MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES

INVESTIGATION OF PHARMACEUTICALS ADSORPTION PERFORMANCE OF A NOVEL FUNCTIONALIZED CELLULOSE BASED ADSORBENT

SAMUEL KALULE

MASTER THESIS
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Prof. Dr. Zehra Semra CAN

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ÖZET

FONKSİYONELLEŞTİRİLMİŞ SELÜLOZ ESASLI YENİLİKÇİ BİR ADSORBENTİN FARMASÖTİK ADSORPSİYON PERFORMANSININ İNCELENMESİ

İlaçlardan oluşan giderek artan sayıda organik kirletici, çevre ve toplum için endişe verici bir tehdit haline gelmiştir. İlaçlar genellikle çok küçük konsantrasyonlarda bulunur ve atık su arıtma tesislerinden geçerek çevreye yayılabilirler. Bu çalışmada, selüloz bazlı yenilikçi bir adsorban ile sudan adsorpsiyon yolu ile giderimini araştırmak için üç yaygın ilaç türü seçilmiştir. Farmasötik içeren çeşitli ilaçlar, kişisel bakım ürünleri veya endüstri bileşikleri atık su sistemlerine atılmaktadır. Organik mikrokirleticilerin sulardan uzaklaştırılması için çeşitli teknolojiler ve yöntemler tasarlanmış ve uygulanmıştır. Farmasötik kirleticilerin atık sulardan uzaklaştırılması için gelişmiş yöntemler ve mekanizmalar uygulanmaktadır. Bu teknolojiler arasında olumlu etkisi olan, aynı zamanda maliyeti uygun adsorpsiyon yöntemi de bulunmaktadır.

Bu çalışmada, ticari selülozdan selüloz bazlı bir adsorban sentezlenerek, çözelti içinde organik mikrokirleticilerle reaksiyona girme yeteneğini artıran adsorban yüzeyi olarak fonksiyonel gruplar ve hidroksil grupları oluşturmak üzere etkinleştirilmiştir. Adsorbanın adsorpsiyon kapasitesinin değerlendirilmesi için sentezlenen iki adsorban seçilmiştir. Sentezlenen adsorbanlar CAc-PPUF ve CMC-HMPUF, adsorpsiyon kapasitelerini belirlemek için toplu adsorpsiyon deneyleri sırasında test edilmiştir. Her iki adsorban da farmasötiklerin sudan adsorpsiyonu için afiniteye sahiptir ancak CAc-PPUF, üç hedef bileşiğin tümü ile daha yüksek bir adsorpsiyon kapasitesi göstermiştir. CAc-PPUF bileşiğinin yapısı ve özellikleri, Fourier Dönüşümü Kızılötesi Analizi (FTIR), Taramalı Elektron Mikroskobu (SEM), BET yüzey alanı (BET), XRD analizi ve Zeta Potansiyeli kullanılarak analiz edilmiştir. İncelenmekte olan yapı FTIR analizi ile doğrulanmıştır. SEM ve BET analizinden elde edilen veriler sırasıyla 4-9 nm gözenek yarıçapına sahip yüksek gözenekli bir yapı göstermiştir. Hücresel yapıdaki adsorbanın kristal kafesini gösteren XRD verilerine ek olarak, zeta potansiyeli ölçümleri, CAc-PPUF'un sucul ortamda, çeşitli pH değerlerinde, negatif yüzey potansiyeline sahip olduğunu göstermiştir.

İzotermleri incelemek ve değerlendirmek ve en uygun izoterm modelini elde etmek için Langmuir, Freundlich, Sips ve Dubinin-Astakhov izoterm modelleri kullanılmıştır. Tüm

izotermlerin deney sonuçlarını tahmin etme potansiyellerinin oldukça benzer olduğu görülmüştür.

Diklofenak ve karbamazepin için elde edilen denge sorpsiyon verileri, doğrusal olmayan regresyon yöntemi kullanılarak iki parametre izotermleri (Langmuir ve Freundich) ve üç parametre izotermleri (Sips ve Dubinin-Astakhov) ile test edilmiştir. Kirletici maddelerin konsantrasyonunun artmasıyla birlikte CAc-PPUF'un denge adsorpsiyon kapasitesindeki yüksek artışın, adsorpsiyon kapasitelerini etkilediği görülmüştür. Ancak daha sonra çözeltilerdeki denge konsantrasyonlarına göre adsorpsiyon kapasitelerindeki artış yavaşlamaktadır. Test edilen tüm modeller, 0,889'dan büyük R^2 değerlerine ve 0,12'den küçük NRMSE değerlerine sahiptir. Ancak Sips modeli ile daha iyi bir uyum elde edildiği görülmüştür. Adsorpsiyon kinetiği, sabit farmasötük başlangıç konsantrasyonunda, zamana göre CAc-PPUF'un giderilme hızını incelemek amacıyla değerlendirilmiştir. Diklofenak ve ibuprofenin CAc-PPUF üzerindeki adsorpsiyon kinetiğini karakterize etmek için PSO ve Elovich adsorpsiyon mekanizmaları kullanılmıştır. CMC-PPUF ve CAc-PPUF adsorpsiyonları, FTIR ölçümleri ile de desteklendiği gibi nispeten karşılaştırılabilir sonuçlar vermiştir. Dolayısıyla her iki adsorbanın aynı kinetiğe sahip olduğu tahmin edilmektedir. CAc-PPUF tarafından farmasötik adsorpsiyonun hızlı kinetiği, başlangıç zamanında yeterli verinin toplanmasını engellemektedir. PSO kinetik denklemi sonuçları daha yüksek tahmin verimliliğine sahiptir ve PSO modeli temel fonksiyonu ile elde edilen tahmin sonuçları deneysel veriler ile oldukça tutarlıdır.

CAc-PPUF'un rejenerasyonu ve yeniden kullanımı, karbamazepin, ibuprofen ve diklofenakın metanol, etanol ve su ile 4:1:1 oranında desorbe edilmesiyle gerçekleştirilmiştir. Rejenerasyon ve yeniden kullanım döngülerinden sonra karbamazepin, ibuprofen ve diklofenakın giderilme oranları sırasıyla %86-71, %73-66 ve %64-57'dir. Elde edilen veriler, adsorban malzemenin beş rejenerasyon döngüsünden sonra bile adsorpsiyon kapasitesini koruduğunu göstermiştir. CAc-PPUF, mükemmel yeniden kullanılabilirlik ve farmasötiklerin etkili bir şekilde uzaklaştırılması özelliklerine sahiptir.

Anahtar Kelimler: Adsorpsiyon, Selüloz, Farmasötikler, Ibruprofen, Diclofenak, Karbamazepin

Ocak 2024 **Samuel KALULE**

ABSTRACT

INVESTIGATION OF PHARMACEUTICALS ADSORPTION PERFORMANCE OF A NOVEL FUNCTIONALIZED CELLULOSE BASED ADSORBENT

An increasing number of organic pollutants comprising of pharmaceuticals have become an alarming threat to the environment and the community. Pharmaceuticals are usually in very small concentrations and can go through wastewater treatments plants through disposal to the environment. In this study, three common pharmaceuticals were selected to investigate the adsorption from water with a cellulose based adsorbent. Various medications, personal care products or industry compounds contain pharmaceuticals thereby are disposed of to the wastewater systems. Various technologies and methods have been designed and applied for the removal of organic micropollutants from water. Advanced methods and mechanisms have been applied for removal of pharmaceuticals pollutants from wastewater. Among these technologies, is adsorption method which have a positive impact at the same time cost effective.

In this study, a cellulose based adsorbent was synthesized from commercial cellulose and activated to create functional groups and hydroxyl groups as the adsorbent surface that enhanced the ability to react in solution with the organic micropollutants. Two synthesized adsorbents were selected for the evaluation of adsorption capacity of the adsorbent. Synthesized adsorbents CAc-PPUF and CMC- HMPUF were tested during batch adsorption experiments to determine their adsorption capabilities. Both adsorbents had the affinity for the adsorption of pharmaceuticals from water, however, CAc-PPUF showed a higher adsorption capability with all the three target compounds.

CAc-PPUF compound structure and characteristics were analyzed using Fourier Transform Infrared Analysis (FTIR), Scanning Electron Microscopy (SEM), BET surface area (BET), XRD analysis and Zeta Potential. The structure being studied was confirmed by FTIR analysis. Data from SEM and BET analysis showed a high porous structure with pore radius of 4-9 nm respectively. The zeta potential indicated a negative potential of CAc-PPUF and additional to the XRD data that show the crystal lattice of the cellular based adsorbent.

Different isotherm models of Langmuir, Freundlich, Sips and Dubinin-Astakhov were used to study and evaluate the isotherms and get the best fit isotherm model. The results

of the analysis of all the isotherms showed that the predictions were very comparable. Equilibrium sorption data obtained for diclofenac, and carbamazepine were tested for two-parameter isotherms (Langmuir &Freundich) and three-parameter isotherms (Sips and Dubinin-Astakhov) using non-linear regression method. A high increase in the equilibrium sorption capacity of the CAc-PPUF with increasing concentration of the pollutants was found to impact the adsorption capacities. However, later, increase in adsorption capacities with respect to equilibrium concentrations in solutions slows down. All models tested fit with R^2 values greater than 0.889 and NRMSE values less than 0.12. However, a slightly better fitting was achieved by Sips model.

Adsorption kinetics were evaluated to demonstrate the rate of the removal of CAc-PPUF with respect to time at constant initial pharmaceuticals concentration. Adsorption mechanisms, PSO and Elovich were employed to characterize the adsorption kinetics of diclofenac and ibuprofen on CAc-PPUF. CMC-PPUF and CAc-PPUF adsorptions are relatively comparable as indicted by FTIR, hence predicted to have identical kinetics. Rapid kinetics of pharmaceutical adsorption by CAc-PPUF hinder the collection of adequate data initially. PSO kinetics equation results were in greater prediction efficiency and the data collected was consistent with the experimental data with a PSO model base function.

Regeneration and reuse of CAc-PPUF was carried out by desorbing carbamazepine, ibuprofen and diclofenac with methanol, ethanol, and water in the ratio of 4:1:1. After regeneration and reuse cycles, the removal rates of carbamazepine, ibuprofen and diclofenac were 86-71%, 73-66% and 64-57% respectively. The data collected showed that the adsorbent material retained its adsorption capacity even after five regeneration cycles. CAc-PPUF exhibits excellent reusability performance and effective removal of pharmaceuticals.

Keywords: Adsorption, Cellulose, Pharmaceutical, Ibuprofen, Carbamazepine, Diclofenac

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SYMBOLS

C_e : Equilibrium concentration (mg/L)

C_i : Initial concentration (mg/L)

K_F : Freundlich constant ((mg/g)/ (mg/L) n)

K_L : Langmuir constant (L/mg)

K_S : Sips constant (mg/L) $^{(-1/nS)}$

m : Mass (g)

n : Freundlich intensity parameter

q_{calc} : Calculated amount of adsorbate uptake (mg/g)

$q_{DA\ (max)}$: Maximum adsorption capacity estimated from D-A model (mg/g)

q_e : Amount of adsorbate uptake at equilibrium (mg/g)

q_{exp} : Amount of adsorbate uptake, experimental (mg/g)

$q_{exp\ max}$: Maximum amount of adsorbate uptake, experimental (mg/g)

$q_{exp\ mean}$: Mean amount of adsorbate uptake, experimental (mg/g)

Q_{max} : Maximum adsorption capacity calculated from Langmuir model (mg/g)

q_t : Amount of adsorbate uptake at time, t (mg/g)

q^s_m : Maximum adsorption capacity calculated from Sips model (mg/g)

χ^2 : Chi square

Re% : The percent (%) removal efficiency

α : The initial sorption rate constant (mg/g min)

β : The extent of surface coverage and activation energy

1/n : The heterogeneity factor

ABREVIATIONS

GC- MS **:** Gas chromatography–mass spectrometry

AC **:** Activated cellulose

BET **:** Brunauer-Emmett-Teller (BET)

CAc **:** Cellulose acetate

CAc-PPUF **:** Cellulose acetate 1,4-phenylene Polyurethane foam

CMC **:** Carboxymethyl cellulose

CMC-PPUF **:** Carboxymethyl cellulose 1,4-phenylene Polyurethane foam

D-A **:** Dubinin-Astakhov

Fig. **:** Figure

FTIR **:** Fourier Transform Infrared Spectroscopy

NRMSE **:** Normalized root mean square error

OMPS **:** Organic Micropollutants

PPCPS **:** Pharmaceuticals and personal care products

PUF **:** Polyurethane foam

SEM **:** Scanning Electron Microscope

Temp. **:** Temperature (^{o}C)

R^2 **:** Correlation Coefficient

V **:** Volume

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1. INTRODUCTION

1.1. Background

An increasing amount of micropollutants have become an increasing threat to the environment and the public. A variety of micropollutants are organic compounds that are found in the aquatic environments at very low concentrations of nanograms and micrograms per liter (Khoo et al., 2022). One of the sources of these micropollutants are hospital waste that has been found to contain toxic pollutants that are dangerous to both humans and the aquatic life (Ajala et al., 2022).

A lot of research has shown that these pollutants i.e. MPs can enter the aqueous environment mainly from wastewater treatment plants since a lot of the wastewater treatment plants are not fully designed to remove micropollutants. Thus many micropollutants are able to go through the treatment process at low concentrations (Luo et al., 2014). Moreover in trace amounts, these pollutants can also have an impact to the ecosystems of the living organisms and aquatic life (Aniagor et al., 2021). Among the sub groups of micropollutants are pharmaceuticals, care products (PPCPs), pesticides, trace metals, nanoplastics and many more accordingly to the sources (Dev, 2017).

In this study we focused on the removals of pharmaceuticals among the micropollutants that are found in water. Even though they are in trace amounts at very low concentrations, they can easily be transported from various sources to the environment. For example, personal care products and pharmaceuticals that are used domestically for treatment of different infections, and other home applications have been known to reach water systems through different routes. Most common are non-steroidal anti-inflammatory drugs (NSAIDs) like ibuprofen, diclofenac etc. and anticonvulsants such as Carbamazepine.

1.1.1. Environmental Significance of Pharmaceuticals

When water from different homes is used, after disposal it is directed to waste treatment plants however some of the water that is disposed from other sources as seen in Figure 1.1. Moreover, with continuous disposal, these pharmaceuticals can accumulate in wastewater and may have an effect to the eco system (Careghini et al., 2015). Research has found out that some micropollutants have had an impact to some bacteria whereby

bacteria have developed resistance to some antibiotics due to the presence of these pharmaceuticals in there environments (Beryani et al., 2023).

