



Adsorption of perfluorosulfonic acids (PFSAs) on an ultrafine potato peel waste grafted β -cyclodextrin (UFPPW- β -CD)

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ABSTRACT

Per- and polyfluoroalkyl substances are widely used in various consumer products. However, these compounds can cause various harm to the environment and health. Considering the high chemical stability, these compounds are not completely removed from the aqueous environment, and consequently, recent studies have detected their presence in water bodies. In this scenario, biomass-based adsorbents are promising. β -cyclodextrin (β -CD) was grafted in an ultrafine potato peel waste (UFPPW) to produce a novel, efficient, and sustainable adsorbent (UFPPW- β -CD) that was used to remove three different perfluorosulfonic acids (PFSAs) from water. The efficient grafting was proved by several characterization techniques, which also demonstrated the main UFPPW- β -CD features. The UFPPW- β -CD was efficient for all PFSAs (perfluorohexanesulfonic acid (PFHxS), perfluoropentanesulfonic acid (PFPeS), and perfluorobutanesulfonic acid (PFBS)), with removal percentage higher than 74 %. The increase in the C—F chain of PFSAs favored the adsorption due to the host–guest hydrophobic interactions between the C—F chains of the adsorbates and the hydrophobic cavity of the β -CD. Removal percentages and adsorption capacities at pH 3.0 were 74.6 % ($49.92 \mu\text{g g}^{-1}$) to the PFBS, 82.6 % ($65.66 \mu\text{g g}^{-1}$) to the PFPeS, and 90 % ($100.89 \mu\text{g g}^{-1}$) to the PFHxS. The kinetic followed the General order model, while the equilibrium agreed with the Sips isotherm. The adsorption capacity increased with the increase in the C—F chain of the adsorbate, but the adsorption rate followed the opposite trend. PFSAs adsorption on the UFPPW- β -CD adsorbent was favorable and exothermic. UFPPW- β -CD could be used seven times, keeping its maximum adsorption capacity constant using ultrasound-assisted desorption. It can be concluded that UFPPW- β -CD is a sustainable adsorbent to uptake PFSAs from water, and this process is dependent on the size of the C—F chains.

1. Introduction

Organic micropollutants, including pesticides, personal care

products, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), etc., are anthropogenic compounds regularly detected in surface water at ng L^{-1} to $\mu\text{g L}^{-1}$ concentrations [1]. As surface water is habitually

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exploited for water drinking, the occurrence of organic micropollutants, even at trace concentrations, has raised growing concerns about drinking water safety and consumers' health [2]. During the past years, PFAS have gained significant disquietude owing to their harmful effects on human health (cancers, women's infertility, children's developmental effects, decreased immunity, etc.) besides their wide distribution and persistence in water sources [3]. The environmental persistence of PFAS and their bioaccumulation result from their highly stable chemical structure, making them difficult to be hydrolyzed, photodegraded, and biodegraded [4]. PFAS are a wide class of chemicals with a perfluoroalkyl moiety where fluorine atoms have replaced all hydrogen substituents on the carbon chains. The enormously strong C—F bonds make PFAS extremely resistant to degradation [5]. In addition to the hydrophobic perfluoroalkyl tail, most PFAS contain a polar functionality formed by a carboxylic or sulfonic acid group for perfluorocarboxylic acids (PFCAs) and perfluorosulfonic acids (PFSAs), respectively. PFSAs remarkably have longer half-lives compared to PFCAs with the same perfluorinated carbon chain length, making them with more damaging environmental and health effects [5,6].

To date, several methods have been established to remove hazardous pollutants, including hydrothermal separation/crystallization [7,8], nanofiltration [9–11], catalytic degradation [12–14], diverse membrane technologies [15–17], adsorption [18], etc. In this context, concerns about the PFSAs have encouraged researchers to implement advanced treatment technologies, including electrocoagulation [19], hybrid nanofiltration and UV-sulfite technologies [20], ion exchange [21], etc. Compared to these technologies, which have some feebleness, mainly high cost and energy consumption, adsorption is a further advantageous method for removing PFSAs from water [3,20,21].

From a sustainability perspective, biomass-based adsorbents are promising due to their inexhaustible availability, low cost, and environmental friendliness. In particular, cyclodextrin-based adsorbents obtained by green crosslinking or grafting of β -cyclodextrins (β -CDs) onto biowaste materials have attracted more and more worldwide attention in water treatment [22–24]. β -CDs are cyclic oligosaccharides formed by seven glucose units and have a hydrophobic inner cavity and hydrophilic surface, which are easily produced by starch degradation using the cyclodextrin glucanotransferase enzymes [25,26]. In addition, β -CDs are characterized by their cheapness, biodegradability, availability, and host–guest inclusion complex forming capacities with a large range of hydrophobic compounds [27,28]. So far, some crosslinked β -CDs-based polymers have been reported to be efficient in mainly removing long-chain PFSAs, namely the perfluorooctanesulfonic acid [29,30]. However, such polymers have been prepared using harmful crosslinkers and chemicals. Many factors should be addressed before selecting the adsorbents for large-scale implementation, including simplicity of design, efficiency, lifetime, cost, desorption/regeneration, and environmental friendliness [20]. Hence, there is still a need for laboratory development of novel, sustainable, green, low-cost, and easy-designed cyclodextrin-derived adsorbents to competently remove PFAS.

The current study adopted a green and low-cost process to develop a polymer (UFPPW- β -CD) by citric acid grafting of β -CDs onto an ultrafine powder obtained from dried potato peel waste (UFPPW). Indeed, discarded potato peels are abundant, daily available, zero-cost waste and their valorization is needed to avoid the negative environmental effects associated with their management by landfilling [31,32]. In addition, citric acid used here as a grafting agent is an inexpensive and eco-friendly polycarboxylic acid. The generated UFPPW- β -CD polymer was then characterized and investigated for the adsorptive removal of persistent PFSAs from aqueous solutions.

