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Enhanced Removal of Diclofenac and Lead by Granular Activated Carbon: Optimization and Mechanistic Insights

Rana Fadhil Hussien*, Waleed M. Sh. Alabdraba

Environmental Engineering Department, College of Engineering, Tikrit University, Tikrit 34001, Iraq

Corresponding Author Email: rana.fadel@st.tu.edu.iq

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ABSTRACT

This study investigates the removal of diclofenac sodium (Voltaren) and lead (Pb) from aqueous solutions using granular activated carbon (GAC) as an adsorbent. To optimize the adsorption process, parameters including pollutant concentration, contact time, pH, temperature, GAC dosage, and agitation speed were evaluated. The optimal conditions for lead removal were 40°C, 250 rpm, and 1.5 g/L of GAC, while Voltaren showed maximum adsorption efficiency at 40°C and 200 rpm with the same GAC dosage. Scanning Electron Microscopy (SEM) confirmed significant changes in the surface morphology of GAC after adsorption, indicating successful uptake of both pollutants. X-ray diffraction (XRD) analysis revealed characteristic peaks of GAC, and new peaks emerged after contaminant exposure, suggesting chemical interaction and adsorption. Among all parameters tested, temperature and agitation speed had the most significant influence on removal efficiency. The adsorption capacities for Voltaren and lead were 1.9 mg/g and 1.7 mg/g, respectively, corresponding to removal efficiencies of 95% and 85%. The slightly lower efficiency for lead may be attributed to its chemical speciation and interaction mechanisms with GAC. These findings highlight the potential of GAC as an effective and sustainable adsorbent for water treatment applications, and provide strategies to improve its adsorption performance and regeneration capabilities.

1. INTRODUCTION

Water pollution caused by pharmaceuticals, herbicides, and other organic contaminants is one of the critical burdens on ecosystems in all regions of the world. Pharmaceuticals and pharmaceutically active compounds (PhACs) are becoming increasingly important as emerging contaminants (ECs) because they pose a threat to human health and aquatic organisms [1, 2]. Pharmaceuticals, including painkillers, antibiotics, and birth control pills, are commonly found in water sources such as surface water, groundwater, and effluent from wastewater treatment plants, which return recycled water to the drinking supply [3]. The release of wastewater contaminated by pharmaceutical residues into these bodies of water results in pollution, which creates risks for ecosystems and human populations [4].

One of the most frequently reported pharmaceuticals in natural waters is diclofenac (DCF) [5]. Diclofenac is a commonly used non-steroidal anti-inflammatory drug (NSAID) for treating rheumatoid arthritis. DCF has been found in surface and groundwater, where it is resistant to degradation due to its relatively low biodegradability [6, 7]. Despite its low biodegradability, it degrades easily in the environment. Even at low levels, the reproductive toxicities of various animal species are recognized as adverse effects [8]. For this reason, effective techniques to remove DCF from contaminated water sources become absolutely necessary for environmental control.

Due to its worldwide use, diclofenac (DCF) has finally emerged as a common contaminant in water systems. Although diclofenac is beneficial to human health, it usually cannot be thoroughly removed in traditional wastewater treatment because only a small portion of it is degraded, leaving residue in surface water, groundwater, and drinking water. DCF could generate environmental risks due to its effects on aquatic life at very low concentrations. Conventional DCF treatment processes, such as membrane filtration, ozonation, and reverse osmosis, are energy-demanding, expensive, or less effective for removing DCF from wastewater; therefore, an alternative cost-effective treatment is required [8].

Alongside pharmaceutical and additionally inorganic poisons, such as heavy metals, including lead (Pb^{+2}), are also important environmental pollutants. Lead is poisonous and can build up in aquatic systems, resulting in major health problems—including neurological harm, reproductive issues, and developmental delays, particularly among kids. Mining, manufacturing batteries, and burning fossil fuels are among the main Pb^{+2} contributors to water systems. Pb^{+2}, which can be solved or alleviated by drinking water, is a significant environmental problem to solve (but according to DCF, it isn't effectively removed by chemical precipitation—anion exchange—or membranes) [7].

Adsorption, especially with granular activated carbon

(GAC), is a promising process for DCF and Pb removal from water. GAC is renowned for its high specific surface area, large pores, and varying surface chemistry, thus capable of effectively adsorbing diverse pollutants such as pharmaceuticals and personal care products (PPCPs) and heavy metals [9]. GAC is a low-cost and convenient material that can be reused several times for water purification. For pollutant reduction, organic (e.g., inorganic contaminants, including pharmaceuticals), such as DCF, and inorganic substances (e.g., heavy metals) have been removed from water by GAC adsorption effectively and economically compared with other technologies [7, 10].

And lastly, a common medicine, DCF, and a poisonous heavy metal, lead (Pb^{+2}), are also very detrimental to the environment as well as your health [11]. The drug, diclofenac, used mainly to treat inflammation, has been detected in several water sources and triggers concerns about how it could be affecting aquatic life as well as human health. Lead is commonly found in contaminated water systems due to industrial use. It is toxic to human health in particularly for children [12, 13].

Due to the fact that both diclofenac and lead are bad for your health, it is crucial to remove them from contaminated water [14, 15]. Chemical precipitation and filtration are two conventional methods that have not been highly successful or economical. And, increasingly, people are looking at other adsorbents, including GAC, in order to get rid of a range of different contaminants in water, and that’s been showing great promise [16].