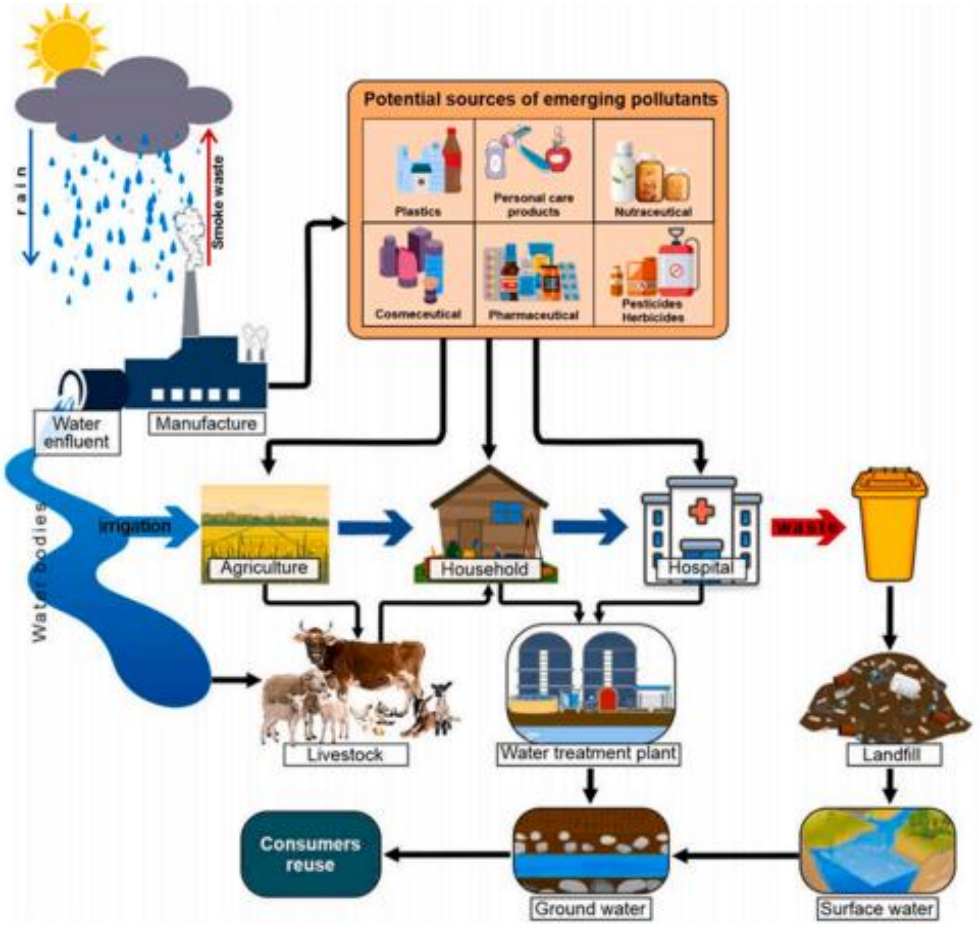


Figure 1.1. Micropollutants route from sources (Miao et al., 2023)

More research and studies are being carried out to determine different methods that can be used to create and develop analytical strategies for detecting low concentrations of pharmaceuticals in water. Some technologies have been invented and improved for water purification such as such as oxidation, photocatalytic degradation adsorption, precipitation, filtration, electrochemical treatment, ion exchange, coagulation & flocculation, solvent extraction, flotation, biological methods etc. (Baig et al., 2021).

Due to the safety and demand for clean water, several conventional methods have been developed and used to purify water. Among these is adsorption which is more applicable as compared to other methods. Adsorption has been found to be highly effective and low costs are incurred. Removal of the pollutants from water can depend on the physiochemical properties of the compound. This approach requires a simple design and

since it is an excellent economical approach for removing pharmaceuticals from wastewater.

In this study, three organic micropollutants were selected as target pollutants i.e. Ibuprofen, Diclofenac, and Carbamazepine. In WWTP effluents, the concentrations reached 0.95 μg/L for carbamazepine, 0.06 μg/L, 0.99 μg/L for diclofenac and 1.3 μg/L for ibuprofen. These pollutants were selected because they are highly used and found in aqueous streams. These pollutants can be discharged in water from pharmaceutical industries, communities, and other sources at low concentrations.

1.1.2. Ibuprofen (IBP)

Among the most used pharmaceuticals in the pharmaceutical industry is 2-[4-(2-methylpropyl) phenyl] propionic acid as seen in Figure 1.1 normally known as ibuprofen. It is usually as an inflammatory drug and one of the most important medications used in the industry (Natalia et al., 2014). In the medical sector the normal doses of Ibuprofen range from 600 to 1200 mg/day. Usually, people take an oral dose of ibuprofen approximately 99% pure form which bonds with plasma and almost 15% of it is excreted by humans as an unchangeable compound (Beryani et al., 2023).

Ibuprofen (IBP) is partially soluble in water at RTP. IBP is a white crystalline solid and soluble in non-polar solvents. Due to the over usage of IBP, it's been found that a concentration of about 24.6μgL can exist in wastewater which is highly risky and dangerous not only for humans but also for the aquatic life. (Kot-Wasik et al., 2007; Miège et al., 2008). Metabolites like carboxyibuprofen, hydroxyibuprofen and carboxyhydratropic acid are also affected and continue to hydrolyze in the environment which can have a positive and negative impact to the environment. As a propionic acid, the structure has a hydrogen at the second position that is substituted with a 4-(methlypropyl) phenyl group. In the Figure 1.2 below, we notice that it is a non-selective inhibitor of Cyclooxygenase-2 (COX-2) and cyclo-oxygenase-1 (COX-1).

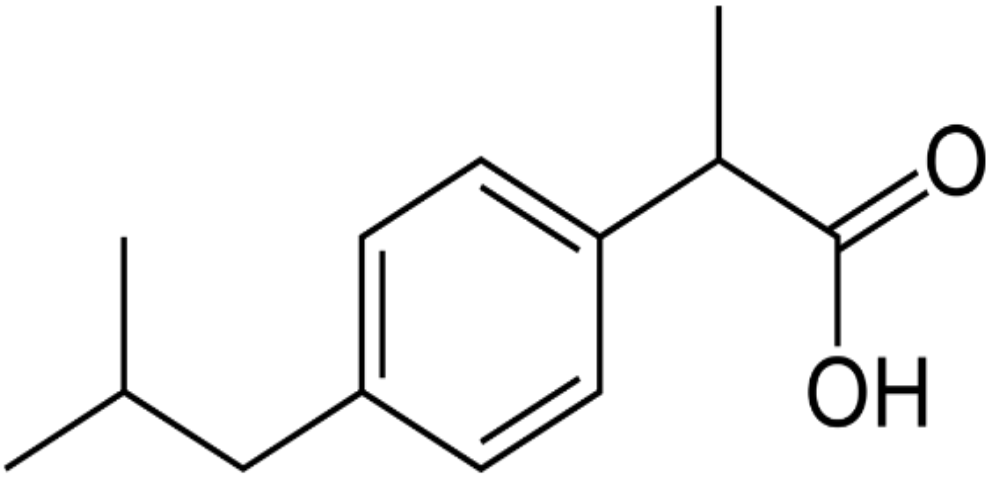


Figure 1.2. Chemical Structure of Ibuprofen

Table 1.1. Chemical Properties of Ibuprofen

Chemical formula	$C_{13}H_{18}O_2$
IUPAC Name	2-[4-(2-methylpropyl)phenyl] propionic acid
Appearance	Solid white crystals
Molar mass	206.28
Solubility in water	21 mg/L
Solubility in organics	Readily sol in most organic solvents
Toxicity	Toxic if swallowed. LD50 is 636 mg/kg in rats.
Boiling point	157 ºC
Safety	Irritant, Health Hazard
Stability in nature	Stable
Melting Point	75–77 ºC
Solubility in acetone (g/100 g)	130.63 (25°C)

1.1.3. Diclofenac (DIC)

Diclofenac is a Nonsteroidal Anti-inflammatory Drug and has a role as a non-narcotic analgesic. It is a monocarboxylic acid comprising of phenyl acetic acid with a (2, 6-dichlorophenyl) amino group at the 2-position as seen in figure 1.3. Like other NSAIDs, diclofenac is usually used in therapy for acute and chronic pain and inflammation from a variety of causes. It's also used to prevent NSAID-induced gastric ulcers.

Additionally, it can used as an active pharmaceutical ingredient for inflammations and pain reductions. Low concentrations can be found in wastewater effluents and hospital effluents thereby making a high concern because it is toxic to the environment.

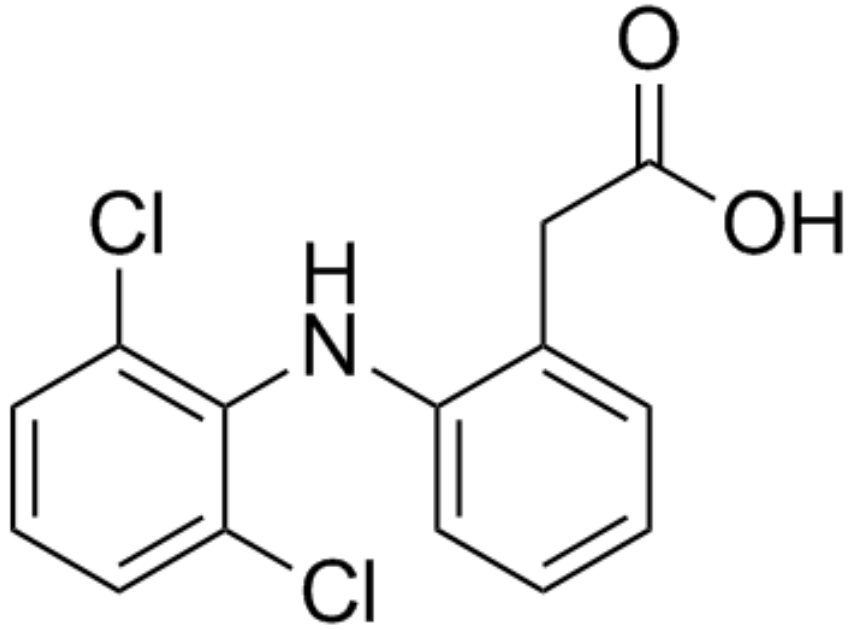


Figure 1.3. Chemical Structure of Diclofenac

Table 1.2. Chemical Properties of Diclofenac

Chemical formula	$C_{14}H_{11}Cl_2NO_2$
IUPAC Name	2-[2-(2,6-dichloroanilino) phenyl] acetic acid
Appearance	white powder
Molar mass	296.1 g/mol
Solubility in water	2.37mg/L (at 25 °C)
Solubility in organics	30 -50 mg/m
Stability in nature	Stable
Melting Point	283-285 °C

1.1.4. Carbamazepine (CBZ)

Carbamazepine is one of many other micro-organic pollutants that can be found in wastewater. It's an anticonvulsant drug that is used mainly for epilepsy and neuropathic patients. Also, can be used with people having bipolar effects. The chemical name as is known as 5H-dibenzo[b,f]azepine-5-carboxamide and the structure as seen in figure 1.4. CBZ is also known to have a significant role as, an analgesic and an environmental contaminant. It has both anti-epileptic and psychotropic properties and generously used in the treatment of epilepsy. Organic micropollutants are generally persistent pollutants that are found in wastewater effluents, and these is carbamazepine.

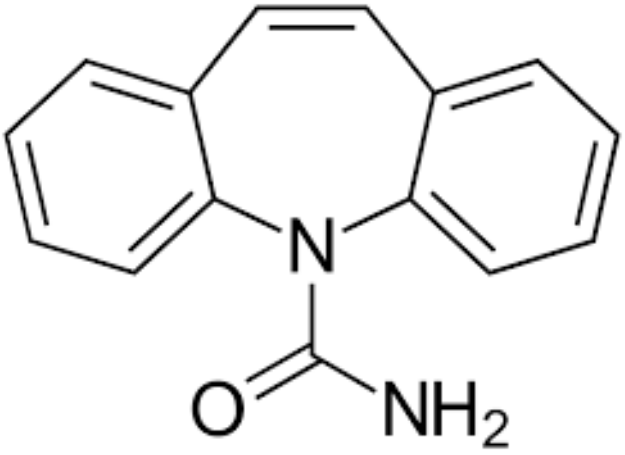


Figure 1.4. Chemical Structure of Carbamazepine

Table 1.3. Chemical Properties of Carbamazepine

Chemical formula	$C_{15}H_{12}N_2O$
IUPAC Name	benzo[b][1]benzazepine-11-carboxamide
Appearance	white powder
Molecular Weight	236.27 g/mol
Solubility in water	<1 mg/mL
Solubility in organics	3 mg/ml
Stability in nature	Stable
Melting Point	190.2 °C

1.1.5. Measurement of Pharmaceutical Micropollutants

Pharmaceuticals are usually at low concentrations in the environment which makes their measurements in aqueous solutions challenging. However due to the improved technologies that have been developed, various methods can be used to measure the pharmaceuticals in aqueous solution. Some of the methods that are used include, solid phase and liquid-liquid extraction; plus others techniques used for analysis such as high performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), gas chromatography tandem-mass spectrometry (GC-MS/MS), liquid chromatography-mass spectrometry (LC-MS), liquid chromatography tandem-mass spectrometry (LC-MS/MS) and liquid chromatography time-of-flight/mass spectrometry (LC/TOF/MS) (Hacıosmanoğlu, 2019). In this study, analysis of the target pollutants is carried out using gas chromatography-mass spectrometry as explained below.

1.1.5.1. Gas Chromatography-Mass Spectrometry

Among the recently used techniques in the measurement of pharmaceuticals at very low concentrations is the gas chromatography- mass spectrometry (GC-MS). The GC-MS helps to provide more accurate results by detecting components in chemical mixtures using gas chromatography (GC) and identifies the compounds at a molecular level using mass spectrometry (MS). The results obtained from the GC-MS, is contrasted a spectrum of compounds and information stored in the National Institute of Standards and Technology Mass Spectral database (NIST) and the WILEY library of GC-MS to determine their viability (Thamer and Thamer, 2023).

When a vial containing a given sample volume is inserted to the GC-MS, a small volume from the sample is taken by the GC-MS and this sample is divided into individual substances on heating. The sample substances are volatized and passed through the column chamber to MS detector. These samples then undergo ionization i.e. electron impact (EI) and chemical ionization (CI) (Hacıosmanoğlu et al., 2019). The achieved ions are then distinguished according to the mass to charge ratio (m/z ratio) by passing through a magnetic field and can be detected.

In this study the GC-MS was used to measure different concentrations of various samples prepared. The initial results from the GC-MMS were used for calibration. After

calibration of the GC-MS, information was stored and saved accordingly followed by adsorption studies that were carried out to determine the adsorption capacity of the adsorbent. Adsorption experiment was applied using a cellulose adsorbent to determine the remaining concentrations.

1.1.6. Cellulose

Cellulose is among the most plentiful organic compounds on earth, and it is mainly composed of plant fiber. Plants have approximately 33% of cellulose as seen in table 1.2 Agro waste contains a very big percentage of cellulose in additional to other compounds like lignin, xylose and other organic compounds (Sundarraj and Ranganathan, 2018). It's estimated that although most of the cellulose is easily found in the forests. Moreover, most of the sources of cellulose are agricultural residues, water plants etc. Commercial cellulose production is mainly from harvested sources like wood and cotton (Heinze et al., 2018).

Other forms of cellulose can be produced from bacteria of the genera Acetobacter, Agrobacterium, Sarcina, and Rhizobium. These have an advantage as compared to others in a way that the produced cellulose contains no lignin, hemicelluloses, more crystalline and with a high degree of polymerization (Heinze et al., 2018).

With proper modifications, major cellulose polymers can be produced from extracted cellulose. There are various methods which are used to extract cellulose from its original state such as liquid extraction, solid phase extraction, acid phase extraction and many more (Chopra and Manikanika, 2021).

The extracted cellulose is a linear polymer comprised of the monomer D-glucose which are connected successfully through ß-1,4-glycosidic bonds having a β-configuration between carbon 1 and carbon 4 adjacent to each other to form a polymeric chain as seen in the Figure 1.4.

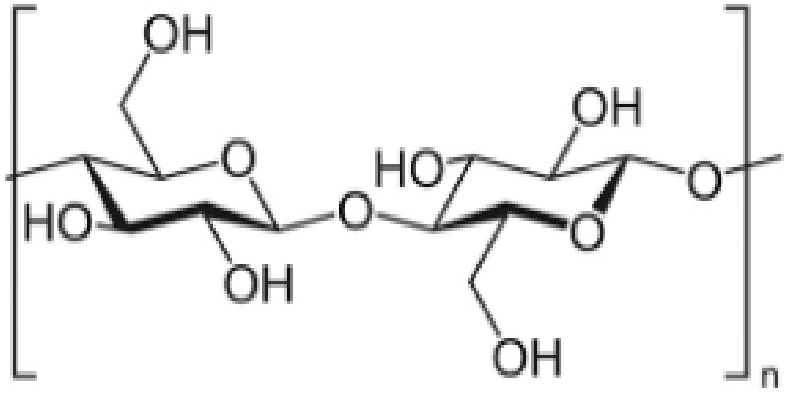


Figure 1.5. Cellulose Structure (Hamidi et al., 2023)

Table 1.4. Chemical composition of some typical cellulose containing material

Source	Composition (%)			
	Cellulose	**Hemicellulose**	**Lignin**	**Extract**
Hardwood	43-47	23-25	16-24	2-8
North American hardwood	66-67	17-21	20-36	3-6
Softwood	40-44	25-29	25-32	1-5
Bagasse	40	30	20	10
Corn cobs	45	35	15	5
Corn stalks	35	25	35	5
Corn stalks f4J	35-45	25	17-21	4-7
Couon	95	2	1	0.4
Flax (retted)	71	21	2	6
Flax (unreued)	63	12	3	13
Hemp	70	22	6	2
Henequen	78	4-8	13	4
Jute	71	14	13	2
Kenaf	36	21	18	2
Ramie	76	17	1	6
Rice straw (SJ)	43	33	20	<1
Sisal	73	14	11	2
Sisal fibers (f7)		13	11	<2
Sugarcane bagasse (61)	5-55	20-25	18-24	>1
Wheat straw (81)	58-73	25-31	16-23	3-5.8
Wheat straw	30	50	15	5

In comparison with other synthetic polymers, one of the main advantages of using cellulose derivatives is its abundance in nature because it is a component of wood, grass etc and its usage is also beneficial for environmental safety (Ibrahim et al., 2015).