2. Materials and methods

2.1. Development of an ultrafine potato peel waste crosslinked β -cyclodextrin (UFPPW- β -CD)

UFPPW- β -CD polymer was developed as follows: Firstly, β -CDs were produced by the enzymatic conversion of starch valorized from potato peels [25]. In parallel, to avoid landfill after starch extraction, the residual potato peel waste was dried at 70 °C and then ground to obtain an ultrafine powder (UFPPW). Afterward, 6 g of this fine powder was mixed in 250 mL of distilled water with 6 g of β -CDs, 6 g of anhydrous citric acid (crosslinker), and 3 g of KH_2PO_4 (catalyst). The mixture was vigorously stirred for 30 min at 60 °C, filtered using a sieve (200 μm), and then heated at 140 °C for about 6 h until dryness. Subsequently, the UFPPW- β -CD polymer was washed several times with distilled water, dried overnight at 50 °C, and kept in an airtight container until use.

2.2. Characterization of UFPPW- β -CD

The precursors UFPPW, β -CD, and the adsorbent (UFPPW- β -CD) were characterized to prove the grafting reaction and demonstrate the new adsorbent's main features. Characterizations were made using FTIR, XRD, TGA, SEM, and EDS techniques according to the common procedures used in the ENGEPAC group to characterize powdered adsorbents. Details can be found in the [supplementary file](#) (S1). The active β -CD and the total carboxyl contents of the UFPPW- β -CD polymer were determined as previously detailed [33].

2.3. Preparation and quantification of the PFSAs solutions

Three PFSAs were used as target adsorbate molecules as follows: perfluorohexanesulfonic acid (PFHxS), perfluoropentanesulfonic acid (PFPeS), and perfluorobutanesulfonic acid (PFBS), all purchased from Sigma-Aldrich. [Table 1](#) shows the main features of these molecules. All solutions were prepared with deionized water and stored in amber flasks until use. The work solutions were prepared from a stock solution with a higher concentration (2.00 mg/L).

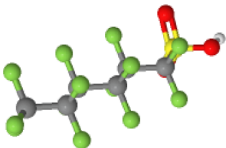
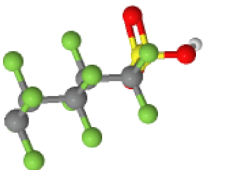
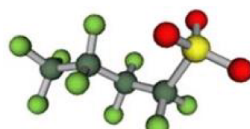
High-performance liquid chromatography (HPLC) was used to quantify the adsorbate molecules. It used an 1100 Series Agilent Technologies liquid chromatographer system (Japan) equipped with a G1312A binary pump, a G1379A vacuum degasser, and a G1313A autosampler with 100 positions for 2 mL vessels (PTFE/silicon septum, Clear vial, Agilent Technologies) coupled with inductively coupled plasma triple quadrupole mass spectrometer (8800 ICP-QQQ, Agilent Technologies).

2.4. PFSAs adsorption experiments

Adsorption experiments were carried out in triplicate and using blanks, according to the ENGEPAC group standards. It used 250 mL Erlenmeyers flasks fed with the adsorbent-adsorbate-water systems and stirred in a thermostated shaker (SOLAB, SL 222). At first, it was evaluated the pH effect on adsorption (pH from 1.0 to 7.0), using 1.00 g/L of UFPPW- β -CD dosage, the volume of the solution of 50 mL, 200 rpm, 298 K, 2 h, and initial PFSAs concentration of 50.0 $\mu\text{g/L}$. Then, in the best pH, kinetic curves were constructed, varying the contact time from 0 to 240 min. These curves were performed using 1.00 g/L of UFPPW- β -CD dosage, the volume of the solution of 50 mL, 200 rpm, 298 K, and an initial PFSAs concentration of 50.0 $\mu\text{g/L}$. Finally, four isotherm curves were obtained at 298, 308, 318, and 328 K. For the isotherms, pH, and contact time were fixed according to the previous experiments, 1.00 g/L of UFPPW- β -CD dosage was used, the volume of the solution was 50 mL, the stirring was 200 rpm, and an initial PFSAs concentration ranged from 0 to 70.0 $\mu\text{g/L}$. Removal percentage (R, %) and adsorption capacity (q , $\mu\text{g g}^{-1}$) were used to evaluate the adsorption ([supplementary file](#), S2).

Table 1

Main features of the PFSA's used in this work.

Acronym	Formula	Structure	Molecular weight (g/mol)	Water solubility (mg/L)
PFHxS	C ₆ HF ₁₃ O ₃ S		400.11	21.73
PFPeS	C ₅ HF ₁₁ O ₃ S		350.10	443.33
PFBS	C ₄ HF ₉ O ₃ S		300.90	510.00

2.5. Adsorption modeling

The adsorption calculations were performed using traditional mathematical modeling. For more details, see [supplementary information](#) ([supplementary file](#), S3-S6).

2.6. Desorption and reuse tests

Several adsorption–desorption cycles were performed to verify the possibility of reusing the UFPPW- β -CD. In this case, the adsorption was performed in a jar test with the volume of the solution of 500 mL, pH 3.0, contact time 6 h, 298 K, 200 rpm, an adsorbent dosage of 1 g L⁻¹, and initial adsorbate concentration of 70 μ g L⁻¹. In these conditions, the adsorption capacities were 64.4 μ g g⁻¹ for PFHxS, 52.0 μ g g⁻¹ for PFPeS, and 42.0 μ g g⁻¹ for PFBS. Desorption was performed using acetone since the PFSA's solubility, in this case, is in the order of 50 g L⁻¹. Besides, it was used an ultrasonic equipment to intensify the process. For instance, 0.500 g of the loaded adsorbent was placed in a beaker with 50 mL of acetone. This beaker was inserted in a thermostated bath at 328 K. Then, the mixture was submitted to ultrasound using a UP200Ht portable US titanium probe (diameter of 7 mm and approximate length of 95 mm) (Hielscher) (frequency of 26 kHz, ultrasonic power of 200 W, pulse 40 % and amplitude 80 %). This cycle was repeated 10 times. Results were presented regarding desorption percentage and adsorption capacity in each cycle.