GAC, a type of granular activated carbon, is studied broadly by scientists because of its large surface area, porosity, and ability to adsorb diverse contaminants, including heavy metals like lead and organic pollutants such as diclofenac [17, 18]. Many studies have demonstrated that GAC can adsorb these pollutants well under different experimental conditions, especially concentrations, temperatures, pH, and dosages of adsorbent.

However, while the GAC has shown promise in removing DCF and Pb^{+2} simultaneously, it is difficult to determine which would interact in the same adsorption system. The competitive relationship between DCF and Pb^{+2} for adsorption sites, combined with the effect of environmental factors such as pH and temperature, makes it difficult to cooperatively remove them [19, 20]. The competitive binding of microorganisms and NOM adsorption, as well as the optimum process operating conditions, needs to be further investigated to determine the GAC service life for co-contaminated water treatment [21, 22].

Although DCF- or Pb-adsorption characteristics have been widely studied, few studies systematically compared the removal of these two pollutants in the same adsorption system [23]. The associations of DCF and Pb in co-contaminated systems, such as the competitive adsorption affected by environmental variables, are unclear. Moreover, there is insufficient information addressing the optimal conditions for simultaneous removal of both pollutants, which is indispensable for designing a more cost-effective treatment system [24, 25].

Filling these knowledge gaps is necessary for the development of methods to control challenging contamination, which comprises pharmaceuticals and HM in real-world water systems.

In this context, the goal of the present research is to contribute such evidence by checking competitive impacts in relation to DCF and Pb co-adsorption on GAC and identifying optimum removal conditions in a single step. The adsorption behavior of these pollutants, as well as the interaction among them in the adsorption process, would provide significant information for designing and developing effective water treatment processes for co-contaminated systems.

1.1 The research objectives

The investigation will focus on the competitive adsorption of DCF and Pb, taking into account the concentration relationship and environmental conditions. We aim to identify the most effective factors, such as pH, contact time, and temperature, for the simultaneous adsorption of DCF and Pb(II).

Moreover, the objectives of the study are to investigate the efficiency of granular activated carbon GAC material in removing diclofenac sodium and lead from water. The work is concerned with the evaluation of adsorption potentialities of GAC towards the two contaminants at different pH, temperature, and contact time. Understanding adsorption isotherms and kinetics is investigated. The research also seeks to find out if GAC can serve as a lasting solution to cleanse water of medicine and heavy-metal contamination.

1.2 The statement of the problem

There is an extensive body of research showing how GAC does adsorb various contaminants; however, not many studies have investigated the effectiveness of this substance in removing the DCF and Pb^{+2} at the same time. Those pollutants are general environmental pollutants, but they have very different chemical characteristics, which makes it difficult to remove them at the same time. Although a variety of studies have reported on GAC adsorption for individual pollutants, such as GAC's removal effectiveness towards medicines like diclofenac and heavy metals like lead, have not been mechanistically studied comparatively in depth. In addition, there are synergistic relationships between critical factors, such as adsorbent dosage, agitation speed, contact time, pH, and temperature, for the removal of these two types of pollutants that were overlooked in numerous related literature studies nowadays.

Previous studies have found that GAC is utilized for adsorbing many contaminants, but we don’t know how it performs with diclofenac and lead in different scenarios. This ignorance complicates efforts to optimize GAC as a feasible adsorbent for the simultaneous removal of the two contaminants [26]. The adsorption mechanism of diclofenac medication and its subsequent release and recapture is different from that of heavy metals such as lead; however, very few works have extensively studied both simultaneously.

2. LITERATURE REVIEW

Since water contaminants harm the environment and people, there has been a lot of research on how to remove them [27]. DCF, a popular medicine, and lead (Pb), a toxic heavy metal, are the most problematic contaminants because they persist in water systems for so long. As a common anti-inflammatory, diclofenac is found in wastewater. Industrial operations and urban runoff cause most lead contamination. While several studies have examined how to remove diclofenac and lead individually, few have examined how to do it simultaneously using granular activated carbon [28].

GAC is noted for its large surface area and capacity to absorb several organic and inorganic contaminants. However, GAC's ability to remove diclofenac and lead simultaneously, and its adsorption mechanisms, are yet unknown. This section reviews the literature on diclofenac and lead adsorption with GAC, concentrating on pH, temperature, adsorbent dosage, and contact duration. We also highlight research gaps, such as the lack of studies that compare the clearance of these two unique pollutants at the same time and investigate their mechanisms.

Espina de Franco et al. [2] represented the most toxic non-steroidal anti-inflammatory drug, diclofenac, which is a common ingredient in wastewater treatment plants and surface waterways. To remove emerging contaminants, such as pharmaceutical compounds, from water sources and wastewaters, adsorption has been widely used. This research looked into diclofenac adsorption in batch operations and fixed-bed columns using activated carbon as the adsorbent. We used batch adsorption experiments to determine adsorption isotherms, and we used a full factorial two-level experimental design with three variables to test fixed-bed adsorption: initial pollutant concentration (20-100 mg/L), adsorbent weight (0.5-1.0 g), and volumetric feed flow rate (3-5 mL min^{-1}). At 298, 308, and 318 K, the Freundlich equation successfully explains the isotherm behaviour, as shown by the adsorption equilibrium at different temperatures. According to the results of the thermodynamic analysis, ΔG0 was negative, whereas ΔH0 and ΔS0 were both positive. The adsorption of diclofenac onto activated carbon is enhanced at higher temperatures and occurs independently, according to this finding. When the starting concentration was higher, and the flow rate was lower, the breakthrough time—the time it takes for the effluent to contain 5% of the original concentration—was shorter. Fractional bed usage increased in tandem with increases in starting concentration and flow rate. However, fractional bed utilisation decreased as activated carbon amounts increased. To fit the experimental data for breakthrough curves, we utilised analytical models developed by Thomas, Bohart-Adams, and Yan. Out of all the experiments, the Yan model exhibited the highest average of the determination coefficients ($R^2 = 0.9842$), although the packed column adsorption was better predicted by the Thomas equation.