As seen in figure 1.5, for every D-anhydroglucopyranose unit, there are three hydroxyl groups, two secondaries' at C2, C3, and one primary at C6 positions that are attached to the structure allowing the hydroxyl groups to react as primary and secondary alcohols. Due to these unique properties of cellulose, chemical modifications can be applied to change some properties.

According to the national center of biotechnology, cellulose has a molecular weight of 342.30 g/mol and density of 1.5 g/cm^3 (NCBI, 2023). Table 1.5 shows the chemical and physical properties of cellulose. The reactivity and characteristics of this compound depends on factors like fiber morphology and regularity, porosity, degree of crystallite order and bonding etc. Moreover, being a polymer, it is insoluble in water and common solvents. Hence, it can dissolve in non-derivatizing solvents but soluble in sulfuric acid and concentrated solutions of Zinc Chloride.

Table 1.5. Chemical and Physical properties of Cellulose, (NIOSH, 2022).

Name	Value
Molecular Weight	342.30 g/mol
Solubility	Insoluble
Density	1.27 to 1.61
Molecular Formula	$C_{12}H_{22}O_{11}$

1.1.6.1. Activation of Cellulose

Transformation or activation of the compound may not be trivial because of the presence of the hydroxyl groups on the cellulose structure. For this reason, the cellulose is processed by pretreatment or an activation step before it is confined to a chemical reaction (Heinze et al., 2018). In the field most treatments are carried out by subjecting the cellulose to an alkaline solution causing dissolution of the polymer followed by activation

of the cellulose. In this study, commercial cellulose was used as the main source to produce the cellulose adsorbent.

1.1.6.2. Adsorption

Various techniques have been developed to improve the quality of water and water purification technologies. Among these is adsorption method. Adsorption uses a physiochemical process whereby a substance attaches to the surface of the adsorbent. In this process, the substance that it's attached to the surface is called the adsorbate and the substance where the adsorption occurs is the adsorbent. This process mainly undergoes four steps; bulk diffusion, film diffusion, pore diffusion, and lastly adsorption (Baig et al., 2021).

Factors such as surface area, functional groups, molar mass, polarity, bonding, etc. and external factors like temperature, pH and many more may affect the adsorption capacity of the adsorbent. Additionally, the difference in molecular weights and other chemical properties may also affect the adsorption capability. For instance, compounds having molecules with a higher molecular weight than others are more likely to be more adsorbed due the different hydrogen bonds and polarity of the substance in the solution. The forces of interaction between adsorbent and the adsorptive molecules play a very important role in controlling the process of adsorption (Tamamushi, n.d.).

1.1.6.3. Pharmaceuticals Removal by Adsorption

Approximately 80% of the wastewater that is released into the streams and environment is municipal and industrial wastewater (Miao et al., 2023). Biodegradability of the micro-organic pollutants and physicochemical properties like solubility, adsorption etc. are important aspects that may hinder the effective removal of these pharmaceuticals from water (Ajala et al., 2022). Different methods such as chemical precipitation, adsorption and electrocoagulation have been developed and tested with positive results. However out of all these methods adsorption has been proved to be one of the most effective methods because it's easy to operate and cost effective. Even though various adsorbents have been found to be effective some may not be preferable. Due to the changing advance in technology, scientists have come to realize that nanotechnology has greatly contributed to the improvement of nanoadsorbents. For example, some pharmaceutical industries,

nanoadsorbents such as carbon nanotubes (CNTs) and titanium nano adsorbents have been used for different applications (Jain et al., 2021). In this study we focus of using cellulose as a novel adsorbent made from commercial cellulose and used to study its effectiveness on the adsorption of three target pollutants i.e. diclofenac, ibuprofen, and carbamazepine.

1.1.7. Objective and Scope of Study

The objective of this study was to evaluate the adsorption capacity of a novel cellulose adsorbent and its ability to remove pharmaceuticals pollutants from water. Three different pharmaceuticals commonly found in wastewater were selected as target pollutants. Two cellulose based foam adsorbents, CAc-PPUF, a product of cellulose acetate and phenylene diisocyanate, and CMC-HMPUF, a product of CMC with hexamethylene diisocyanate were prepared from commercial cellulose, and tested as the novel cellulose based adsorbents for the adsorption of selected pharmaceuticals from water. The two newly synthesized adsorbents were compared for their adsorption capacities, and the one having the highest capacity was selected to be used in further isotherm, kinetics, and pH effect adsorption studies.

The scope of this study can be divided into six major categories.

- To develop appropriate GC-MS analytical methods to quantify the selected pharmaceuticals accurately in aqueous samples.
- To synthesize cellulose based polyurethane foams, CAc-PPUF, and CMC-HMPUF, having different ionic functional groups.
- To test their affinities for the selected pharmaceuticals with batch adsorption experiments.
- To identify the foam sample that has higher affinity for the selected pharmaceuticals, and to investigate its adsorption behavior under different conditions such as pH, temperature, and time, with batch adsorption experiments.
- To characterize the foam sample having higher affinity by Zeta potential, BET surface area, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) analyses.
- To conduct desorption and reuse studies to evaluate the reutilization possibility, stability and durability of the adsorbent.

2. MATERIALS AND METHODOLOGY

2.1. Materials

Certified standard of diclofenac (98% purity), carbamazepine (99% purity) and ibuprofen (99% purity) were purchased from SIGMA-ALDRICH Co. GmbH, Germany, and Toronto research chemicals, Canada. Primary solutions were prepared by dissolving the pharmaceuticals standards in GC acetone (Germany). The solutions were calibrated and used for the adsorption method and kinetics experiments. For Isothermal adsorption experiments that needed to be diluted, Ultra Purified water UPW) was added to a given volume of the standard solution to achieve the required concentration needed. GC MS analysis was used with a surrogate Anthracene D10, (CAS RN: 1719-06-8; 99.5% purity) that was purchased from Germany. The novel cellulose adsorbents were manufactured by Al-Istiqlal University in Palestine.

Other materials used were GC Acetone, Hexane and dichloromethane were GC-MS grade and purchased from Merck, Germany.

2.2. Methods

2.2.1. Production of the Adsorbents.

A variety of derivatives of cellulose can be made using different protic and aprotic solvents of cellulose (Grandgirard et al., 2002). Commercial cellulose is used in this study for the production of the adsorbents. 1 g of the cellulose is suspended in distilled water (50ml) while mechanically mixing for 2 hours. The water is the removed by suction method to create a vacuum. The cellulose is then suspended in 50ml of methanol for another 1 hours (3 times) continuously. This enables to separate the water cellulose from the nano-cellulose (Roman et al., 2021). In this study, the cellulose is left in DMAc overnight, then the activated cellulose is collected by suction filtration. To activate the cellulose, 1.0 g of substance were added to 50 mL of distilled water in a round-bottomed flask and contents were mixed for a given period of 120 minutes. Water was removed using vacuum filtration. Then 50ml of methanol were added and stirred 1 hour. This is repeated 3 times filtered and removed. 50 mL of N,N-dimethyl acetamide (DMAc) was added for 24hrs to activate the cellulose. A solution of lithium chloride i.e. (LiCl, 2.4g) in

DMAc (27 mL) is then added to the cellulose in the round-bottomed flask equipped with a magnetic stirring bar, the mixture was mechanically stirred at room temperature for 3 hours to form a clear gel.

2.2.2. Carboxymethyl cellulose (CMC)

Carboxymethyl cellulose (CMC) can also be referred to as cellulose gum. It is a cellulose derivative composed of hydroxyl groups of the glucopyranose bonded to carboxymethyl groups (-CH2-COOH) hence making up the backbone of the compound. It is generally used as sodium salt (sodium carboxymethyl cellulose).

As seen in Figure 2.1 and 2.2 respectively, addition of sodium hydroxide solution to the mixture was used for the conversion of the cellulose-to-cellulose alkoxide by attracting acidic hydroxyl protons from the cellulose structure. The produced cellulose alkoxide then reacted with chloroacetic acid to form CMC which was found nontoxic and can be used as a food modifier since it is a water-soluble polymer.

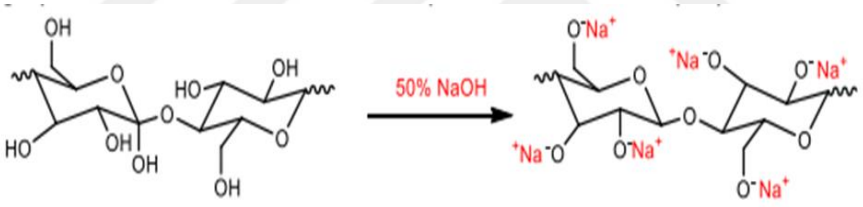


Figure 2.1. Conversion of Cellulose Alkoxide

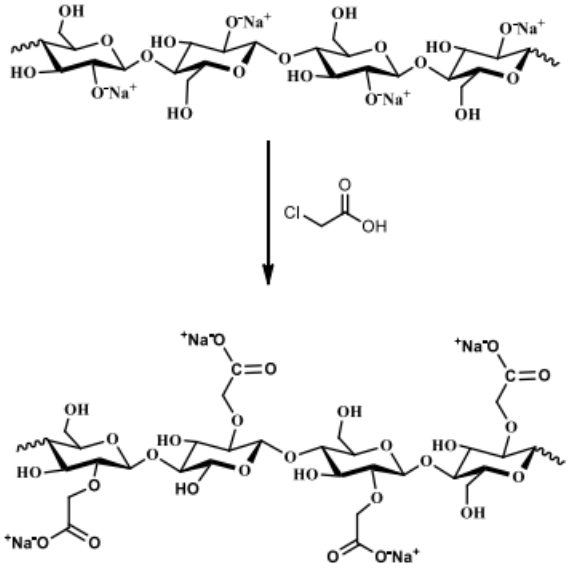


Figure 2.2. Cellulose Alkoxide is converted to CMC.

2.2.3. Synthesis of Cellulose Acetate Based Foam (CAc-PPUF)

CAc-PPUF is termed as Cellulose acetate + 1,4-phenylene diisocyanate. To produce the CAc-PPUF adsorbent as seen in Figure 2.3, 1, 4-phenylene diisocyanate (1g) was added to the produced gel, followed by addition of THF (0.5 mL) and catalytic amount of diisopropyl amine (6 drops). The mixture was stirred at room temperature for an hour, then few drops of water were added. The resulting foam was washed with distilled water (100.0 mL) several times, filtered, and dried at 60°C for 1 hr. Resulting product was kept in a dry environment at RTP as seen in figure 2.3.

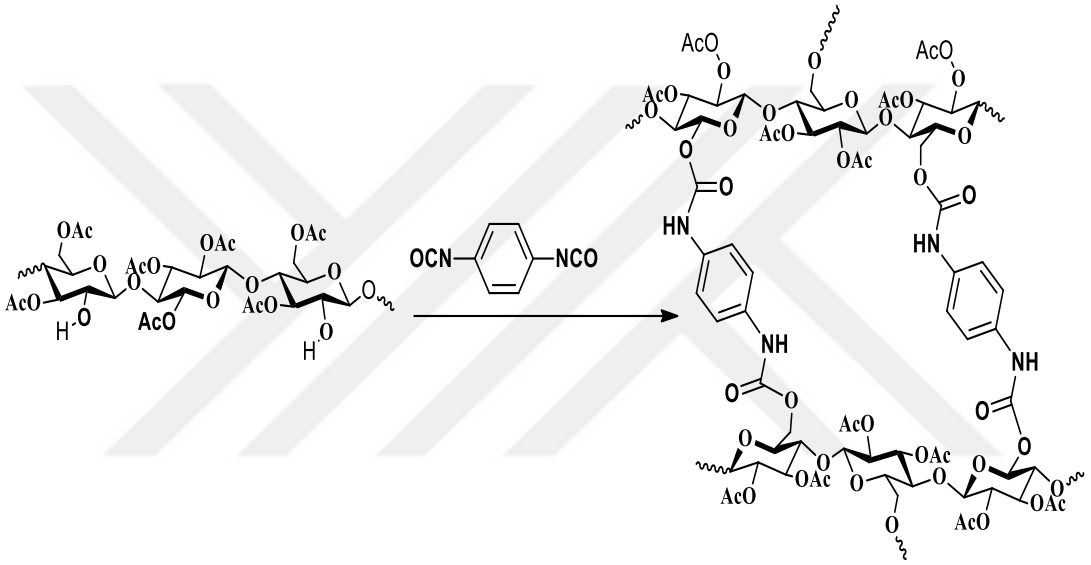


Figure 2.3. Synthesis reaction and the proposed structure of CAc-PPUF

2.2.4. Synthesis of Carboxymethyl Cellulose Foam (CMC-HMPUF)

As can be seen in Figure 2.3, a mixture of CMC (1g) with distilled water (1 mL) was stirred in a beaker with 1,6-hexamethylene diisocyanate until a clear gel was obtained (30 mins). DMAc (10.0 mL) was added to the gel followed by addition of catalytic amount of diisopropyl amine (2 drops). Excess amount of 1,6-hexamethylene diisocyanate (3mL) was then added and the mixture was stirred at room temperature for an hour with addition of a few drops of water. The resulting foam was washed with distilled water (100.0 mL) several times, filtered, and dried at 60°C for an hour. As shown in Figure 2.4, polyurethane based and carboxymethyl cellulose (CMC) were mixed in accordance with the ratio 1:1 to make CMC + 1,6-hexamethylene diisocyanate and stored in a dry container.

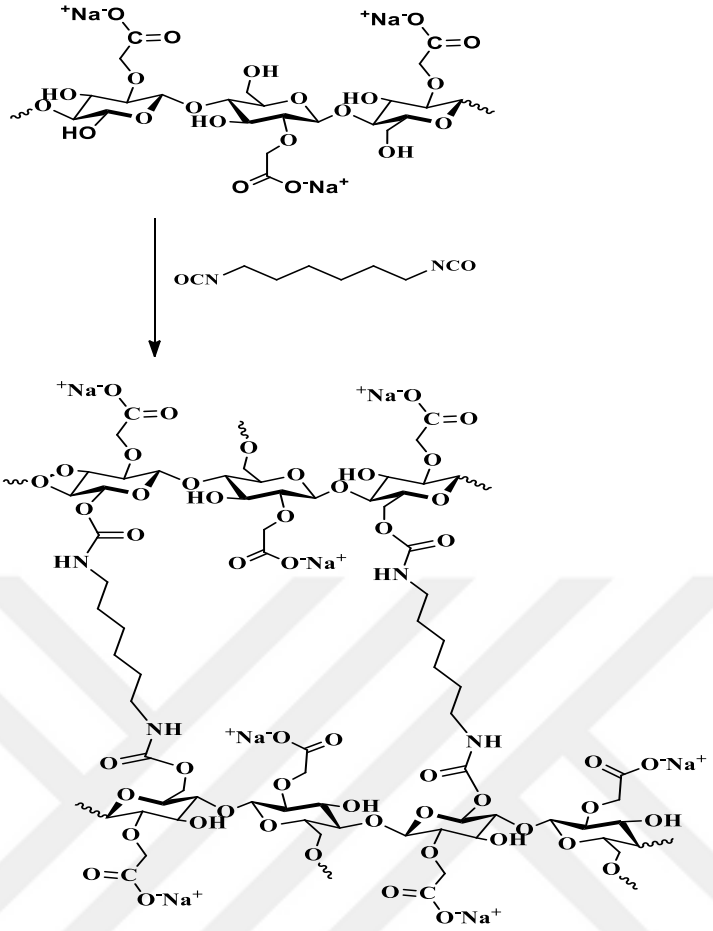


Figure 2.4. Synthesis reaction and the proposed structure of CMC-HMPUF

2.3. Zeta Potential Measurement of the Synthesized Foams

The charge that forms at the interface between a solid surface and its liquid medium is known as the zeta potential. There are various possible causes for the formation of this potential, which is expressed in millivolts. The dissociation of ionogenic groups on the particle surface is one of them. Zeta potential is therefore a function of the surface charge of the particle and is highly relevant to the charge state of surfaces.