3. Results and discussion

3.1. Characteristics of UFPPW- β -CD

In the current study, a green and low-cost UFPPW- β -CD polymer was produced by β -CD grafting on potato peel fibers using citric acid cross-linkage ([Fig. 1](#)), giving a synthesis yield of about 50 %. The total carboxyl content was evaluated as 4.54 mmol g⁻¹, which can provide the polymer with numerous anionic charges. In addition, the active β -CDs content was estimated to be 0.126 mmol g⁻¹, which is expected to supply enough binding sites for hydrophobic pollutants.

FTIR analysis ([Fig. 2a](#)) validated the grafting by esterification links between carbohydrates hydroxyl groups and citric acid carboxylic groups since the UFPPW- β -CD polymer spectrum showed the appearance of a novel band at 1726 cm⁻¹ correlated to the stretching vibration of carboxyl ester groups, which confirm the crosslinking reaction between UFPPW and β -CD. While this band is absent in the raw materials used for the polymer synthesis, both β -CD and ultrafine potato peel waste (UFPPW) showed similar profiles with similar adsorption bands. In particular, the absorption bands at approximately 3380 cm⁻¹, 2926 cm⁻¹, 1647 cm⁻¹, 1157 cm⁻¹, and 1028 cm⁻¹, which are assigned to the symmetric and asymmetric stretching vibration of OH groups, the C–H stretching vibration, the H–O–H bending, the asymmetric C–O–C stretching vibration, and the symmetric C–O–C stretching vibration, respectively [33,34]. As for the β -CD oligosaccharide formed by seven linked glucose units, the occurrence of these functional group characteristic bands in potato peel waste indicated that this waste is rich in glucose-based carbohydrates herein starch, cellulose, and hemicellulose [35].

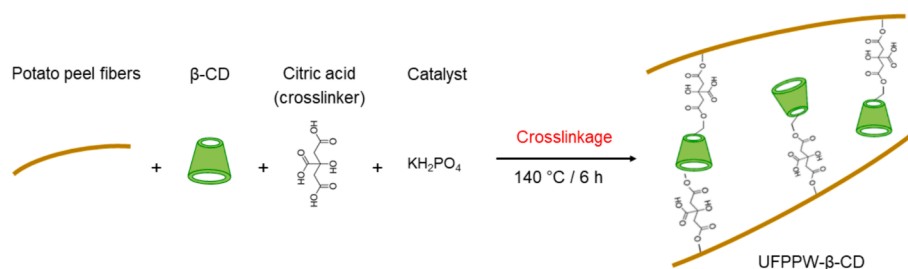


Fig. 1. Simplified schematic representation of the β -CD grafting process on UFPPW by citric acid crosslinkage.

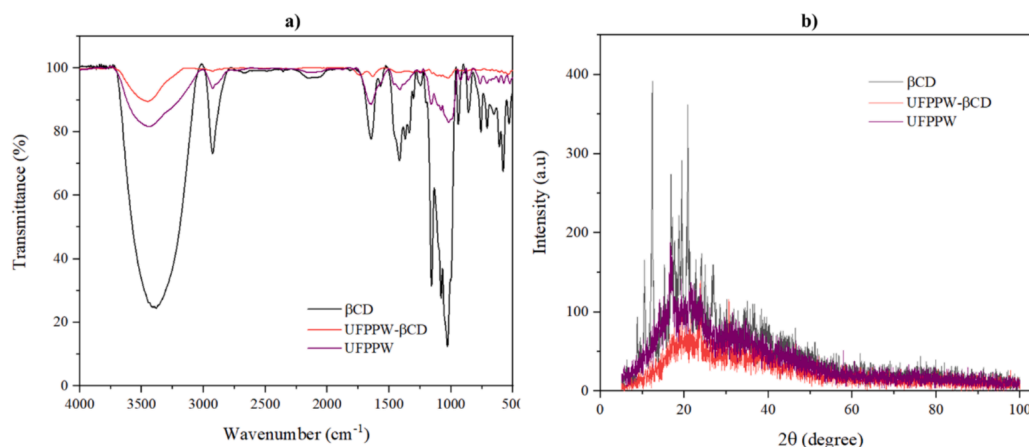


Fig. 2. FTIR (a) and XRD (b) spectra of β -CD, UFPPW- β -CD and UFPPW.

XRD analysis (Fig. 2b) showed that β -CDs have many sharp and intense diffraction peaks (mainly at 12.3, 16.8, 19.3, and 20.8°), indicating a clear crystalline nature as already reported [36,37]. The XRD pattern of UFPPW showed distinctive peaks (mainly at 16.6 and 22.1°) assigned to the cellulose I crystalline structure [38]. The UFPPW- β -CD polymer displayed a diffuse diffraction pattern with mainly two distinctive and moderate peaks at 23.78 and 30.62° as well as the disappearance of characteristic peaks of β -CD and cellulose I, indicating the interaction between them via citric acid grafting.