According to Tünay et al. [29], the goal of this study is to evaluate the efficacy of phosphoric acid-activated hazelnut shell carbon (HSAC) in removing the antibiotics diclofenac (DC), ciprofloxacin (CIP), and sulfamethoxazole (SMX) from various water-based solutions and wastewater. Numerous pits of varied sizes and forms were found on the surface of HSAC through a scanning electron microscopy study. The Brunauer-Emmett-Teller surface area of HSAC was determined to be 1,173 mg g^{-1}. Concerning the batch adsorption of DC, CIP, and SMX, several factors were examined, such as pH, contact time, initial concentration, dosage, and temperature. We utilized the Freundlich, Dubinin-Radushkevich, Temkin, and Langmuir isotherms to simulate the adsorption equilibrium of DC, CIP, and SMX. Using the Langmuir isotherm, we can confirm that DC, CIP, and SMX were adsorbed onto HSAC. At 125, 95.2, and 285.7 mg g^{-1}, respectively, DC, CIP, and SMX exhibited the highest adsorption capabilities. The pseudo-second-order model was found to be the most appropriate for describing the adsorption kinetics of DC, CIP, and SMX after extensive deliberation. Endothermic and spontaneous adsorption of DC, CIP, and SMX onto HSAC was shown in thermodynamic investigations. Based on the results, HSAC is a great adsorbent for cleaning wastewater of DC, CIP, and SMX; it's also environmentally friendly and readily available.

Stjepanović et al. [28] reported that drugs in natural waters have been the subject of extensive study over the past decade due to concerns that they pose health risks to humans and ecosystems. It is a fact that drugs make it into municipal sewage due to their excessive use. Wastewater treatment plants do not prioritise drug removal since ongoing drug testing in natural waters and drinking water is not mandated by international and national regulations. When you need pain relief, inflammation reduction, or fever reduction, reach for diclofenac, also known as 2-[2-(2,6-dichloroanilino)phenyl] acetic acid (DCF), a nonsteroidal drug. Due to its characteristics, DCF is able to survive in water and quickly ascend the food chain. Accordingly, DCF should be removed from wastewater before discharging it into aquatic bodies. Eliminating DCF from water using adsorption is a simple and fast process. The potential for DCF removal by adsorption onto activated carbon is investigated in this work. As adsorbents, we tested modified commercial activated carbon Cullar (MC), which is activated carbon derived from commercial Cullar that has been modified for a specific application (e.g., adsorption, catalysis, biofuel production). The modification can be done by chemical activation, surface functionalization, or impregnation with other materials to enhance its performance over the unmodified form. Other materials used are modified hazelnut shell (MHS), and unmodified commercial activated carbon CULLAR (C) in batches. To characterise the adsorbents that were examined, we utilised FTIR, zeta potential, and pHpzc. To further evaluate the adsorbent's performance across a pH range of 2–10, we conducted isothermal tests. The most effective adsorbent that was evaluated was the modified activated carbon Cullar, which had a maximum absorption capacity of 48.7 mg g^{-1}. Freundlich and Langmuir isotherm models were both satisfactorily applied to the data. There was an effective elimination of DCF using modified activated carbon that was generated from hazelnut shells.

Futalan et al. [4] synthesised activated carbon (RHAC-LJ), and the adsorptive capability of RHAC-LJ in removing Pb(II) from water was investigated. As far as FTIR analysis can tell, RHAC-LJ contains hydroxyl, carboxyl, alkene, and amide groups. SEM micrographs reveal that the material's pore volume and diameter were significantly increased after activation with lemon juice. One method for removing pollutants is to activate the adsorbent surface with acid from lemon juice. The surface area and pore volume of the RHAC-LJ are 112.87 m^2 g^{-1} and 0.107 cm^3/g, respectively. The kinetics of adsorption were characterised by the pseudo-second-order equation ($R^2 = 0.9941$), with a rate constant of 3.3697 mg g^{-1} min for Pb (II). This indicates that chemisorption was the most time-consuming step. To discover how pH, stirring speed, adsorbent dosage, and their interactions affected the removal efficiency of RHAC-LJ, the BBD model using RSM was employed. To determine the significance of the model, independent parameters, and interactions between them, we used analysis of variance. Furthermore, a removal efficacy of 98.49% can be achieved under the following optimal conditions: 197 rpm, pH 5.49, and an adsorbent dosage of 0.3487 g. Overall, our research suggests that RHAC-LJ could be an affordable strategy for treating synthetic wastewater with Pb(II) removed.