0.1 g/L of adsorbent mixture was prepared in 20 mL of 0.1 M NaCl solution. Then, the pH of the mixture was adjusted to the desired pH in the range of 4 to 9 by the addition of appropriate amount of 0.1 M NaOH or 0.1 M HCl. In order the surface reactions to reach to equilibrium, all the adsorbent samples were shaken for 24 hours. The Zeta potentials of the mixtures were then measured by Malvern Zetasizer (Nano ZS90, UK).

2.4. FTIR Analysis

Fourier transform infrared (FTIR) spectrometry was employed to analyze the functional groups of the synthesized PUF adsorbents. FTIR analysis was also performed on PUF samples after adsorption to investigate the adsorption mechanisms and identify the active sites of foam samples that were responsible for pharmaceutical adsorption. FTIR spectra were recorded on Jasco Japan 4700 FTIR spectrometer with the wave number range of 4000-500 cm^{-1}.

2.5. Material Characterization of the Selected PUF Sample

Following the identification of the PUF adsorbent with a superior adsorption capacity, its surface area and pore volume distribution were analyzed by Brunauer-Emmett-Teller (BET). BET was examined using AUTOSORP-1C/MS. The specific surface area (m^2/g) and pore volume distribution of an adsorbent are important characteristics because of their significant impact on adsorption efficacy. The surface area and pore volume distribution were determined using N_2 adsorption and desorption isotherms. (Mukhtar et al., 2020)

The surface examination of the selected PUF was further carried out using QUANTA 400F Field Emission SEM with high resolution.

2.6. Batch Adsorption Experiments

Adsorption tests of synthesized adsorbents with different micropollutants were conducted in an IKA (Germany) temperature-controlled shaker in batch mode at 25 °C for 24 hours unless otherwise noted with a mixing speed of 200 rpm. After the adsorption process, the samples were filtered with 0.2 μm PTFE filter. Then, the remaining micropollutant concentrations were measured. The analytical methods used for micropollutant analysis are described in the following sections. To assess the adsorption capacity, the mass of micropollutant adsorbed per unit mass of foam material was calculated using Equation 1.

$$q_e = \frac{(\mathrm{C} - C_o)V}{m} \tag{2.1}$$

where C_0 and C_e are the initial and equilibrium concentrations of pollutants (m/L), q_e is the mass of pollutant adsorbed per unit mass of adsorbent (mg/g), V is the solution volume (L) and m is the adsorbent mass (g).

The percent (%) removal efficiency was calculated using Equation 2.

$$Re\ (\%) = \frac{(\mathrm{C} - C_o)V}{m}\ \mathrm{x}\ 100\% \qquad (2.2)$$

Where Re% is the percent removal efficiency.

2.6.1. Comparison of Adsorption Capacities of CAc-PPUF and CMC-HMPUF for Pharmaceuticals

The adsorption capacities of the two foam samples that were synthesized for the first time in this study were compared after they were tested for their abilities to remove organic micropollutants from aqueous solutions. For this purpose, batch adsorption experiments were conducted by adding 0.05 g of adsorbent into 20 mL of 20 mg/L carbamazepine, ibuprofen, diclofenac, and solutions. The adsorption capacity, q, and removal efficiency of the pharmaceuticals for each adsorbent were determined under the experimental conditions described in Section 3.

2.7. Adsorption isotherm studies with the selected PUF

For isotherm studies, batch adsorption experiments were carried out as described in Section 3. 0.05g of the selected PUF adsorbent was added into 20 mL of pharmaceutical solutions. After adsorption equilibrium is reached, the residual concentrations in aqueous solutions were determined by GC-MS, and the isotherm models were derived from the equilibrium data.

2.7.1. Determination of the Adsorption Isotherm Models with the Selected Adsorbent.

Isotherm model fitting efforts provide us to assess the adsorbent performances, including the adsorption mechanism, adsorption capacity, and basic characteristics of the adsorption process. In this study, we investigated the Langmuir, Freundlich, Sips, and Dubinin-Astakhov isotherm models because they are the most used models in aqueous phase adsorption studies. The isotherm model parameters were determined by a nonlinear optimization technique using the Microsoft Office Excel program (Microsoft Corp., USA). The model predictions were assessed using the normalized root mean square error

(NRMSE), the correlation coefficient (R^2), and the Chi square (X^2) (Kopinke et al., 2018). The equations used to assess model predictions are shown in Table 2.1.

Table 2.1. Statistical parameters used to assess model predictions.

Parameter	**Equation**
Chi square	$\chi^2 = \sum_{i=1}^{n} \frac{(q_{exp} - q_{calc})^2}{q_{calc}}$
Correlation coefficient	$R^2 = 1 - \frac{\sum_{i=1}^{n} (q_{exp} - q_{calc})^2}{\sum_{i=1}^{n} (q_{exp} - q_{exp,mean})^2}$
Normalized root mean square error	$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n} (q_{exp} - q_{calc})^2}{n}}}{q_{exp,max} - q_{exp,min}}$

2.8. Kinetics of Organic Micropollutant Adsorption by the Selected PUF

The kinetic studies for organic micropollutants were conducted using diclofenac, and ibuprofen. The initial adsorbate concentration was 30 mg/L and the adsorbent dose was 1 g/L. (These conditions were selected to be able to clearly observe the kinetic changes). Different contact times between 1 min to 24 hours were applied at 25 °C and 200 rpm. At the end of the pre-determined contact times, the samples were filtered and prepared for GC/MS analysis.

2.8.1. Determination of the Adsorption Kinetic Model for the Selected Adsorbent

Adsorption kinetics provides valuable information on the possible adsorption mechanisms. PFO, PSO, and Elovich models usually fit well with the organic matter adsorption kinetics of carbonaceous adsorbents in an aqueous medium (Revellame et al., 2020) . Therefore, in this study these three models were employed to characterize the adsorption kinetics of diclofenac, and ibuprofen on CAc-PPUF. The isotherm model parameters and the goodness of fit measures were determined as described in Section 3.

2.9. Effect of pH on Organic Micropollutant Adsorption

The impact of pH on the adsorption of organic micropollutants was evaluated at pH levels 6 and 8. pH effect was assessed by conducting adsorption experiments with diclofenac and ibuprofen at the selected pH levels. Batch adsorption experiments were carried out using initial concentrations of target pollutants varying between 20-80 mg/L. pH of each mixture containing a predetermined concentration of pharmaceuticals and the PUF adsorbent was adjusted to the desired pH by the addition of appropriate amount of 0.1 NaOH or 0.1 HCl. During these experiments, the adsorbent dose was 1 g/L and the adsorption temperature was 25 °C with 24 hours contact time. After 24 hours of mixing, the samples were filtered and prepared for GC/MS analysis.

2.10. Regeneration and Reuse Studies

Considering the cost-effective application of the synthesized adsorbent in water and wastewater treatment, the possibility of regeneration and reusability was investigated. IBP was selected as the model for the target pollutant. The desorption and reuse experiments were conducted with 10 mL aqueous IBP samples with an initial concentration of 20 mg/L. The adsorbent dose was 0.5 g/L. The regeneration of the PUF adsorbent was carried out by desorbing IBP from the adsorbent surface with methanol ethanol/water mixture in a volumetric ratio of 4:1. After reaching the adsorption equilibrium, centrifugation was applied to separate the adsorbent material from the aqueous phase. The supernatant was collected for IBP analysis. 10 mL of ethanol/water mixture was added to the used PUF adsorbent, and the sample was sonicated for 5 min to solubilize the adsorbed IBP. The supernatant was discarded. Then, the adsorbent was washed 3 times with 5 mL of distilled water to wash out any remaining regenerant solution, and solubilized IBP. After vacuum drying the adsorbent at 60 °C for 24 hours, it was subjected to IBP adsorption again, and the adsorption capacity was calculated each time after reaching equilibrium. After each use, centrifugation was applied to separate the adsorbent material from the aqueous phase. The adsorption / drying / desorption / drying processes were carried out 5 times.

2.10.1. Preparation of PUF Samples for FTIR Analysis Following Pharmaceutical Adsorption

FTIR analysis was employed to determine the active sites of foam samples responsible for pharmaceutical adsorption based on the changes in vibrational frequencies of the functional groups. For that purpose, 0.1 g of adsorbent material (CAc-PPUF or CMC-HMPUF) was added to 10 mL of the target pollutants solution to get 1 mg/L concentration. The prepared mixtures were shaken for 24 hours at 25 °C. After the adsorption process was complete, the liquid supernatant was discarded using syringes. The remaining solid samples were washed by 10 mL deionized water. After discarding the liquid phase, the solid samples were dried in a vacuum oven at 60 °C.

2.11. Analytical Methods

Concentrations of the selected pharmaceuticals are measured after each batch adsorption experiment. The initial concentration of the compounds is measured, and noted as Co. The measured concentration is reported as the equilibrium concentration, C_e, in isotherm studies, and as the concentration at time t, C_t, in kinetic studies. All the pharmaceutical concentrations are measured using the gas chromatograph-mass spectrometer (GC-MS). For GC-MS to be more effective, we filter the samples through PTFE filters. According to Godby and Conklin, 2017, phenolic compounds adsorb less to the PTFE filter as compared to other filters which make them more suitable for this study (Godby and Conklin, 2017). After filtration, 100 µL of samples were filtered and put in small vials then transferred to the dryer for 24 hours at a temperature range of 40^{o}C- 60^{o}C. The samples are then reconstituted using 100 µL GC-MS grade acetone before they are inserted to the GC-MS. Analysis is carried out by separating the injected 1 µL of the sample to Trb-5ms capillary GC column thereby identifying the mass ions according to their m/z ions. The parameters that were used in this study were saved in the GC-MS used as seen in Figure 2.5 according to Table 2.2.

Figure 2.5. GC/MS used for pharmaceuticals in solution measurement.

Table 2.2. GC-MS Parameters

GC	Column:	TRB-5MS (30 m x 0,25 mm x 0,25 μm)
	Injection temperature:	280 °C
	Injection mode:	Splitless
	Helium gas flow rate:	1.0 ml/min
	Sample volume:	1 μl
	Control mode:	Linear (37.5 cm/s)
	Oven temperature program	120 °C (1 min) → (10 °C /min) →190 °C (1 min) →(5 °C /min) →250 °C (10 min) →(20 °C /min) → 290 °C (5 min)
	Injection unit:	250 kPa (1 min)
MS	Ionsource temperature:	250 °C
	Interface temperature:	280 °C
	Measurement mode:	5.00-6.50 min: Scan (0.50 s) 6.50-22.00 min: Scan (0.30 s) 6.50-22.00 min: SIM (0.20 s) 22.00-24.0 in: Scan (0.50 s)

2.11.1. Preparation of Calibrations Standards

Stock solution of target pollutants having 10^6 ng/mL concentration is prepared by adding 0.01g of compounds in a 10ml capacity amber vial. To this vial we add 10ml of GC MS grade acetone and mix mechanically to allow uniform mixing. The resulting mixture is used as stock solution and used in the preparation of other solutions by dilution method. An example of the calibrated solution is prepared by taking 2ml of standard pharmaceutical solutions (10^6 ng/ml) and adding 18ml of GC grade acetone to make 10^5 ng/ml of the diluted solution. In the table 2.3 as seen below, were the calibrated values of the three pharmaceuticals used in this study.

Table 2.3. Calibrated values for the target pollutants

	m/z value	Retention time (RT)
Diclofenac	214	12.95
Carbamazepine	193	15.69
IBP	161	6.166

3. RESULTS AND DISCUSSIONS

3.1. Comparison of Adsorption Capacities of Synthesized Adsorbents

In this study, two cellulose based foam adsorbents were synthesized. Firstly, the adsorbents were tested for their abilities to adsorb the pharmaceuticals, carbamazepine, ibuprofen, and diclofenac from aqueous solutions. For this purpose, batch adsorption experiments were conducted by adding 0.05 g of adsorbent into 20 mL of 20 mg/L carbamazepine, ibuprofen, and diclofenac solutions. The adsorption capacity, q, and pharmaceutical removal efficiency of each adsorbent were determined under the experimental conditions at a given concentration q. The pharmaceutical removal efficiencies of CAc-PPUF, and CMC-HMPUF for each pharmaceutical are presented in Figures 3.1a, and 3.1b, respectively.

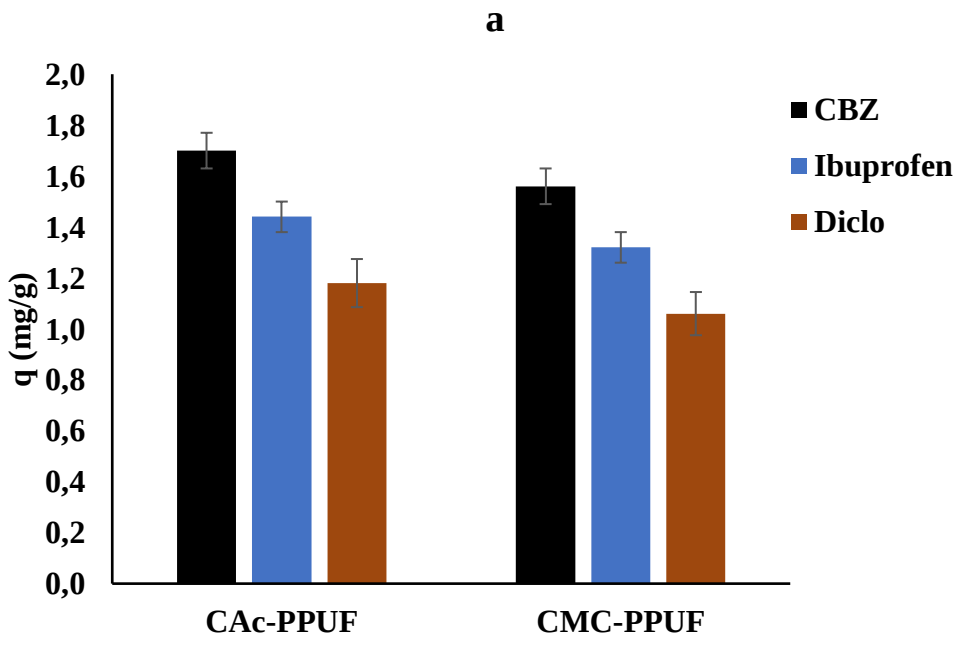


Figure 3.1a: Pharmaceutical adsorption capacities of CAc-PPUF and CMC-PPUF a) in terms of surface concentrations, q (mg/g), b) in terms of % Removal (pH=6.5, temperature= 25 °C)

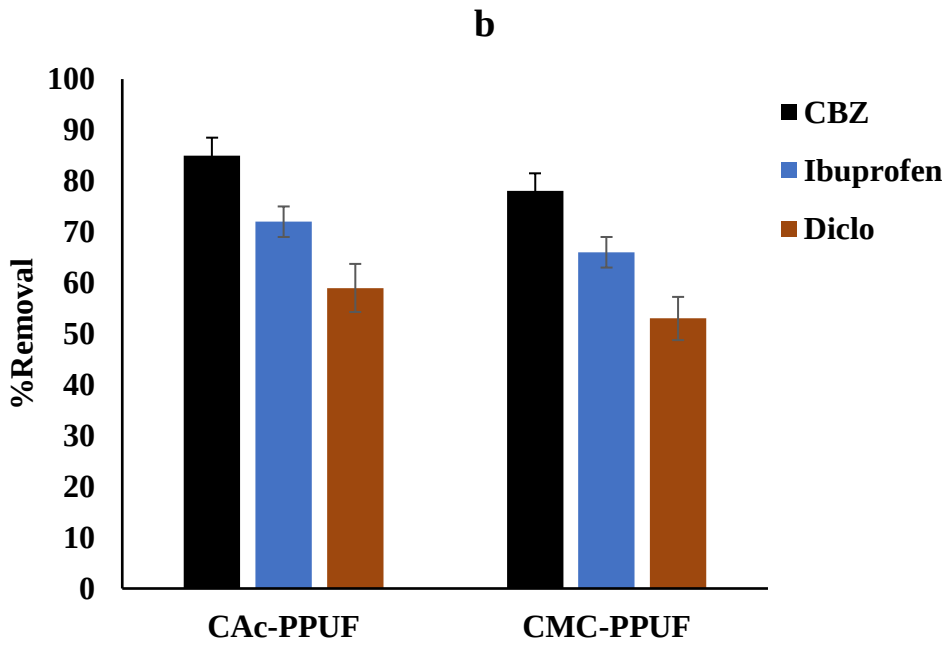


Figure 3.1b: Pharmaceutical adsorption capacities of CAc-PPUF and CMC-PPUF a) in terms of surface concentrations, q (mg/g), b) in terms of % Removal (pH=6.5, temperature= 25 °C)

The adsorption capacities of CMC-PPUF are between 1.06 mg/g and 1.56 mg/g, whereas those of CAc-PPUF for the pharmaceuticals under evaluation vary from 1.180 to 1.990 mg/g. The tested pharmaceuticals exhibit removal efficiencies ranging from 59% to 85% for CAc-PPUF, and between 53% and 78% for CMC-PPUF. Figures 3.1a and 3.1b demonstrate CBZ is adsorbed by both adsorbents to greater extend. Conversely, diclofenac has the lowest tendency to be adsorbed by the adsorbents.