A TGA study was performed to evaluate the thermal stability of the samples. As shown in Fig. 3, β -CD and UFPPW showed similar profiles with two zones of weight loss. The first zone, with a minor weight loss at around 100 °C, is attributed to superficial water evaporation. In contrast, the second zone with a significant weight loss at approximately 305 °C is assigned to the organic matter degradation [37]. The UFPPW- β -CD polymer remarkably showed better thermal stability, especially at temperatures under 180 °C and above 310 °C, indicating that the synthesis of composite improved the stability of isolated compounds. The TGA result is similar to those reported in the literature. Yuan et al. [39] synthesized the β -cyclodextrin-carboxymethyl cellulose-graphene oxide composite. The thermogravimetric analysis showed that the material exhibited higher thermodynamic stability. Similarly, citric acid crosslinked natural bi-polymer-based composite hydrogels also showed better thermal stability after the crosslinking reaction [40].

The SEM analysis was performed to examine the surface morphology

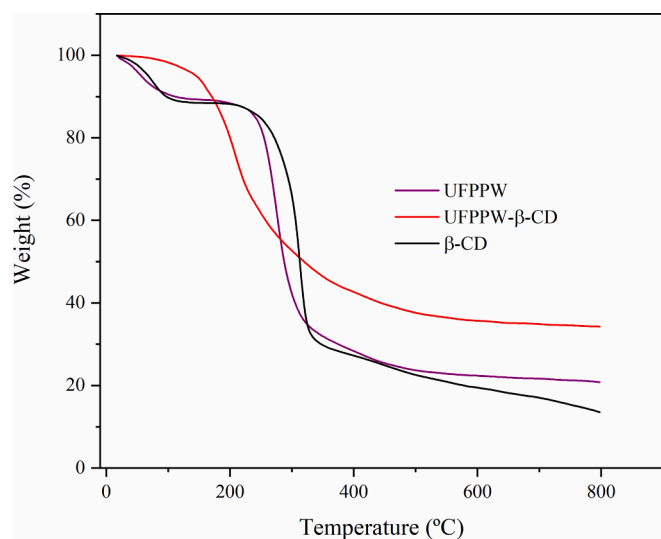


Fig. 3. TGA curves of β -CD, UFPPW- β -CD and UFPPW.

feature of the polymer (Fig. 4). The SEM image at a magnification of 250x showed that the polymer surface is principally covered by globular structures with irregular shapes (Fig. 4a). The SEM image at higher magnification (10kx) showed that the surface is rough with the occurrence of some cavities of variable size (Fig. 4b). Such cavities may have a key role in the adsorbates diffusion to the small pores inside the polymer, facilitating the pollutants uptake (see Fig. 4).

The EDS spectrum (Fig. 5) showed that carbon ($\approx 48\%$) and oxygen ($\approx 38\%$) are the main organic elements found in the polymer matrix.

3.2. pH effect and PFASs adsorption mechanism

The pH effect on PFASs adsorption performance is shown in Fig. 6. As observed, it was possible to infer that the removal efficiency for all pollutants was affected by the increase in the pH solution. For instance, the PFHxS adsorption decreased from 91 % to 78 % when the pH increased from 3.0 to 7.0. Also, the removal percentage values increased with the size of the chain of PFAS.

The perfluoroalkyl acids are anionic molecules commonly found in wastewater. Some mechanisms were proposed considering this behavior and the pH effect on the PFASs adsorption processes. Remarkably, the acidic conditions favored the interaction between adsorbent and adsorbate molecules (high values for removal efficiency). In these conditions, both PFASs and UFPPW- β -CD carboxylic groups are neutral or protonated. Therefore, it is inferred that hydrogen bonds may be involved in the process at acidic pH. With the pH increase, the adsorption decreases to some extent which could be associated with the weakening of hydrophobic interactions. Deng et al. [41] also observed similar behavior to remove PFAS substances from the aqueous medium using biochar composites. Taking into account that the removal percentage remained significant above pH 3.0 (pH of ionization of carboxylic groups) and that long chains PFASs (herein PFHxS) were higher adsorbed thereby, the hydrophobic interactions via host-guest interactions could be the main mechanisms to explain the adsorption performance [3,42].

Fig. 7 shows how hydrophobic molecules are embedded into the inner hydrophobic cavity of β -CD via host-guest interactions (note that the outer surface of β -CD is hydrophilic). Recently was described that Per- and polyfluoroalkyl substances can be adsorbed by different mechanisms, including electrostatic interactions, host-guest interactions, and ionic exchange. The adsorption mechanisms depend on pH, adsorbent characteristics, and adsorbate charge. Also, it was related that PFAS with longer chains tend to form aggregate structures on the adsorbent surface by hydrophobic interactions, while PFAS molecules with lower hydrophobicity follow the diffusion into the pores and electrostatic interactions [43]. Corroborating these assumptions, Wang et al. [44] reported in an interesting study that the shorter-chain PFAS