3. MATERIALS AND METHODS

All components used in this experiment were of analytical grade or higher, obtained from reputable suppliers. While we received lead ($Pb(NO_3)_2$) from Tikrit University's Environmental Engineering Laboratory, we received pure diclofenac sodium ($C_{14}H_{10}Cl_2NO_2Na$) from the Samarra Pharmaceutical Laboratory. Each of the two pollutants has a 1000 mg stock solution. Diluting solutions ranging from 10 to 50 mg/L were procured. We were also provided with granular activated carbon by Tikrit University's Environmental Engineering Laboratory. The size of the particles ranged from 1 to 2 mm, and their surface area was 900 BET. The BET surface area of the GAC was found to be 900 m^2/g, which means it has a large surface area, which is important for effective adsorption. To see how well diclofenac sodium ($C_{14}H_{10}Cl_2NO_2Na$) and lead (Pb) might be eliminated, we conducted batch adsorption studies. All of the experiments were conducted in 250 mL conical flasks containing 100 mL of water, although the circumstances were varied. We put the stopped dirty solution in a shaker with a specific amount of granular activated carbon. The temperature and rotational speed of these flasks were kept constant at 25°C and 150 rpm, respectively.

3.1 Experiments on batch adsorption

Batch mode adsorption testing was used to assess the efficacy of eliminating diclofenac sodium ($C_{14}H_{10}Cl_2NO_2Na$) and lead (Pb^{+2}) from water-based solutions. Each experiment used 250 mL conical flasks that were contaminated with 100 mL of the generated solution. The mixture was shaken vigorously to distribute the granular activated carbon evenly after it was added to each flask in a certain proportion. The experimental setting was a temperature-controlled room with a shaking speed of 150 rpm and a relative humidity of 5%. These settings were chosen to deal with the usual adsorption process conditions. To begin, we made the stock solutions for the contaminants by combining the correct quantities of diclofenac sodium and lead nitrate in distilled water. To get the right concentrations for the studies, we mixed these stock solutions with water.

Prior to use, GAC was rinsed thoroughly with distilled water to remove any residual impurities. The GAC was then air-dried at room temperature before use in the experiments.

In each conical flask, 100 mL of the polluted solution and a preset quantity of granular activated carbon were combined to prepare for batch adsorption. The next step was to use a shaker to continuously mix the flasks at 150 rpm.

Temperature Control: The incubation temperature of the shaker was kept at 25°C to mimic external conditions that could impact the adsorption process.

When it came time to collect samples, the solutions were filtered after a set amount of time—usually 24 hours—to separate the liquid part from the activated carbon. We used the proper analytical methods to find out how much lead and diclofenac sodium were still in the water solution. For lead, we used atomic absorption spectroscopy, and for diclofenac sodium, we used UV-Vis spectrophotometry.

Figure 1 shows the method of using granular activated carbon to remove diclofenac sodium and lead from a water solution.

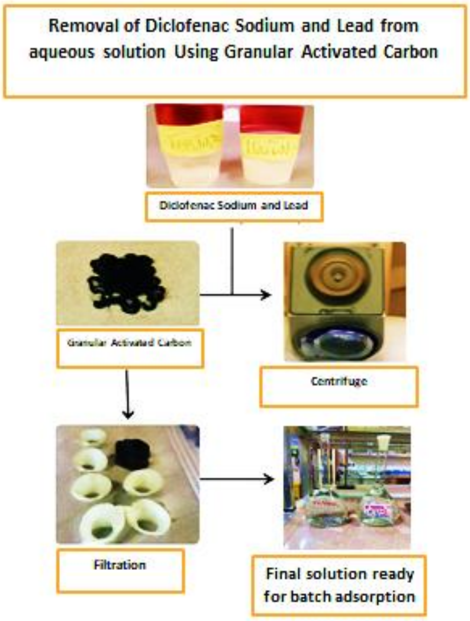

Figure 1. Experimental flowchart for the removal of diclofenac sodium and lead from aqueous solution using granular activated carbon

3.2 Analysis of adsorption efficiency

We evaluated the granular activated carbon by measuring the removal of diclofenac sodium and lead, which were used to test the activated carbon.

Adsorption isotherms can facilitate further insight into the influence of diclofenac sodium and lead contents on their affinity as well as aggregated adsorption capacity, since it provides information about how various pollutant concentrations in solution affect adsorptive potential.

A comprehensive discussion is provided regarding the adsorption kinetics and the maximum removal capacity, evaluated under varying experimental conditions including contact time, adsorbent dosage, and initial pollutant concentration. Figure 2 represents the experimental setup for the removal of lead and Voltaren.

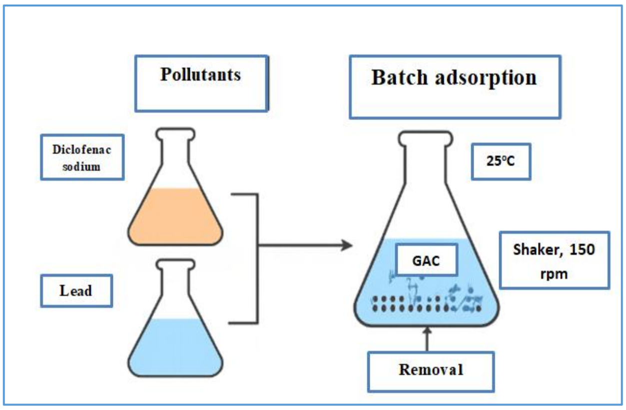

Figure 2. The experimental setup for the removal of lead and Voltaren

3.3 Properties of activated carbon

GAC was chosen for the task, as it is a great adsorbent. Activated carbon with a large surface area and numerous micropores can be a perfect chemical adsorbent. The activated carbon of the present study had an area of approximately 900 to 1200 square meters per gram and was known to have specific properties.