As suggested by Rogers (1996), log Kow<2.5 refers to low sorption potential, log Kow>2.5 and<4 refers to medium sorption potential, and Kow>4.0 advances high sorption potential (Rodgers-Gray et al., 2000; Rogers, 1996). As can be seen in Table 3.1, all three pharmaceuticals tested have log Kow values lower than 2.5, indicating relatively higher solubility, and higher hydrophilicity.

Adsorption of a compound inversely depends on its solubility, and on its polarity or degree of ionization. Many drugs are known to be weak bases or weak acids. The more the drug is in its ionized form, the less likely it is to be adsorbed. In general, for a weak acid or base, the pK_a value will determine its degree of ionization, as described by the Henderson–Hasselbalch equation (Novack and Robin, 2016a).

For a weak acid the ionization reaction is:

$$pH = pK_a + log\{[A^-]/[HA]\} \quad (2.3)$$

and for a weak base it is:

$$\mathrm{pH} = \mathrm{pK_a} + \log\{[\mathrm{B}]/[\mathrm{BH^+}]\} \quad (2.4)$$

The pK_a is a measure of the relative strength (degree of ionization) of a weak acid or base. When the solution pH equals pK_a, weak acid or base is 50% ionized in solution. When pH exceeds the pKa, the dominant form in solution is negatively charged ionized species (Novack and Robin, 2016b)**.**

Table 3.1. pKa, and log Kow values of pharmaceuticals

	pKa	**log Kow**
CBZ	2.3-13.9[a]	1.51[b]
IBU	4.85[c]	2.48 [b]
Diclo	4[d]	1.90[b]

[a](Al-Mashaqbeh et al., 2021)
[b](Scheytt et al., 2005)
[c](Ertürk et al., 2017)
[d](Leyva et al., n.d.)

IBU and Diclo have pKa values of 4.85, and 4, showing they are present as negatively charged ionized species in solution. As will be discussed in Section 3.4, cellulose based foam samples have negative surface charges confirmed by their negative zeta potentials measured throughout a wide pH range. Charge repulsion is therefore very likely reducing the degree of contact between the adsorbent and the adsorbate. Carbamazepine has two pKa values indicating that this antibiotic can exist as cations, zwitterions, or as anions under different pH conditions. At the experimental pH of 6.5, it is present in solution as zwitterions having a positively charged functional group, and a negatively charged functional group. This chemical property of carbamazepine may be enhancing its adsorption potential. The adsorption mechanism of pharmaceuticals will be further discussed in Section 3.

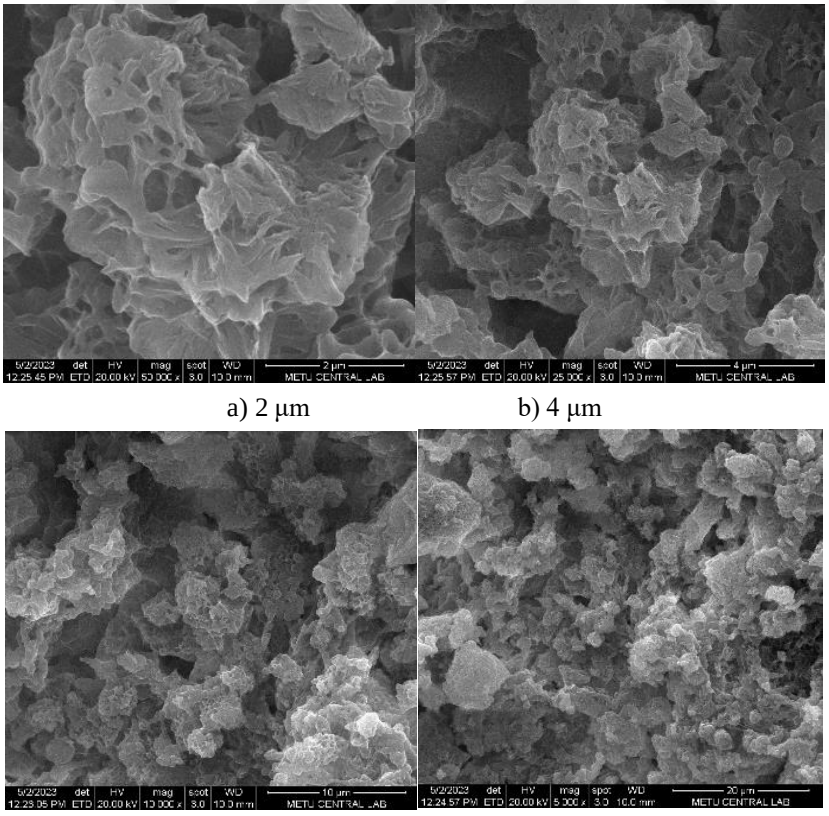
3.2. Material Characterization of CAc-PPUF

Comparison of pharmaceutical adsorption capacities of CAc-PPUF and CMC-PPUF demonstrated that CAc-PPUF has a slightly higher pharmaceutical adsorption capacity

and pharmaceutical removal efficiency. Therefore, CAc-PPUF was further subjected to the characterization tests, as SEM, FTIR, XRD, BET, and zeta potential.

3.2.1. SEM

SEM images of the prepared CAc-PPUF were collected to identify its morphology. The high-resolution QUANTA 400F Field Emission SEM was used for this purpose. Additionally, the elemental analysis of synthesized CAc-PPUF was performed using energy dispersive X-ray spectroscopy (EDAX). Figure 3.2 q,b,c and d, display the SEM images produced for CAc-PPUF in the scale range of 2 - 20 μm. The images indicate a very porous, amorphous material with varying micropore spaces. According to EDAX results, the structure contained 21.69% oxygen and 78.31% carbon. The nitrogen atoms in the structure were not able to be distinguished by the EDAX results. This could be because, in comparison to carbon and oxygen atoms, there are comparatively fewer nitrogen atoms in CAc-PPUF.



a) 2 μm b) 4 μm

c) 10 μm d) 20 μm

Figure 3.2. SEM images of the prepared CAc-PPUF a) 2 μm b) 4 μm c) 10 μm d) 20 μm

3.2.2. Surface Characterization of CAc-PPUF by FTIR

The Fourier transform infrared spectroscopy (FTIR) is an important tool to identify characteristic functional groups of an adsorbent, which are capable of adsorbing contaminants. The functional groups of the prepared CAc-PPUF were identified using FTIR spectroscopy. Figure 3.3 displays the corresponding FTIR curve in transmission mode. The urethane linkage by condensation reaction between OH groups of cellulose acetate and CNO groups of 1,4-phenylene diisocyanate is demonstrated by the peaks at 3300 cm-1 for N-H and at 1656 cm-1 for CO-NH. The symmetric and asymmetric stretching vibration absorbance bands observed at 2933 and 2910 cm-1 confirms the presence of C-H bonds of the aromatic rings. A prominent absorbance band at 1740 cm-1 suggests that cellulose acetate has a carbonyl (C=O) functional group. The stretching vibrations of hydroxyl groups are responsible for the broad band spanning from 3672 to 2940 cm-1. C=C bond stretching of the aromatic ring is responsible for the increased intensity of the absorption bands at 1627 and 1507 cm-1. There are clear indications of C–O–C stretching vibrations at 1215 and 1034 cm−1. As a result, the proposed structure presented in Figure 3.1 for the prepared CAc-PPUF is validated by the FTIR spectrum.

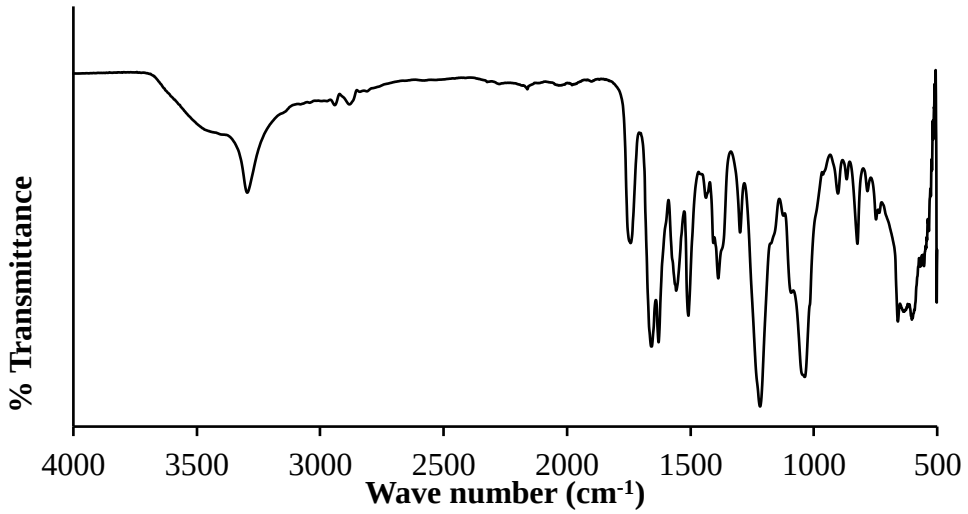


Figure 3.3. FTIR spectrum of CAc-PPUF

3.2.3. XRD Analysis

X ray diffraction (XRD) is an effective method that is commonly used to analyze evaluate the crystallographic structure of materials. The size of the crystal with the lattice strain of

different nanomaterials have been studied using X-ray peak analysis whereby usage of different techniques has led to a simple approach of determing the crystal size (Shitu et al., 2023). This is useful in the making of crystallinity verification possible.

The incident radiations are scattered depending on their intensity by the surface of the material. These scattered X-rays are analyzed according to their intensity and scattered angles. The intensity and scattered angles from the surface of the material are then examined. The X ray diffraction patterns of CAc-PPUF are shown below in Figure 3.4 The main peaks of the XRD are shown to be at 25^{o} degrees, which match with the crystal lattice planes of cellulose thereby confirming the cellulose based structure of CAc-PPUF as proposed.

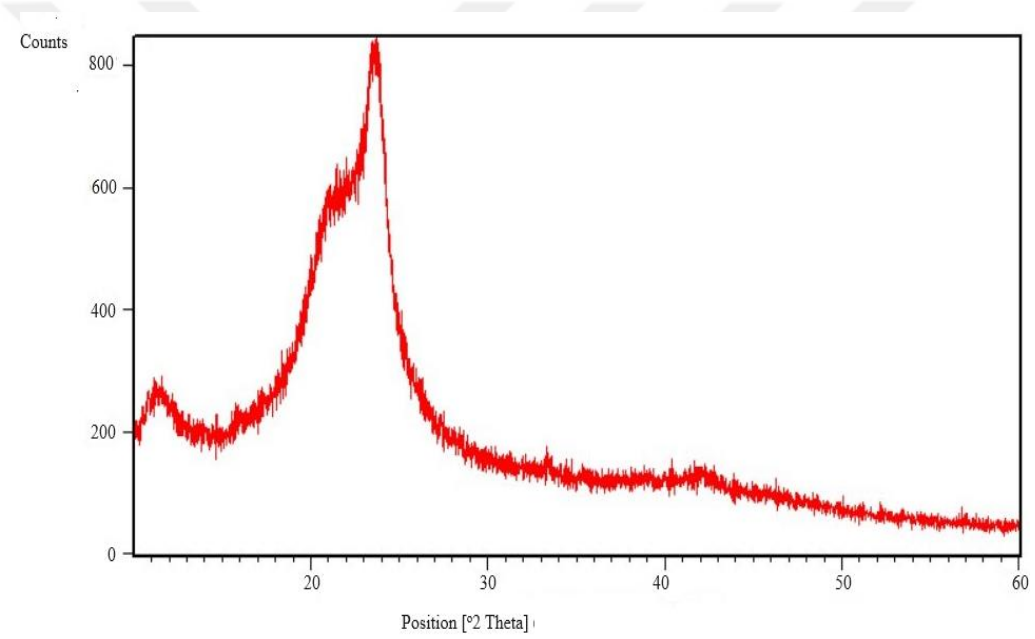


Figure 3.4. X-ray diffraction pattern of CAc-PPUF

3.3. BET Results

Surface area and pore size distribution (PSD), which have a significant impact on adsorption effectiveness, are essential characteristics of adsorbent materials (Mukhtar et al., 2020b). The Brunauer-Emmett-Teller (BET) technique is widely employed to ascertain the surface area of adsorbents. During the BET process, an inert gas such as nitrogen is continuously introduced to the adsorbent sample. Because of the weak van der Waals forces, nitrogen gas molecules are adsorbed by the pores and surface of the

adsorbent, forming an adsorbed gas monolayer. The nitrogen gas adsorption-desorption isotherms can be used to measure the specific surface area (m2/g) and pore structure of the adsorbent (George & Stephen Brunauer, 1938). In this study, the BET method with nitrogen gas was applied to identify the surface area and pore size distribution of CAc-PPUF.

As demonstrated in Figure 3.5a, the resulting isotherm can be classified as type-IV with an H3 hysteresis loop based on the IUPAC classification. The adsorption-desorption isotherm Type-IV N2 denotes mesoporous materials. Capillary condensation in mesopores caused by an increase in relative pressure is the cause of the big H3 hysteresis loop produced by the adsorption and desorption branches of the isotherm. It provides more evidence that CAc-PPUF is mesoporous (Thommes et al., 2015). Furthermore, pores with a slit morphology are indicated by H3 hysteresis (Mohammadi et al., 2011). Figure 3.5b displays the CAc-PPUF pore size distribution curve. The average pore radius of CAc-PPUF is estimated by the Barrett-Joyner-Halenda (BJH) model to be 19.96 nm, which provides additional evidence for the mesoporous (2–50 nm in size) character of CAc-PPUF.