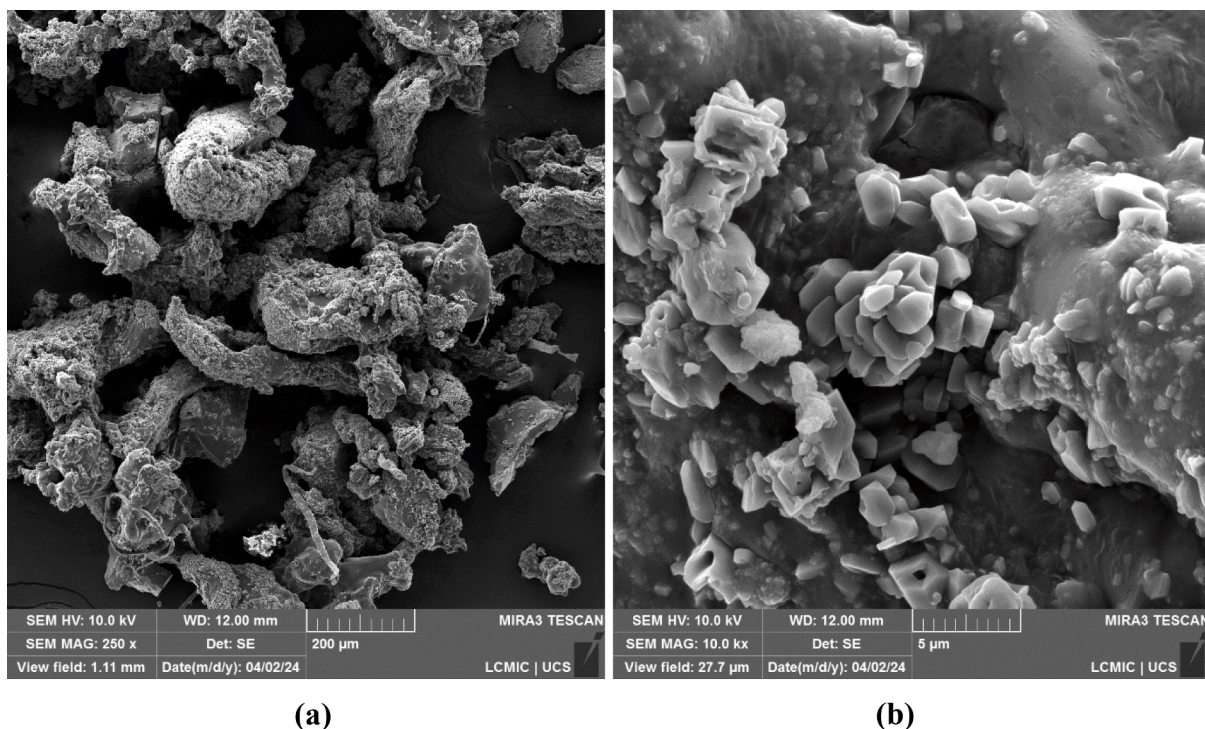


Fig. 4. SEM images of the UFPPW- β -CD polymer at 250 $\times$ (a) and 10000 $\times$ (b) magnifications.

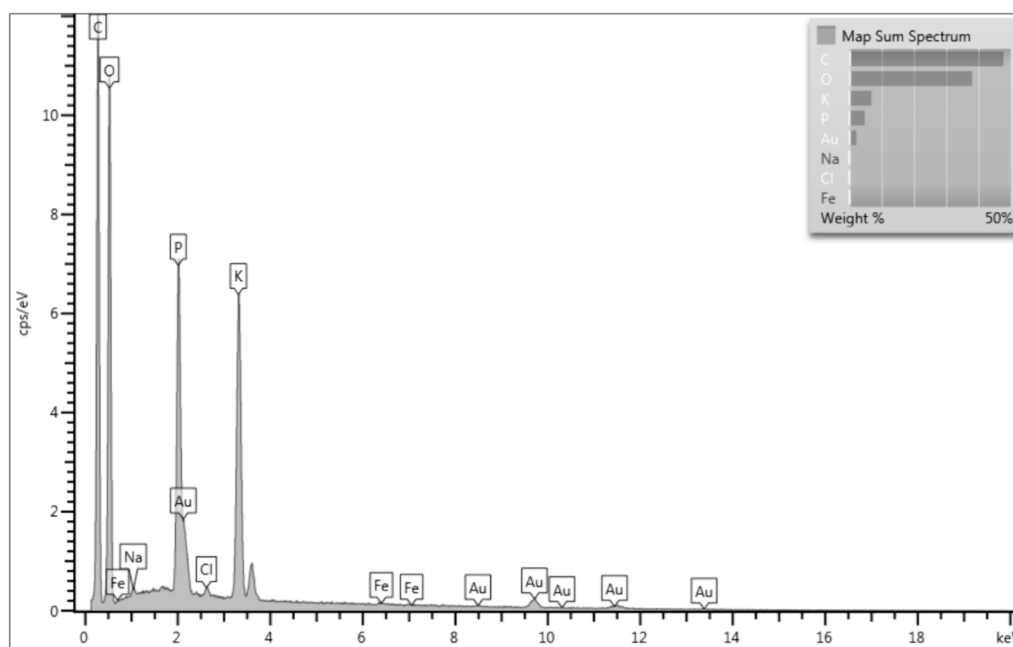


Fig. 5. EDS spectrum of the UFPPW- β -CD polymer.

are more difficult to adsorb and relies most strongly on electrostatic interactions. Meantime, the longer-chain PFAS are easily adsorbed by hydrophobic interactions.

3.3. PFASs adsorption kinetics

The kinetic data of all adsorptions were adjusted using the traditional kinetic models (pseudo-first-order, pseudo-second-order, and general order). According to kinetic parameters summarized in Table S1, it was possible to verify that the general order model described well the

experimental data of all pollutants (PFHxS, PFPeS, and PFBS) due to high values for determination coefficients. This model assumes that the adsorption onto the adsorbent surface is the rate-controlling step [45].

The kinetic curves for PFASs adsorption onto UFPPW- β -CD are displayed in Fig. 8. The adsorption kinetic exhibits a typical behavior in three steps. Initially, a high adsorption rate is verified, followed by a slow stage until it reaches the equilibrium. Also, the adsorbent presented a high adsorption capacity for the PFHxS removal. This result can be attributed to the size of the chain, showing the involvement of hydrophobic interactions [46].