We used a ball mill to confirm the size of the carbon powder. They also employed 150-micron holes to separate the carbon and recover its smaller particles. Unground granular carbon, with higher adsorptive properties of the pollutants and having a diameter of 1-2 mm, was used as well.

3.4 Batch experiments

Batch experiments were conducted to examine the effects of various parameters on the efficiency of pollutant removal. In these experiments, activated carbon was mixed with solutions containing known concentrations of contaminants. Then, the effects of variables such as initial pollutant concentration, contact time, and activated carbon weight were examined to determine the adsorption capacity.

For the contact time experiments, 0.59 g of granular activated carbon (GAC) was added to 250 mL bottles containing 100 mL of a contaminated solution with a known initial concentration. Thorough mixing of the solution was achieved by a mechanical shaker at 50 rpm. Samples were collected every 5–180 minutes. Analytical measurements were used to evaluate the level of pollutant removal and to assess the effect of contact time on removal efficiency.

The effect of initial contaminant concentration was investigated. Test solutions contained Pb^{2+} and diclofenac sodium in the ranges of 10–50 ppm and 0.05–70 ppm, respectively. By keeping contact time, adsorbent mass, temperature, and pH constant, we isolated and analyzed the effect of initial concentration on removal efficiency.

Effect of the weight of activated carbon: The weight of activated carbon was studied for removal efficiency for all types of contaminants. The temperature, the concentration of the pollutant, and the duration of contact were kept constant at 120 minutes, but the weight of activated carbon was varied. The optimal dosage of activated carbon for effective removal was determined based on the experimental results.

The pH effect: These solutions were treated with hydrochloric acid (HCl) and sodium hydroxide (NaOH) to modify the pH and to determine which would be the most favorable conditions for each pollutant. The pH variation from 4 to 12 was used to study the adsorption capacity of pollutants on activated carbon. Variations in pH, a critical factor in the adsorption process, significantly influence the interaction between pollutants and activated carbon.

The temperature effect: A water-jacketed incubator maintained the desired temperature, and experiments were performed at 5°C, 30°C, 35°C, and 40°C. There was no change in either the contamination concentration or the time of contact with the sample. As the rate of a wide variety of chemical and physical reactions is influenced by temperature, it is a strongly influential factor in the adsorption process. Elevated temperatures enhance the molecular mobility of adsorbates, thereby facilitating more effective interactions with the activated carbon surface.

Effect of shaking speed: A series of experiments was carried out using different shaking speeds (100, 150, 180, 200, and 250 rpm) to study the effect of speed on removal efficiency. All other parameters (concentration, temperature, and contact time) were kept the same. The shaking speed significantly influences the homogeneity of the solution and the adsorption sensitivity of activated carbon, particularly in acidic conditions. Figure 3 shows the flowchart of the batch experimental study.

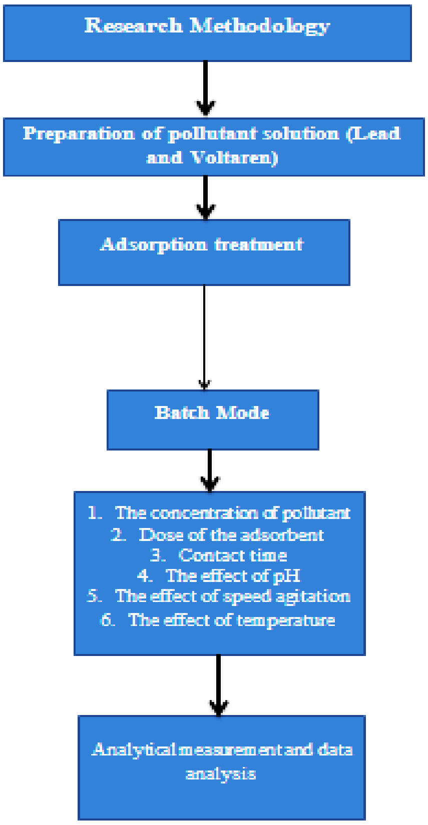

Figure 3. The flowchart of the batch experimental study

4. RESULTS AND DISCUSSION

4.1 The characterization of GAC

4.1.1 XRD analysis of GAC and pollutant-loaded GAC

These X-ray diffraction (XRD) patterns are for granular activated carbon (GAC), a mixture of GAC and diclofenac sodium (Voltaren), and Pb in the presence of GAC. Radiation XRD is one of the most important instruments to investigate material crystal structures. Figure 4 shows the diffraction intensities of the figure's measurements, which indicate the strength of X-ray scattering, on the y-axis. The diffraction angles (2θ degrees) are presented on the x-axis. These numbers enable us to calculate the spacing between the planes of the material.

For reference, the GAC peak is typically broad and centered at 2θ about 20°-30° in most materials. The broad peak indicates that the structure of GAC contains both microcrystalline and amorphous carbon phases. The peak, although not very sharp, is assigned to activated carbon due to its high intensity and presence of pores. Such a structure allows GAC to treat various parameters of water, which is important for its adsorption capabilities. The absence of a well-defined crystalline structure of the powder reveals that amorphous material is attained. This is a waste product from the activated charcoal industry.