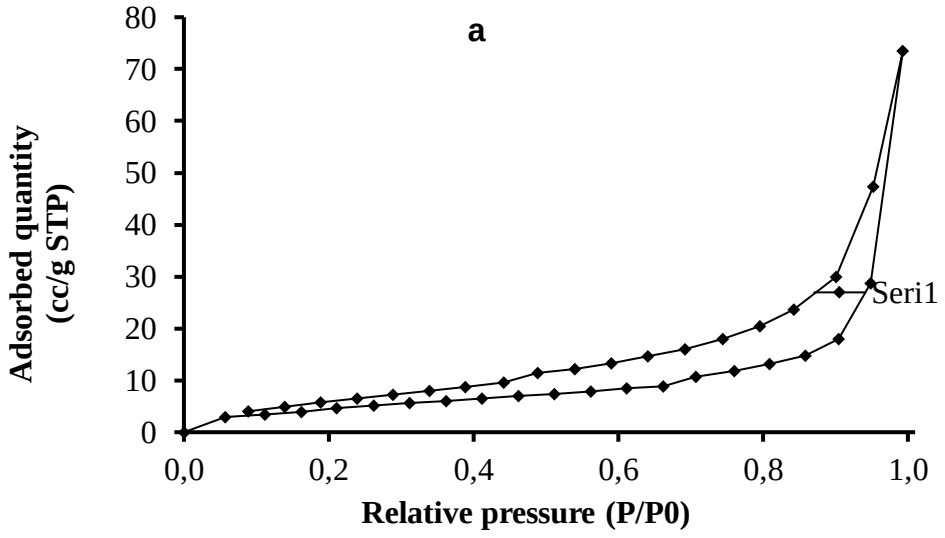


Figure 3.5a: N_2 Adsorption-Desorption Isotherm of CAc-PPUF

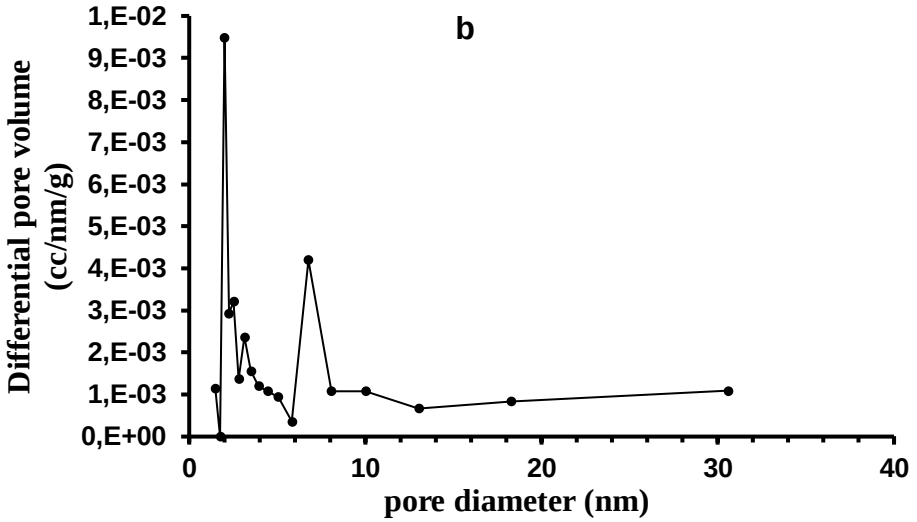


Figure 3.5b: Pore size distribution curve of CAc-PPUF

3.4. Zeta potential studies

Figure 3.7 displays the zeta potential versus pH graph of the prepared CAc-PPUF. As can be seen in the Figure 3.7, the zeta potential of CAc-PPUF gradually lowers as pH rises (H+ ion concentration drops). At pH 3.35, the zeta potential is 1.23. At around pH 3.73, it reaches zero. It drops to -12 mV at pH 9. When the pH is 4 or above, the zeta potential of CAc-PPUF is negative. A net negative surface charge is produced by the carboxylate (-COO-) and hydroxyl (-OH) functional groups present in CAc-PPUF.

The zeta potential of CMC-PPUF is also negative between pH 3 and pH 10, as shown in Figure 3.6. Furthermore, the zeta potential of CMC-PPUF is somewhat more negative at pH 6.5, which is the test solution pH of adsorption capacity studies. This could account for the relatively reduced adsorption capacities determined for CMC-PPUF.

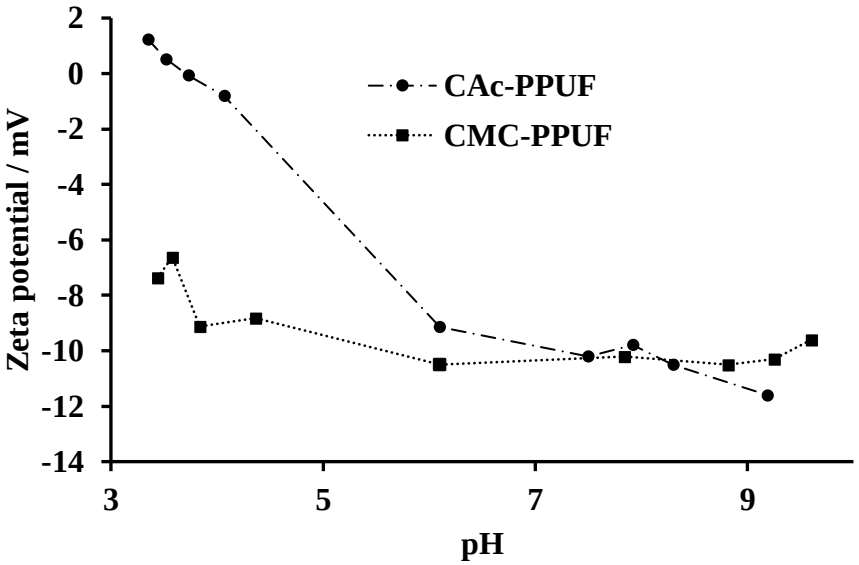


Figure 3.6. The effect of pH on zeta potential of CAc-PPUF and CMC-PPUF

3.5. Effect of pH on Pharmaceutical Adsorption by CAc-PPUF

Effect of pH on pharmaceutical adsorption by CAc-PPUF was studied at two different pH values, 6 and 8. The fact that the pH levels of water and municipal wastewater generally fall within the range of 6 to 8 led us to the selection of these two pH values. To study the effect of pH on pharmaceutical adsorption, ibuprofen and diclofenac were selected. pH effect was assessed by conducting adsorption experiments with ibuprofen and diclofenac at the selected pH values. Batch adsorption experiments were carried out as described in Section 2.6 with initial concentrations of pharmaceuticals varying between 20-80 mg/L. pH of each mixture containing a predetermined concentration of pharmaceutical and CAc-PPUF was adjusted to the desired pH by the addition of appropriate amount of 0.1 NaOH or 0.1 HCl. Then, the removal efficiencies were calculated for different initial concentrations, and pH values. Figures 3.7 a and b graph the adsorption efficiencies of the pharmaceuticals at the selected pH values. Figures 3.7 a and b show that the removals of diclofenac and ibuprofen slightly decreased when solution pH is increased from 6 to 8. The phenomena can be explained by the nature of the pharmaceuticals, and the surface functional groups of CAc-PPUF. Pharmaceuticals adsorption onto CAc-PPUF surface possibly occurs via interactions with the hydroxyl groups, carboxyl groups, and the aromatic rings on the surface of CAc-PPUF. Based on the zeta potential measurement, these groups are shown to be negatively charged at the studied pH values. Diclofenac and

ibuprofen are negatively charged due to their low pK_a values. At pH 8, concentrations of negatively charged ionized forms of diclofenac and ibuprofen are slightly higher compared to their concentrations at pH 6. This could intensify the charge repulsion between the negatively charged ions and the surface functional groups, and lead to a reduction in the removal efficiencies.

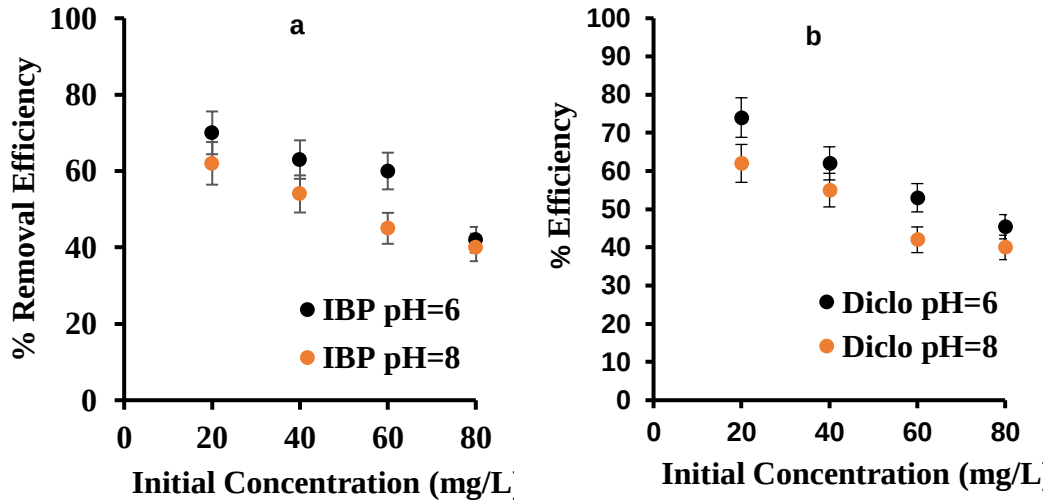


Figure 3.7. Effect of pH on pharmaceuticals adsorption by CAc-PPUF (a) IBP, and (b) Diclo (temperature = 25 °C)

3.6. Investigation of Pharmaceuticals Adsorption Mechanism by FTIR Spectroscopy

FTIR analysis provides information on possible mechanism(s) involved in pharmaceuticals adsorption by the cellulose based foam adsorbent. For this purpose, FTIR analyses were conducted on CAc-PPUF before and after pharmaceuticals adsorption. 0.1 g of CAc-PPUF was added to 10 mL of 1 mg/L pharmaceuticals solution. The prepared CAc-PPUF- pharmaceutical aqueous mixtures were shaken for 24 hours at 25 °C. After the adsorption process, the liquid supernatant was discarded using syringes. The remaining solid samples were washed by 10 mL deionized water. After discarding the liquid phase, the solid samples were dried in a vacuum oven at 60 °C.

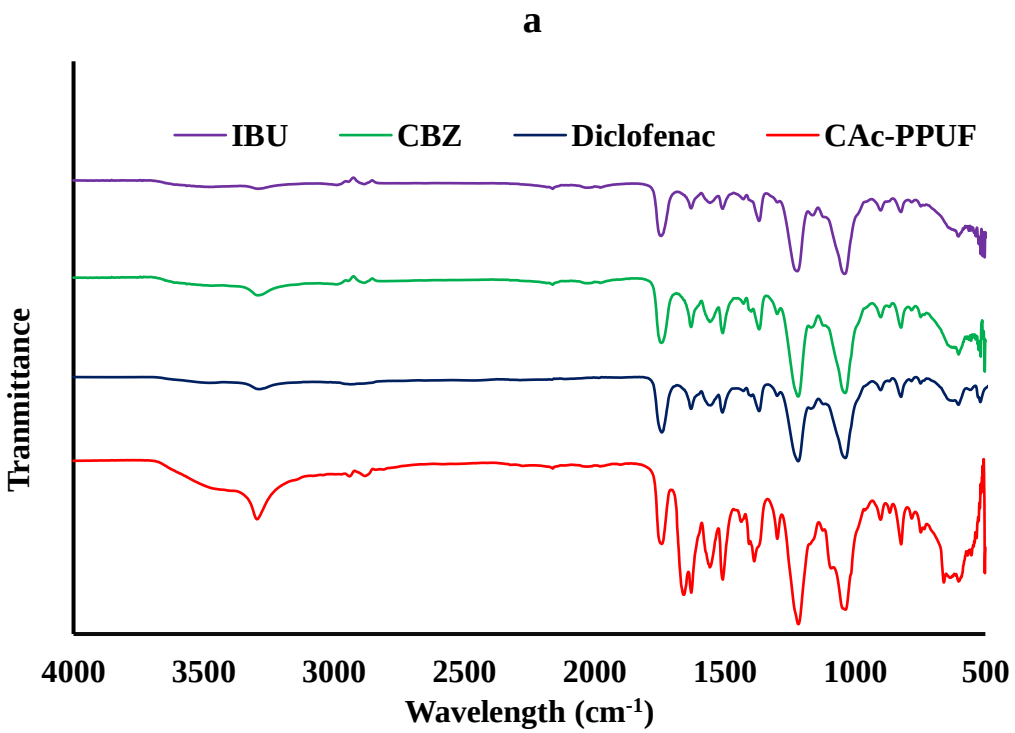
FTIR spectrum of CAc-PPUF was discussed earlier in Section 3.2.2, Figure 3.3 and 3.8, show the band positions in the FTIR spectra of CAc-PPUF before and after pharmaceuticals adsorption. The presented FTIR spectra show some of the adsorption peaks are shifted, changed, or decreased in intensity due to the adsorption of the target pollutants onto the adsorbent surface. FTIR is a vibrational spectroscopy, and any possible

changes in the environment of the chemical bonds affect the intensity as well as the positions of the peaks in the spectrum. The adsorbates in this study, coordinate with the functional groups in the adsorbent, and this results in the disappearance, shift and/or change in the intensity of the peaks (Hospodarova et al., 2018).

In Figure 3.8 a, it is highly evident that the wide OH band between 3672 to 2940 cm^{-1} due to the stretching vibrations of hydroxyl groups disappears in all the CAc-PPUF FTIR spectra that have been subjected to pharmaceutical adsorption. The symmetric and asymmetric stretching vibration absorbance bands for C-H of the aromatic ring detected at 2933, and 2910 cm^{-1} also disappeared in most of the adsorption spectra, except EE2, BPA, IBU, and CBZ adsorption spectra. The strong absorbance band at 1740 cm^{-1} due to the presence of carbonyl, C=O, functional group, is slightly shifted, and decreased in intensity after pharmaceuticals adsorption. The split peaks at 1651, and 1626 cm^{-1} due to C=C stretching in the aromatic ring were combined into one single peak at or around 1630.4 cm^{-1}, and went through some intensity loss. The adsorption band at 1507 cm^{-1} due to C=C stretching in the aromatic ring is present in all the CAc-PPUF spectra after adsorption. However, the peak intensity decreased significantly. The sharp peaks detected at 1215, and 1034 cm^{-1}, which display the presence of C–O–C stretch vibrations, are shifted, and lost intensity. The shoulder at 1070 cm^{-1} disappeared completely after adsorption. Finally, the peaks at 822 cm^{-1} lost intensity, and changed position while the peak at 657.1 cm^{-1} disappeared completely. These changes indicate the interactions between the target pollutants and the CAc-PPUF surface. It is apparent from Figure 3.8 a that different functional groups could be responsible for the adsorption of pharmaceuticals onto CAc-PPUF surface. All these observations indicated the possible involvement of hydroxyl groups, carboxyl groups, and the aromatic rings on the surface of CAc-PPUF in the adsorption process.

Once again, it is apparent from Figure 3.8 b that the wide OH band between 3699 to 3000 cm^{-1} present in CMC-PPUF spectrum disappears following target pollutants adsorption. The symmetric and asymmetric stretching vibration absorbance bands for C-H of the aromatic ring detected at 2936.1, and 2857.1 cm^{-1}, respectively, are shifted and lost their intensities. The shoulder at 1653 cm^{-1} due to the CO-NH bond, present at the bare CMC-PPUF, disappeared after pharmaceuticals adsorption. Intensity of the strong absorption band at 1613 cm^{-1} due to the carboxylate groups stretching vibrations

decreased significantly indicating the possible involvement of carboxylate groups in the pharmaceutical's adsorption process. The wide band between 1145 and 982 cm^{-1}, which includes several small bands, due to the characteristics of the C-O stretching on the polysaccharide skeleton is significantly reduced leaving one small band at 1073 cm^{-1} after adsorption. There are noticeable changes in intensities as well positions of the signals at 1012.5 cm^{-1} and 594.4 cm^{-1}. These changes indicate the interactions between the target pollutants and the adsorbent surface. Since CAc-PPUF and CMC-PPUF have similar functional groups adsorption of the target pollutants onto CMC-PPUF is occurring through a similar adsorption mechanism which involves hydroxyl groups, carboxyl groups, and the aromatic rings on the surface of CAc-PPUF in the pharmaceuticals adsorption process as suggested by the differences in the adsorption spectra.