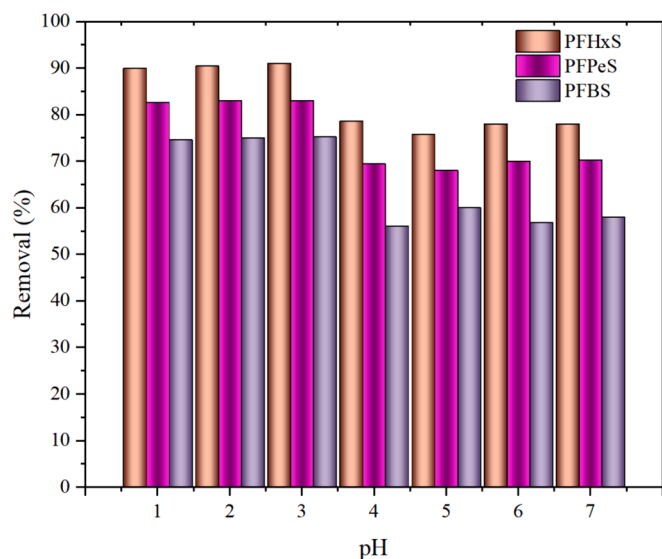


Fig. 6. Ph effect on pfsas adsorption.

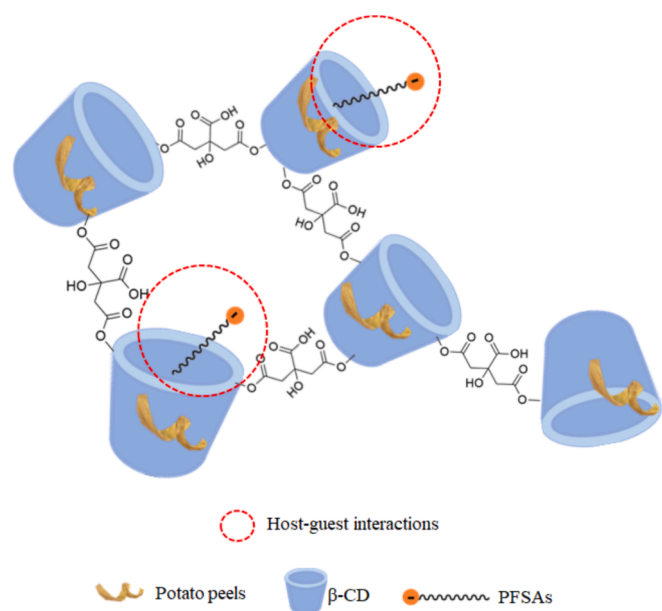


Fig. 7. Potential adsorption mechanism of PFASs onto UFPPW-βCD.

3.4. PFASs adsorption isotherms

The equilibrium data of three adsorptions were adjusted using the Langmuir, Freundlich, and Sips models. The equilibrium parameters for PFHxS, PFPeS, and PFBS adsorptions are shown in Table S2, S3, and S4, respectively. According to parameter values, it can be inferred that the Sips isotherm model was more suitable to describe the adsorption equilibrium data for all adsorbates than other models [47]. Similarly, Deng et al. [41] reported that the PFAS adsorption onto biochar composites was well described by Sips and Langmuir-Freundlich isotherm models. The maximum adsorption capacities estimated by these models were higher than $\geq 264 \text{ mg g}^{-1}$.

Regarding the adsorption capacity value calculated from the Sips model, it was observed that the adsorbent exhibited high performance to remove the PFHxS compared to other PFASs (Figs. 9–11), which can be attributed to better interaction between adsorbate and adsorbent molecules. In addition, the adsorption capacity and the Sips constant (K_s) values of all adsorptions decreased with an increase in the system's

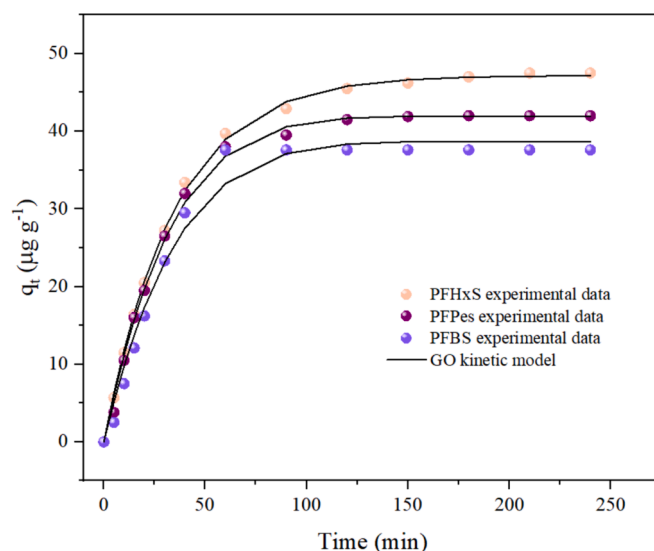


Fig. 8. Kinetic profiles for PFASs adsorption onto UFPPW-βCD.

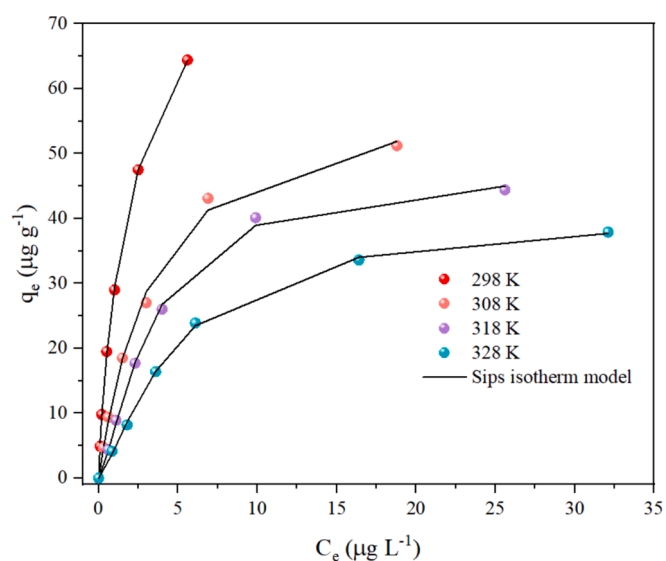


Fig. 9. Fitting the isotherms data (PFHxS) with the Sips model.

temperature, which indicates that the processes are exothermic adsorptions corroborating with thermodynamic study. At the same time, the values for the heterogeneity factor ($m_s > 1$) indicate that processes occurred at heterogeneous surfaces [48]. Finally, all isotherm curves were convex concerning the y-axis. This trend confirms the effectiveness of the new adsorbent since the adsorption is favorable, and interesting capacity values can be found together with low values of final concentration in the liquid phase. The maximum adsorption capacities were 100.89 , 65.66 , and $49.92 \mu\text{g g}^{-1}$ for PFHxS, PFPeS, and PFBS, respectively.