The XRD pattern is altered when GAC is mixed with Voltaren (Diclofenac Sodium). Moving and strengthening of the pattern peaks demonstrate that the GAC surface had been changed by diclofenac sodium. The medicine might have adhered to the carbon or even seeped into it. Depending on the extent to which they broaden or truncate the GAC peak, sodium diclofenac can modify carbon microstructure. The structure of the GAC can be slightly changed by diclofenac sodium (e.g., interplanar distances or crystal lattice), as proved also by a peak shift (Figure 4). The XRD pattern of GAC and diclofenac sodium physically varies in their combination at the peak intensities. As the drug modifies the crystallinity of carbon upon binding to GAC, weak forces or physisorption between the drug and carbon can be expected.

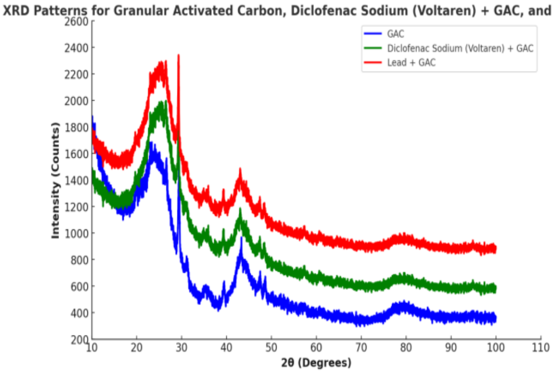

Figure 4. The XRD for the GAC, Voltaren with GAC, and lead with GAC

The XRD pattern experiences much greater change with lead doping for GAC. The GAC peaks are present and have their location and intensity altered differently again, as for the diclofenac sodium peaks. These differences show that in the presence of lead, the activated carbon is attached to the surface. The heavy ion nature of lead may result in more interaction between lead ions and surface functional groups of GAC. This could have a huge impact on the structure of the carbon. Insoluble lead phases (Pb oxide and Pb hydroxide) showed more or less XRD peaks because of the chemical combination. The additional peaks evidence that the lead phase is generated upon lead adsorption on GAC. The intensity of the GAC peak can be enhanced or reduced due to the lead-carbon interaction. It can be inferred that lead can be absorbed by GAC, and the configuration changes according to its XRD pattern. Both lead and diclofenac sodium shift the peaks, indicating that they alter GAC plane spacing. The diffraction peaks of GAC shifted upon interaction with these pollutants as its crystallinity changed. One of the ways that its peak position and intensity can be adjusted is by the adsorption of molecules or ions. This effect modifies the electronic density near the carbon atoms and thus also the X-ray diffraction pattern. The structural changes are due to the existence of diclofenac sodium and lead. Therefore, GAC is obviously an excellent material for removing pollutants from water and adsorption of chemicals.

Finally, XRD patterns made scenarios such as diclofenac sodium + GAC or lead + GAC provide information on the interactions of GAC. It can be seen that diclofenac sodium and lead have an influence on the crystal structure of GAC from the patterns in Figure 5. Such impurities are adsorbed by GAC and also influence the structure of the activated carbon, indicating the intensity degree and position shift of peaks. The outcomes also underscore the great potential of GAC to remove undesired substances from water, such as lead and diclofenac sodium. This interaction is evident, and the contributions to the adsorption mechanism can be realized by observing the XRD patterns.

A wide peak at 2θ = 23° with having intensity of ≈2400 counts is observed in the XRD of GAC with Lead. So GAC is not a crystal. The maximum positions are slightly shifted, and the intensity is largely modified with the addition of diclofenac sodium (Voltaren) (1321 counts at about 2θ = 23°). Further evidence that diclofenac modifies the structure of GAC crystals according to interactions with them. In the same way, in Figure 5, the lead + GAC pattern also shows variable peaks with a more intense peak at about 2θ = 23° and a count of 1131. This indicates that lead ions attach to the carbon surface. The adsorbed pollutants and GAC are interacting, as manifested by variable changes and intensity.

4.1.2 SEM analysis of GAC before and after Voltaren adsorption

Figure 5 displays the SEM images at different magnification factors of the surface of GAC doped with diclofenac sodium (Voltaren).

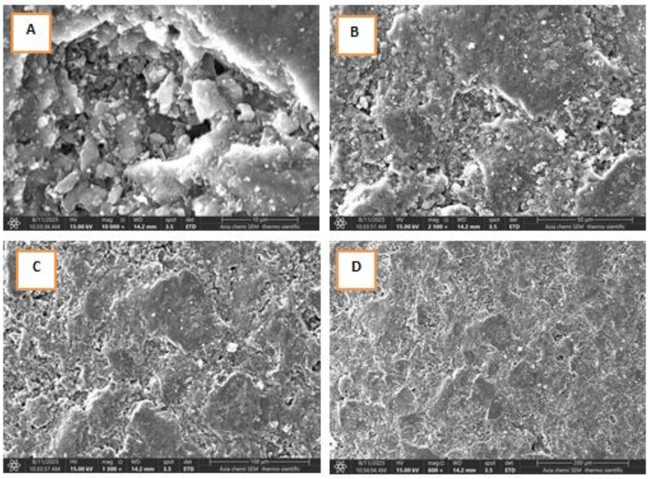

Figure 5. The SEM for Voltaren with GAC (A, B) before adsorption, (C, D) after adsorption

The GAC surface coated by Voltaren has a rough and grainy morphology at this magnification (Figure 5(A)). The surface is rough, and the particles seem to be non-uniformly distributed because of the rough surface. This is why the GAC might be having an interaction with the diclofenac molecules, or could be, in fact, beginning to start bonding up somewhere.