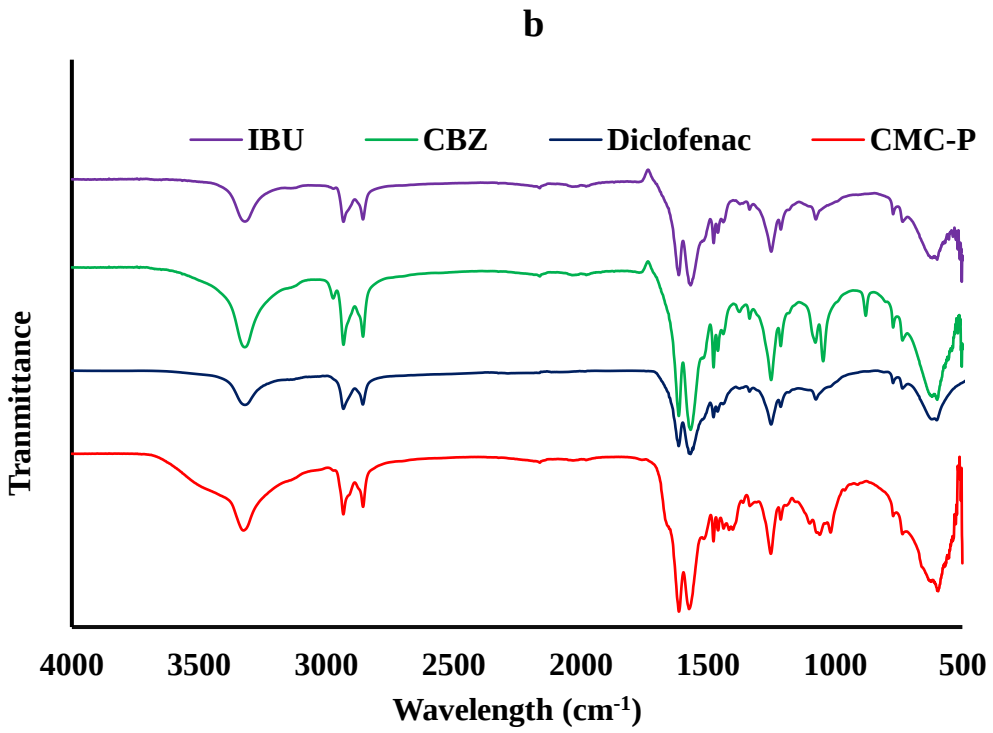


Figure 3.8. FTIR spectra before and after pharmaceuticals adsorption (a) CAc-PPUF (b) CMC-PPUF

3.7. Pharmaceuticals adsorption isotherms

In order to understand how the pharmaceuticals are dispersed from the liquid phase to the CAc-PPUF surface until equilibrium under fixed conditions, adsorption isotherms study were carried out. Exploring various adsorption isotherms gives valuable insights into the type of isotherm, adsorptive process, affinity held by the adsorbent, underlying reaction, and whether adsorption occurs in one or multiple layers (Alibrahim, 2023). For this purpose, diclofenac, and carbamazepine adsorption isotherm experiments were conducted by adding 0.01 g of CAc-PPUF into 10 mL of aqueous solution of target pollutants to achieve concentrations between 10-100 mg/L. Experiments were carried out at the original pH values of the mixtures. The pH values without adding acid or base were 6.5. The mixtures were shaken in the IKA (Germany) temperature-controlled shaker in batch mode at 25 °C for 24 hours with a mixing speed of 200 rpm. The samples were filtered with 0.2 µm PTFE filter. The remaining target pollutant concentrations in solution were measured by GC-MS. The adsorption capacity, q, was determined as described in Section

3.1. The equilibrium sorption data obtained for diclofenac, and carbamazepine were tested for two parameter isotherms (Langmuir and Freundlich) and three parameter isotherms (Sips and Dubinin-Astakhov) using the non-linear regression method as described in Section 2.7. Figures 3.9a and 3.9b present the experimental data, and the isotherm model predictions for diclofenac, and carbamazepine, respectively. The model parameters for the four selected isotherm models, and the goodness of fit measures for diclofenac, and carbamazepine adsorption by CAc-PPUF are presented in Table 3.1.

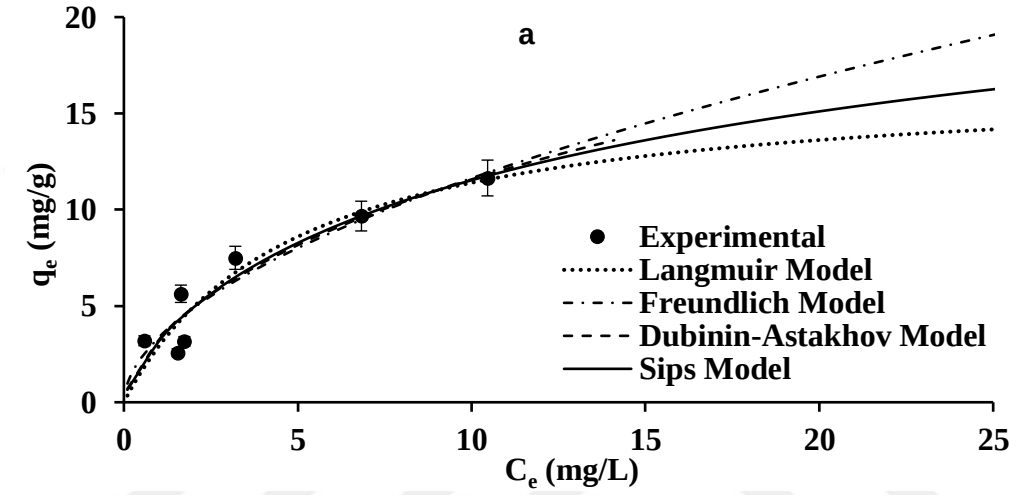


Figure 3.9a: The experimental data, and the isotherm model predictions for (a) diclofenac, and (b) carbamazepine.

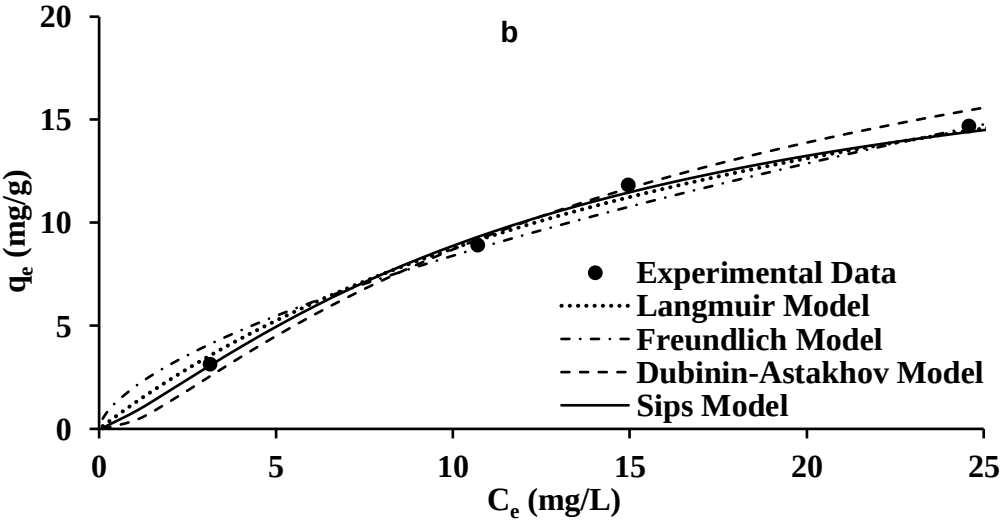


Figure 3.9b: The experimental data, and the isotherm model predictions for (a) diclofenac, and (b) carbamazepine.

Figures 3.9a and 3.9b reveal an increase in the equilibrium sorption capacity of the CAc-PPUF with increasing equilibrium concentrations of target pollutants in solution. This is due to the higher probability of collisions between CAc-PPUF particles and pharmaceuticals in solution. The higher equilibrium concentrations of the pollutants impacted the adsorption capacities since the driving force is higher at the initial stage to overcome all mass transfer resistances of the compounds between the adsorbent and adsorbate (Abdullah et al., 2021a). In the later stages, the increase in adsorption capacities with respect to equilibrium concentrations in solution slows down. The adsorption of these pharmaceuticals depends on the total available sorption sites of adsorbent, which become relatively limited as the concentration increases, resulting in a drop in their percentage removal when most of the active sites are fully occupied (Abdullah et al., 2021b).

Table 3.1 lists the values for the model parameters and error functions. As Table 3.1 shows, all four isotherm models tested fit the adsorption experimental data with R^2 values greater than 0.889, and NRMSE values less than 0.12. However, a better fitting was achieved by the Sips model with the best R^2, and the lowest NRMSE values for diclofenac, and carbamazepine adsorption by CAc-PPUF.

Table 3.2. Isotherm model parameters, and goodness of fit measures for diclofenac, and carbamazepine adsorption by CAc-PPUF

Model	Model parameters	R^2	χ^2	NRMSE
	Diclofenac			
Langmuir	Q_{max} = 16.9 mg/g	0.889	2.477	0.120
	K_L = 0.207 L/mg			
Freundlich	K_F = 3.361	0.890	1.845	0.120
	n = 0.5393			
Sips	Q_{max} = 28.3 mg/g	0.891	1.925	0.119
	K_s = 0.126			
	$1/n_S$ = 0.734			
Dubinin-Astakhov	$Q_{DA\ max}$ = 39.9 mg/g	0.893	1.980	0.118
	K_{DA} = 0.001			
	n_{DA} = 1.524			
	Carbamazepine			
Langmuir	Q_{max} = 26.2 mg/g	0.991	0.088	0.035
	K_L= 0.050 L/mg			
Freundlich	K_F = 2.034	0.965	0.359	0.069
	n = 0.0616			
Sips	Q_{max} = 20.4 mg/g	0.969	0.271	0.065
	K_s = 0.042			
	$1/n_S$ = 1.266			
Dubinin-Astakhov	$Q_{DA\ max}$ = 25.415 mg/g	0.996	0.033	0.025
	K_{DA} = 0.000002			
	n_{DA} = 2.938			

Sips model is an empirical equation with three parameters that combines Langmuir and Freundlich isotherms, approaching Freundlich model at low solution concentrations, and Langmuir isotherm at high concentrations (Hernández-Abreu et al., 2020; Tang et al., 2012). Likewise, the good adjustment obtained with Sips model could be due to that this isotherm takes into account the heterogeneity of the adsorbent surface (Álvarez et al., 2015). The adsorption process indicated in Section 3.7 to be based on various functional groups is further supported by the Sips model, which indicates the heterogeneous nature of the CAc-PPUF surface.

3.8. Pharmaceutical Adsorption Kinetics

Adsorption kinetics is the measure of the adsorption uptake with respect to time at a constant concentration, and it provides valuable information on the possible adsorption mechanisms. PFO, PSO, and Elovich models usually fit well with the organic matter adsorption kinetics of carbonaceous adsorbents in an aqueous medium (Revellame et al., 2020). Therefore, in this study these three models were employed to characterize the adsorption kinetics of diclofenac and ibuprofen on CAc-PPUF. During the study of adsorption kinetics, only CAc-PPUF was employed since it provided somewhat better removal efficiency. Furthermore, both their CAc-PPUF and CMC-PPUF adsorption mechanisms are relatively comparable, as indicated by their FTIR spectra taken after pharmaceuticals adsorption. As a result, the two adsorbents are predicted to have identical kinetics.

Figures 3.10, a and b show the time dependence of the adsorbed mass, q_t, and the model predictions for diclofenac and ibuprofen adsorption by CAc-PPUF, respectively. The model parameters for the three selected isotherm models, and the goodness of fit measures for diclofenac and ibuprofen adsorption by CAc-PPUF are presented in Table 3.2. Table 3.3 shows that the correlation coefficients for the PFO and PSO kinetic models for ibuprofen, 0.899 for PFO and 0.910 for PSO, are highly comparable. More experimental data in the early stage of adsorption, where the adsorbed mass significantly increases with time, are needed to differentiate between the two models. Nevertheless, the rapid kinetics of pharmaceuticals adsorption by CAc-PPUF hinder the collection of adequate data in the initial phase. The results presented in Figure 3.10 a, b, and Table 3.3 suggest that the PSO kinetic equation results in a greater prediction efficiency compared to the other two kinetic equations. The experimentally gathered data are more consistent with a PSO model-based function. Thus, it can be concluded that the adsorption mechanism of CAc-PPUF is well described by the pseudo-second order kinetic equation.

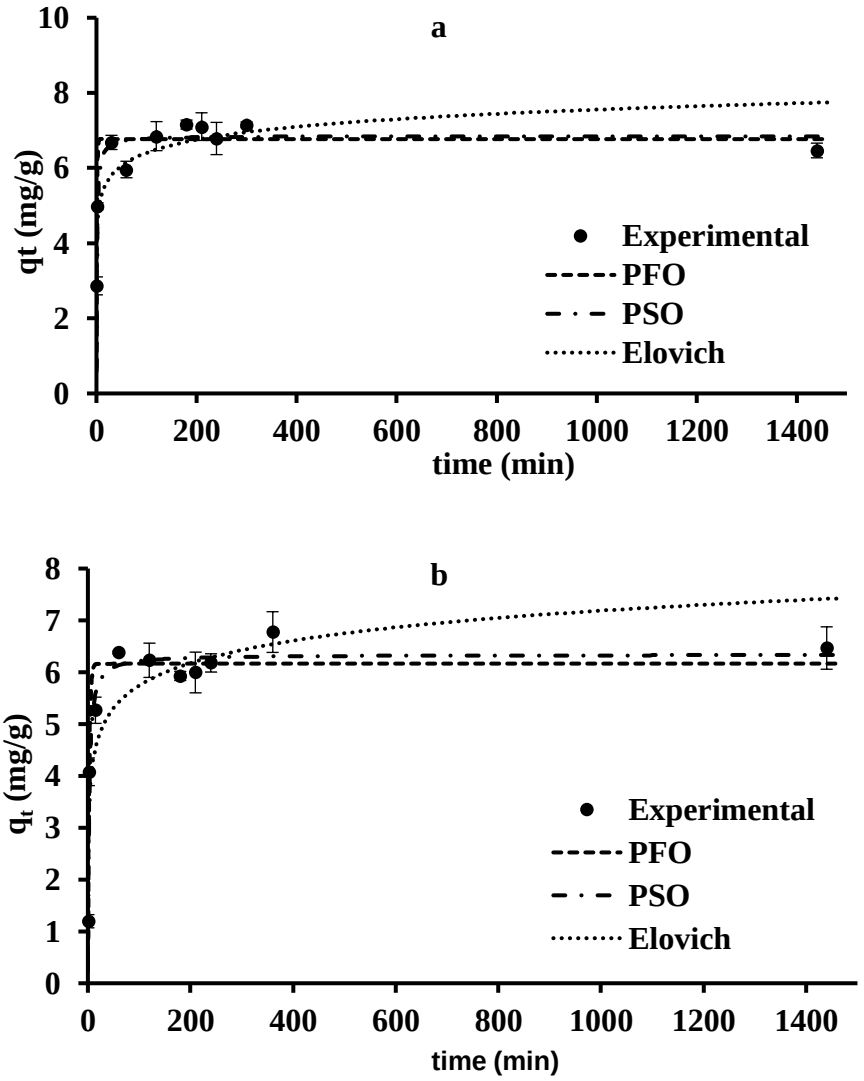


Figure 3.10. Kinetic data and model predictions for pharmaceuticals adsorption by CAc-PPUF (a) diclofenac, and (b) ibuprofen adsorption by CAc-PPUF (pH= 6.5, t=25 °C, initial concentration=100 ppm, time=24 hours)

Table 3.3. Kinetic model parameters, and the goodness of fit measures for diclofenac and carbamazepine adsorption by CAc-PPUF

Model	Model constants	R2	$\chi 2$	NRMSE
	Diclofenac			
PFO	K_1 = 1.079 min^{-1}	0.710	0.916	0.160
PSO	K_2 = 0.136 g/(mg x min)	0.907	0.277	0.091
Elovich	α = 1840.2 mg/(g*min) β = 2.001 g/mg	0.711	0.860	0.160
	Ibuprofen			
PFO	K_1 = 0.403 min^{-1}	0.899	0.707	0.090
PSO	K_2 = 0.078 g/(mg x min)	0.910	0.760	0.086
Elovich	α = 58.1 mg/(g*min) β = 1.591 g/mg	0.763	1.608	0.139

3.9. Regeneration and Reuse Studies on Pharmaceuticals Adsorption

For a cost-effective production, the reusability of adsorbent is a significant factor. In this section, the regeneration and reuse of CAc-PPUF is demonstrated. The regeneration of CAc-PPUF was carried out by desorbing carbamazepine, ibuprofen, and diclofenac from CAc-PPUF surface with methanol, ethanol, water mixture in a volumetric ratio of 4:1:1. The data are shown in Figure 3.11.