The adsorption capacity values for PFHxS, PFBS, and PFPeS adsorption were compared with other adsorbent materials. Based on the results shown in Table 2, it was possible to verify that UFPPW-βCD exhibited excellent adsorption performance.

3.5. PFASs adsorption thermodynamics

Thermodynamic parameters for PFHxS, PFPeS, and PFBS are summarized in Table 3. According to the data, it was possible to infer that all adsorptions were spontaneous ($\Delta G^0 < 0$) and thermodynamically

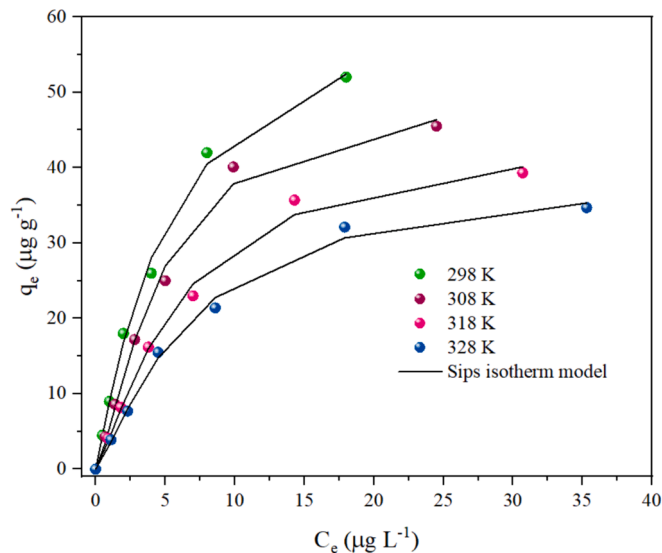


Fig. 10. Fitting the isotherms data (PFPeS) with the Sips model.

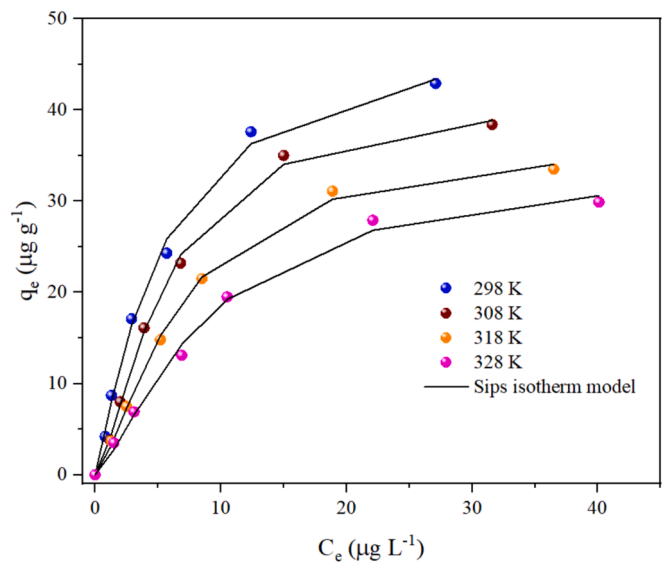


Fig. 11. Fitting the isotherms data (PFBS) with the Sips model.

Table 3

Thermodynamic parameters for PFASs adsorption onto UFPPW-β-CD.

	T (K)	K _e	ΔG ⁰ (kJ/ mol)	ΔH ⁰ (kJ/ mol)	ΔS ⁰ (kJ/mol K ⁻¹)
PFHxS	298	164528.80	-29.77	-32.56	-0.009
	308	115549.74	-29.86		
	318	76110.57	-29.73		
	328	49671.44	-29.50		
PFPeS	298	55935.39	-27.09	-16.06	0.036
	308	42403.02	-27.29		
	318	35373.30	-27.70		
	328	30843.26	-28.20		
PFBS	298	42366.77	-26.40	-27.21	-0.003
	308	24426.99	-25.88		
	318	19935.40	-26.18		
	328	14938.65	-26.22		

liquid–solid interface. The magnitude of the ΔH^0 values indicated that all adsorptions are mainly governed by physisorption mechanisms [52]. Hydrogen bonds and host–guest interactions are physical forces, so thermodynamic results confirm the PFASs interaction mechanism with the new adsorbent.

3.6. Desorption and reuse of UFPPW-β-CD

It was tested acetone as a chemical eluent because PFASs solubility, in this case, is in the order of 50 g/L. H-bonds and host–guest interactions are expected to weaken or corrupt, releasing the adsorbates into the eluent. So, PFASs could be recovered, and the adsorbent could be reused. Besides, the desorption process was intensified using ultrasound. Results revealed that the desorption percentage of all adsorbates was higher than 96 % after only 25 min of operation. These results confirm the break of H-bonds and host–guest interactions and the effectiveness of our proposed desorption process.