This is a slightly flatter and a bit less rough surface in Figure 5(B) than that of Figure 5(A); perhaps it occurs because the Voltaren molecules that are in the GAC on average keep more separated from each other. It still has some pits and bumps, suggesting that the adsorption process may still continue.

From the side, it looks a bit smoother with less grain showing (Figure 5(C)). This could mean that the surface is either more homogeneous than the adsorption at certain stages of adsorption. If things are humming along as they should, it could mean that GAC and Voltaren are collaborating smoothly.

Because the surface texture is more uniform and smoother in Figure 5(D), it appears less pronounced. There are no densely packed features to give us the sensation that it is rougher or structured. This might suggest that the GAC polymer absorbed the drug better. They show the change of the surface form due to the interaction between Voltaren and GAC. From this morphological study, we can have a better understanding of the adsorption of Voltaren with GAC. It has important medical and environmental consequences, such as the removal of controlled-release systems or drugs.

4.1.3 SEM analysis of GAC before and after lead adsorption

This scanning electron micrograph represents the combination of granular activated carbon (GAC) with lead, as shown in Figure 6. Figures 6 (A, B, C, and D) are offered in four sizes. The surface of the GAC is observed with different levels of roughness and graining at this magnification. The GAC possibly dos not yet reached the lead adsorption on its upper side since it possesses larger channels and holes. The rough surface of the texture has multiple sites for lead ion interaction. In Figure 6(B), the evidence presented in this photo shows that lead particles may be more evenly distributed on the GAC surface. Although the texture is not yet perfect (some 'lumps' and 'bumps'), it looks better in comparison to Figure 6(A). The growth of a more refined structure suggests that lead ions start to move into the GAC matrix, i.e. clear indication of an adsorption process pronounced.

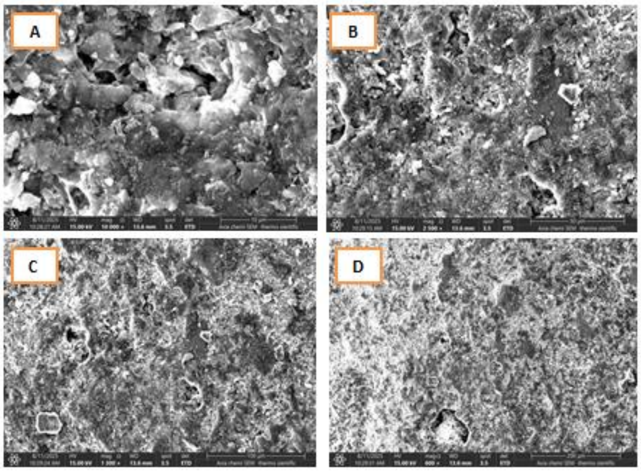

Figure 6. The SEM for lead with GAC (A, B) before adsorption, (C, D) after adsorption

The surface is even smoother and uniform, with fewer visible grains in Figure 6(C). There appears to be a little more bonding or absorption between the lead itself and the GAC, as evidenced by the smoother surface. As the pores got larger, the lead may have begun to close some of them up, and as the surfaces at this point changed from gritty to smooth, it would have been more secure to the GAC.

Under the microscope, the surface texture in Figure 6(D) looks a lot smoother, and fewer pores are visible. A full, smooth surface can also indicate that the GAC has taken up all the lead ions and is near capacity. This illustration has used up our lead count for the current GAC.

These scanning electron micrographs show the process by which GAC absorbs and reacts with lead. Surface morphology variations from rough to smooth textures provide valuable insights into the lead-activated carbon interaction at different time points. In order to clean the air or water, this is essential.

4.1.4 Physicochemical properties of GAC

In contrast, the SEM analysis indicates a highly porous and rough surface with the presence of mesopores and macropores in the range of 2-50 nm, which is a characteristic pattern for GAC.

The XRD results indicate the amorphous character of the GAC, with a broad peak at approximately 22°, indicating that it is crystalline in structure. GAC usually has pore volume between about 0.4-0.8 cm³/g and surface area from 800 to 1200 m²/g, depending on the source and activation procedure used. Due to the literature information and properties of GAC, such particles are expected to have surface oxygen-containing groups, such as –COOH or –OH, providing their acidic surface chemistry.

4.2 Adsorption performance of GAC: Experimental parameters

The amount of lead (Pb) ions was tested at the Environmental Engineering Laboratory using an atomic absorption spectrometer (AAS). The concentration of diclofenac sodium was determined using a UV-Vis spectrophotometer that operates at a wavelength of 276 nm. We measured the pH with a digital meter. For each experiment, we utilised one of two sizes of carbon:

1. Activated carbon in a granular form, with a size range of 1-2 mm.
2. Activated carbon in granular form that has been passed through a fine-mesh screen measuring 150 µm after being processed in a ball mill.

4.2.1 Effect of contact time on adsorption efficiency

Lead and diclofenac sodium were absorbed in increasing amounts within 120 minutes. Powdered activated carbon samples exhibited peak lead adsorption in the initial half an hour. That the GAC sites absorbed the lead so rapidly is demonstrated by this. Adsorption of the granular activated carbon was sluggish at 120 minutes but quickened to 180 minutes. That the granular carbon that isn't powdered is more effective is demonstrated here. More time to make contact is required to accelerate the removal rate.