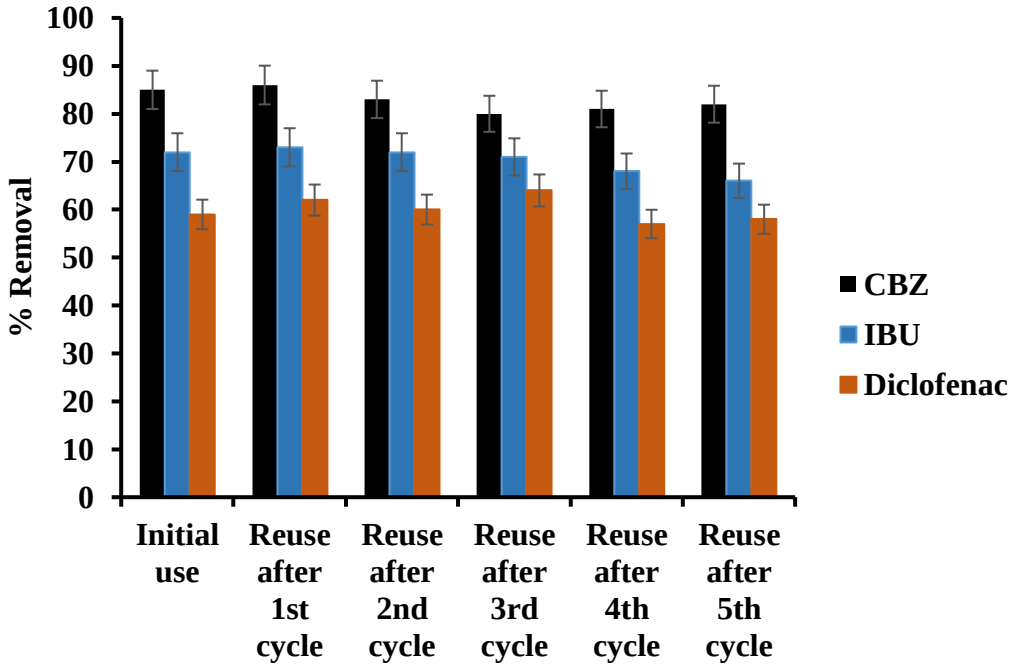


Figure 3.11. Regeneration performance of CAc-PPUF (pH=6.5; concentration = 20 mg/L; adsorbent dosage = 0.5 g/L; contact time = 2 pharmaceuticals)

After five regeneration and reuse cycles, the removal rates of carbamazepine, ibuprofen, and diclofenac were 86-71%, 73-66%, and 64-57%, respectively. For the three pharmaceuticals examined, the removal rates had averages and standard deviations of 82.8±2.31%, 70.3±2.73%, and 60±2.61%, for carbamazepine, ibuprofen, and diclofenac, respectively. These results show that the adsorbent material retained its adsorption capacity even after five regeneration cycles. CAc-PPUF exhibits excellent reusability performance, suggesting that it can be effectively applied to remove pharmaceuticals from contaminated aquatic settings.

4. CONCLUSIONS

The aim of this study was to investigate a cost effective cellulose based foam adsorbent that was tested for the removal of pharmaceutical organic pollutants from water. The cellulose-based foam was developed with functional groups that were to be effective for the removal of target pharmaceuticals from water using adsorption mechanism. Three target pollutants were selected as carbamazepine (CBZ), Ibuprofen (IBP) and Diclofenac (DICLO).

Two cellulose based adsorbents were synthesized i.e. CAc-PPUF and CMC-HMPUF, and were tested for the removal of three selected target pharmaceuticals from water. The adsorption capability of the synthesized adsorbents was studied under the same conditions in order to determine the best adsorbent. The tests were all carried out with similar conditions and concentrations of 100mg/L and 10g/L at room temperature and pressure (RTP) using the same GC-MS device. According to the results obtained, both adsorbents i.e. CAc-PPUF and CMC-HMPUF were proven to be effective adsorbents for the removal of diclofenac, carbamazepine, and ibuprofen. The adsorption capacities of CMC-PPUF were between 1.06 mg/g and 1.56 mg/g, whereas those of CAc-PPUF varied from 1.180 to 1.990 mg/g. The tested pharmaceuticals exhibited removal efficiencies ranging from 59% to 85% for CAc-PPUF, and between 53% and 78% for CMC-PPUF. According to these results, it indicated that CBZ is adsorbed by both adsorbents to greater extend and diclofenac has the lowest tendency to be adsorbed by the adsorbents. CAc-PPUF having shown a higher affinity to adsorption, it was used as the adsorbent material in all of the batch adsorption experiments in the following sections of the study. All three pharmaceuticals tested showed log K_{ow} values lower than 2.5, indicating relatively higher solubility, and higher hydrophilicity. Adsorption of a compound inversely depends on its solubility, and on its polarity or degree of ionization, thus, drugs are known to be weak bases or weak acids. The more the drug is in its ionized form, the less likely it is to be adsorbed.

Fourier Transform Infrared Analysis (FTIR), scanning electron microscopy (SEM), Brunauer-Emmett-Teller (BET), XDR analysis and Zeta Potential studies were used to analyze CAc-PPUF. The FTIR investigation verified the structure of CAc-PPUF. A very porous, amorphous material with variable micropore gaps was seen in the SEM. Using

BET analysis, the mesoporous nature of CAc-PPUF was investigated. The results show that the material's surface is 23.15 m^2/g and its average pore radius is 19.96 nm. At pH 3.35, the zeta potential of CAc-PPUF is 1.23. At roughly 3.73 pH, it reaches zero. At pH 9, it falls to -12 mV. The zeta potential of CAcPPUF showed a negative charge in the pH range of 4 to 9. This is also due to the low K_a values of surface functional groups. The adsorbent CAc-PPUF has a wide pH range of negative zeta potential, rendering it a potentially effective method for extracting pharmaceuticals from water.

Different batch experiments were carried out to determine the adsorption isotherms of the pharmaceuticals in the aqueous solutions for different test conditions. The tests were repeated for the target pharmaceutical pollutants, carbamazepine, ibuprofen and diclofenac, using CAc-PPUF adsorbent. Diclofenac, and carbamazepine adsorptions were studied by adding 0.01 g of CAc-PPUF into 10 mL of aqueous solution of target pollutants to achieve pharmaceutical concentrations between 10-100 mg/L at pH 6.5. Equilibrium sorption data obtained for diclofenac, and carbamazepine were tested for the two parameter isotherms (Langmuir and Freundlich) and the three parameter isotherms (Sips and Dubinin-Astakhov) using the non-linear regression method to determine the goodness of fit.

Increase in the equilibrium sorption capacity of the CAc-PPUF with increasing equilibrium concentrations of target pollutants is observed due to the higher probability of collisions between CAc-PPUF particles and pharmaceuticals in solution. High concentrations of pharmaceuticals impact the adsorption capacities whereas the increase in adsorption capacities with respect to equilibrium concentrations in solution slows down. The adsorption of these pharmaceuticals depends on the total available sorption sites of adsorbent, which become relatively limited as the concentration increases. Four isotherm models were tested and fit the adsorption experimental data with R^2 values greater than 0.889, and NRMSE values less than 0.12. The Sips model achieved a higher value with the best R^2, and the lowest NRMSE values for diclofenac, and carbamazepine adsorption by CAc-PPUF.

Adsorption experiments were carried out to evaluate the adsorption capability with time at a given constant concentration. Three models were used to characterize the adsorption kinetics of diclofenac and ibuprofen on CAc-PPUF. Both CAc-PPUF and CMC-PPUF

adsorption mechanisms are relatively comparable as indicated by their FTIR spectra and are predicted to have identical kinetics. CAc-PPUF was used for this study due to the higher adsorption capacity values as discussed.

Correlation coefficients for the PFO and PSO kinetic models for ibuprofen were 0.899 and 0.910 respectively and highly comparable. The rapid kinetics of pharmaceuticals adsorption by CAc-PPUF affect the collection of enough data in the initial adsorption phase, however, PSO kinetic equation results in a greater prediction efficiency compared to the other two kinetic equations. The data collected are more consistent with a PSO model-based function, hence, it can be concluded that the adsorption mechanism of CAc-PPUF is well described by the pseudo-second order kinetic equation.

Regeneration and reuse studies were carried using CAc-PPUF and evaluated with the three pharmaceuticals. Pharmaceuticals being evaluated were tested for disorbing from CAc-PPUF surface using methanol, ethanol, water mixture in a volumetric ratio of 4:1:1. The data collected indicates that after five regeneration and reuse cycles, the removal rates of carbamazepine, ibuprofen, and diclofenac were 86-71%, 73-66%, and 64-57%, respectively. Removal rates showed averages and standard deviations of 82.8±2.31%, 70.3±2.73%, and 60±2.61%, for carbamazepine, ibuprofen, and diclofenac, respectively. This indicated that the adsorbent maintained its adsorption capacity even after five regeneration cycles.

The aim of this study was to investigate the pharmaceuticals adsorption capacity of a newly synthesized cellulose adsorbent from water. The new CAc-PPUF adsorbent shows very good adsorption and reusability performance, which indicates CAc-PPUF can be successfully used for the removal of pharmaceuticals from contaminated water environments.

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APPENDIX

APPENDIX A. GCMS CALIBARTION FOR PHARMACEUTICALS ANALYSIS

Individual sets of calibration standards were prepared for each pharmaceutical separately. In order to prepare a calibration standard containing a single pharmaceutical, appropriate amounts of reference standards were dissolved in 10 mL of GC grade acetone to obtain 1000 ppm stock standard solution of the pharmaceutical. Calibration standards at 500, 1000, 2500, 5000 and 10000 pg/μL concentrations were then prepared in GC grade acetone by dissolving an appropriate volume of stock standard solution in 10 mL GC grade acetone.

In the calibration graphs, picograms of mass values injected into the GCMS were used instead of concentration. The preparation of GCMS calibration graphs based on the mass values injected into the GCMS facilitates the calculation of pharmaceutical concentrations in aqueous samples subjected to various pretreatments such as drying and redissolution in an organic solvent. Calibration curves of pharmaceuticals were obtained using surrogate dilution technique. In analytical methods where various pretreatments are applied to the samples before analysis, as in this study, it is inevitable to obtain calibration curves using surrogate dilution technique to minimize errors caused by pretreatments. In the surrogate dilution technique, the calibration curve is obtained for each injected mass of pharmaceutical by calculating the ratio of the peak area of the pharmaceutical to the peak area of the surrogate added to the sample. The same amount of surrogate is added to all the standard solutions, test samples and witness samples analyzed. Thus, when calculating the concentrations of the samples, losses during pre-treatment are directly taken into account. Figures A.1, A.2 and A.3 present the calibration curves obtained for diclofenac, ibuprofen and carbamazepine obtained by surrogate dilution technique.

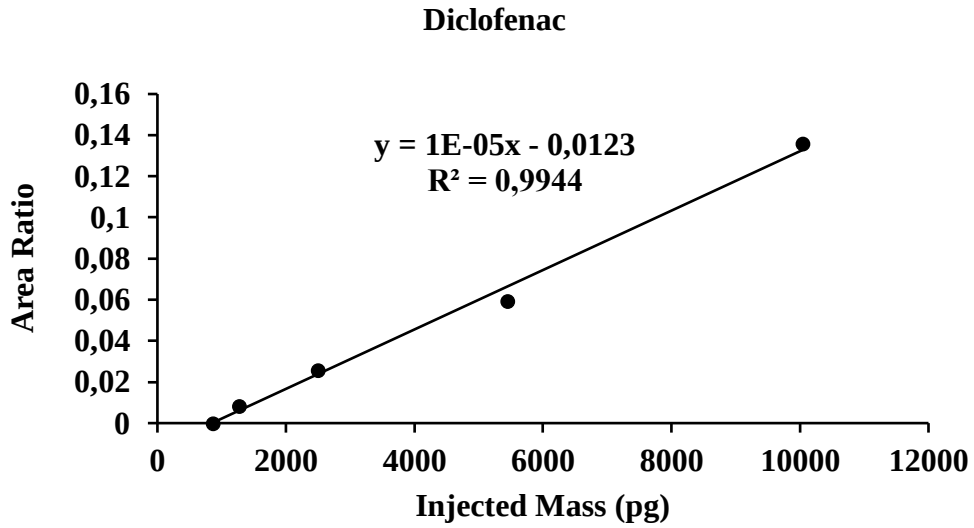

Figure A.1. Calibration curve of diclofenac.

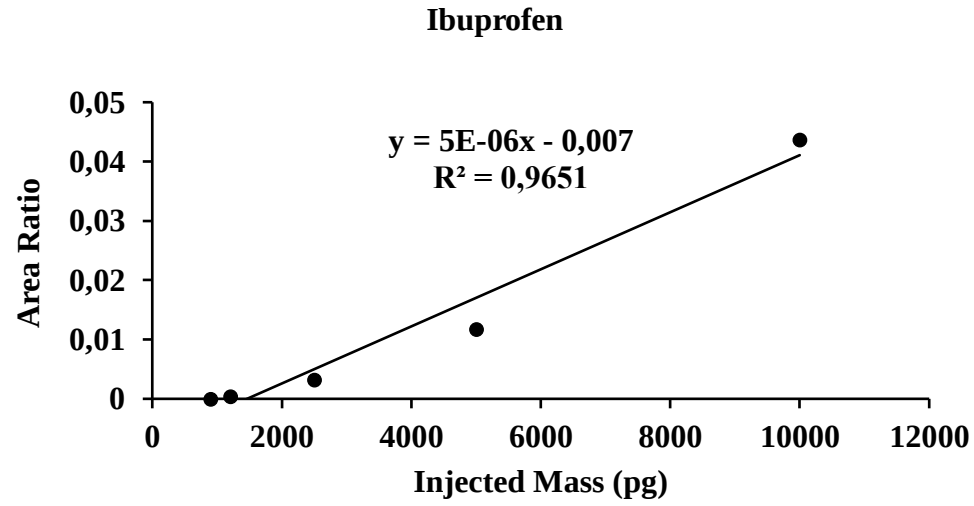

Figure A.2. Calibration curve of ibuprofen

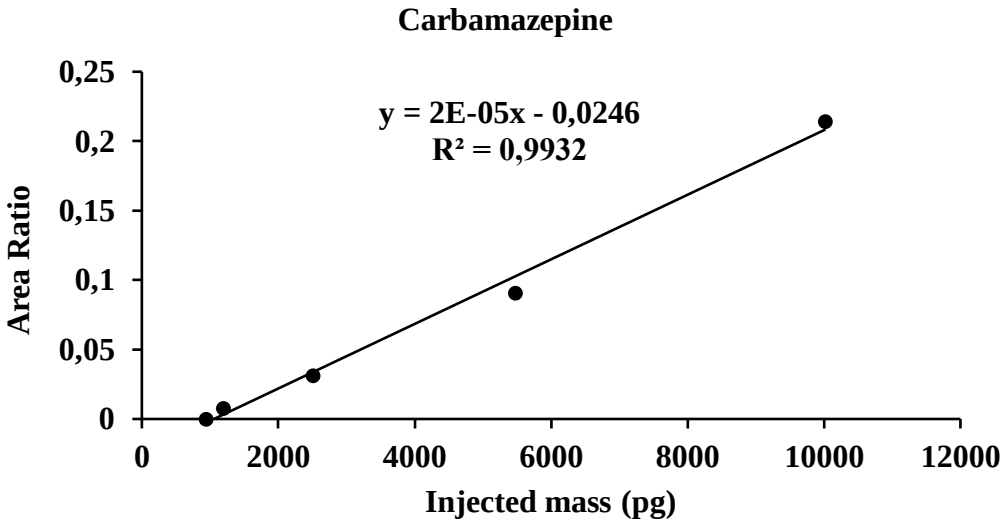

Figure A.3. Calibration curve of carbamazepine

CURRICULUM VITAE

Summary:

A dynamic and ambitious professional engineer with experience in engineering, production, and sales.

Experience:

2021- 2023 TUBİTAK / MSc. Environmental Engineer Research
GCMS analysis.
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Business Development, Production & Sales Engineer Responsible for improving markets in all regions,
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2016 – 2017 INTERNSHIP - TPAO (Turkish Petroleum),
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Directional drilling and MFR systems),
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2012 -2014 MUSTAFA AKGÜL MACHINES
International marketing manager for machinery and gas industry.

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Articles / Conferences Participation and certificates

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