Adsorption-desorption cycles were repeated 10 times, and the results of the adsorption capacity for each cycle are presented in Fig. 12. For all PFASs, the adsorption capacity remained constant and maximum until the 7th cycle. After this, adsorption decreased until the 10th cycle. It was observed that after the 7th cycle, the ultrasound destroyed the adsorbent, leading to a great mass loss and making the process non-viable. It

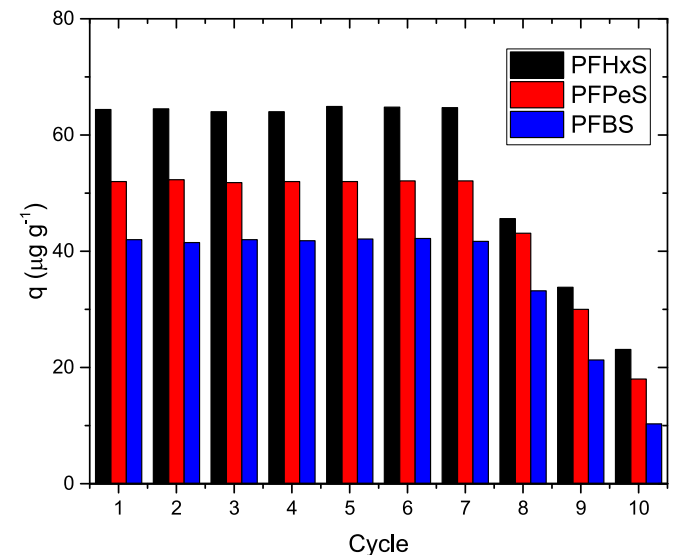


Fig. 12. Adsorption capacity of UFPPW- β-CD during several adsorption-desorption cycles.

Table 2

Comparison of PFAS adsorption performance of different adsorbents.

Adsorbent	Adsorbate	q _{max} (µg/g)	References
Bio-based polyurethane /chitosan(PU/CH) adsorbent	PFHxS	61.83	[49]
	PFBS	52.94	
Chitosan/polyethyleneimine xerogel	PFBS	305 mg g ⁻¹	[50]
Organo-montmorillonites	PFHxS	179.60 mg g ⁻¹	[51]
	PFBS	59.20 mg g ⁻¹	
UFPPW-βCD	PFBS	49.92	This work
	PFPeS	65.66	
	PFHxS	100.89	

favorable. The negative values for standard enthalpy change indicated the exothermic nature of processes. Also, the entropy value revealed that the adsorption of PFHxS and PFBS presented a decrease in randomness after the adsorption, while for the PFPeS removal onto UFPPW-βCD, the positive value for ΔS^0 showed an increase in the randomness at the

can be concluded that UFPPW- β -CD is an efficient and reusable adsorbent for the PFASs, keeping the maximum potential for 7 adsorption-desorption cycles. Methods combining thermal and chemical desorption were used by Deng et al. [41]. The adsorbent regeneration was performed at 50 °C for 12 h following the use of NaI/NaOH solutions for the complete desorption. The removal efficiency remained around 70 % after five cycles of adsorption/desorption. The electro-sorption method was used to regenerate graphite after PFAS adsorption [53]. The outcomes showed that adsorbent material exhibited an adsorption efficiency varying between 60–80 % after five cycles of desorption.

4. Conclusion

This study successfully synthesized the UFPPW- β -CD adsorbent through the grafting reaction between β -CD and ultrafine potato peels to remove PFASs from aqueous solutions. The active β -CDs and total carboxyl content were evaluated as 0.126 mmol g⁻¹ and 4.54 mmol g⁻¹, respectively. The characterization data showed the esterification links by the appearance of a new absorption band at 1726 cm⁻¹, confirming the presence of ester function. Also, XRD results displayed the disappearance of the characteristic peaks of β -CD and cellulose I, indicating their interaction via citric acid grafting. Thermal analysis revealed that the adsorbent presented good thermal stability, especially at temperatures under 180 °C and above 310 °C.

UFPPW- β -CD efficiently adsorbed PFASs with percentage removal values higher than 75.2 % using an initial pollutant concentration of 50 μ g/L and an adsorbent dosage of 1.0 g/L at pH 3.0 and 298 K. Based on the results pH effect on the adsorption, it can be supposed that the adsorption phenomenon is governed by hydrogen bonding and hydrophobic interactions. The thermodynamic and desorption results proved these interactions. The adsorption kinetics followed the general order model, while the Sips isotherm described adsorption equilibrium data. Thermodynamic parameters revealed that removing PFASs in UFPPW- β -CD was spontaneous and exothermic. Furthermore, the magnitude of the enthalpy change values indicated that the adsorption involved physisorption mechanisms. The system acetone/ultrasound provided a 96 % desorption percentage in 25 min. The adsorbent could be used 7 times with the same adsorption capacity.

The outcomes clearly indicated that UFPPW- β -CD is a sustainable, green, and cost-effective biomaterial that holds promise for PFASs adsorption. However, there are still challenges ahead. One is to improve the uptake of PFASs with small tails, low molecular weight, and high water solubility via further engineering of the adsorbent. In addition, it is necessary to have an assessment of the actual performance of the adsorbent based on the actual use of the wastewater matrix to investigate competitive adsorption or potential interference with other contaminants in water samples. Further investigations are also needed for the development of UFPPW- β -CD scale-up production for wastewater treatment plants or simply as a tap water filter useful in everyday life.

CRediT authorship contribution statement

Franciele da Silva Bruckmann: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonia Jemli:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fakhreddine Ben Amara:** Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Bashir Adelodun:** Software, Resources. **Luis Felipe Oliveira Silva:** Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition. **Samir Bejar:** Resources, Project administration, Methodology, Investigation, Conceptualization. **Mohammad Rizwan Khan:** Project administration, Funding acquisition. **Naushad Ahmad:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Conceptualization.

Gladyson Simões dos Reis: Visualization, Validation, Supervision, Software, Formal analysis. **Guilherme Luiz Datto:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seppur.2024.127972>.

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