching 0.42 mg/g, which is significantly greater than that of untreated CF. The adsorption process was best described by the pseudo-first-order kinetic model. Furthermore, the Langmuir isotherm provided the best fit for the adsorption data, suggesting monolayer coverage of the microplastics on the fiber surface. These findings highlight the viability of using acid-pretreated coconut fiber as a sustainable and low-cost material for the removal of microplastics from water, offering an eco-friendly solution to mitigate the increasing pollution caused by these contaminants.

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