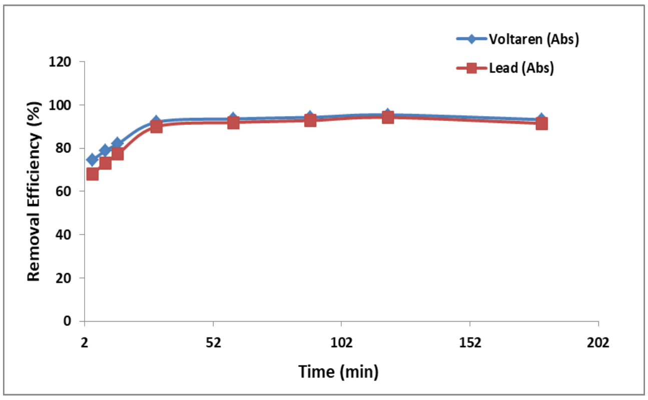

Figure 7. Effect of contact time on the removal efficiency (%) of Voltaren and lead using 0.5 g GAC at 150 rpm and 25°C (contact time: 120 min)

Figure 7 illustrates the process of removing lead and diclofenac sodium (Voltaren) from water by use of granular activated carbon (GAC). The absorbance of the two substances was plotted against time from 5 minutes to 180 minutes. The slight decrease in lead uptake during an experiment would appear to show that this metal is also being eliminated very slowly. Since the absorbance decreases to 0.0147 after 5 min, this indicates the presence of lead in the solution. In contrast, this value also decreases with time, and the absorbance at the end of 180 min. increases to 0.0101. The lead is scavenged from the slurry by GAC. Lead may not easily or rapidly adsorb to GAC's surface because of lead's bigger molecular size and/or stronger interaction with water. Children might play a role due to other compounds. Adsorption might also be slower in the case of GC because of the lower number of active sites for lead, or it may be more difficult to access (hence the slow removal).

Under test, Voltaren (diclofenac sodium) shows a much more dramatic and rapid reduction in absorbance. High concentration of Voltaren in the solution is confirmed by the highest relief reading of 0.385 at 5 min. A rapid decline of the absorbance to a minimum value of 0.12 is evident in the first half an hour. From there, it diminishes slightly until the end of the time and is found to be 0.180. First, this rapid decrease shows the speed with which Voltaren interacts with the GAC. It could also be the reason is that it has more time to get trapped in the pores of activated carbon because its molecular size is smaller. The initial, more rapid adsorption of this is apparent. The rate of absorbance drops after 30 min, but not as fast as that in lead. The system is almost saturated, where uptake of the compound becomes more time-consuming owing to a reduction in the available active sites, although GACs are really very efficient at removing Voltaren.

Granular activated carbon is an effective adsorbent for both contaminants, as seen in Figure 7. However, it does demonstrate a significant disparity in the elimination rates: GAC rapidly gets rid of Voltaren, while lead adsorbs at a much slower rate. The distinction arises from the fact that GAC and the two substances exhibit distinct chemical properties and engage in distinct molecular interactions. Both substances are removed from the water according to the findings, but Voltaren is far more effectively adsorbed, particularly in the first stages of the experiment. It is possible that other factors, including the physical or chemical properties of lead, influence its adsorption kinetics, or that GAC needs more time or a larger surface area to effectively adsorb lead, as its removal is slower than expected.

4.2.2 Effect of initial concentration

When arsenic concentration was between 10 to 50 mg/L, the adsorption rate increased with the lower concentration, and the clearance rate decreased with higher concentrations. Significant removal of material was attributable to active sites, with both powdered and non-powdered granular GAC. Lead is adsorbed to GAC, followed by its absorbance determination. Figure 8 shows the optical adsorption of lead from 0.05 g/L to 10 g/L. The results show the correlation between lead quantity and GAC sorption rate. The absorbance values are very low and slowly increase when the lead concentration is lowered from 0.05 g/L to 1 g/L. This indicates the fact GAC is unable to adsorb any lead ions from solution despite having enough active sites to adsorb the same. At high concentrations, increasingly more lead comes into contact with the GAC surface, causing an increase in adsorption as indicated by linearly increasing absorbance. The adsorption process still proceeds smoothly without reaching the limit level, such that the GAC surface is not overloaded, as indicated by no excessive increase in absorbance with increasing concentration.

At this concentration level, the absorbance increases sharply (0.042), and hence it can be seen that the GAC is approaching its highest ability, where a large part of the lead is held by it. A rapid spike in GAC rapid absorbance flow charts causes a highly intensive absorption rate; thus, the total absorption capacity increases with increasing lead ion concentration. Since these interactions are known to be based on pH, it may be that lead ion adsorption at the GAC surface is stronger for this higher concentration.

Such absorbance falls below 5 g/L at 10 g/L, which is now 0.0097. At the highest concentration, the absorbance decreases due to saturation of adsorption.

Lead causes the GAC surface active sites to load up to capacity. Lead ions can no longer be adsorbed effectively after the surface is saturated. As a result, the absorbance value becomes flat or even decreases. After a certain concentration, the GAC isn't very effective in adsorbing new lead ions, and adding more lead to the solution may prevent it from being adsorbed.

There appears to be a sweet spot for lead adsorption concentrations, according to the trend. At low to moderate concentrations, GAC works effectively; however, once the concentration reaches a specific point, it reaches its adsorption capacity, and further addition of GAC has little effect on its adsorption efficiency. The ability of adsorbent materials, such as GAC, to efficiently remove contaminants is crucial in real-world applications like water treatment.

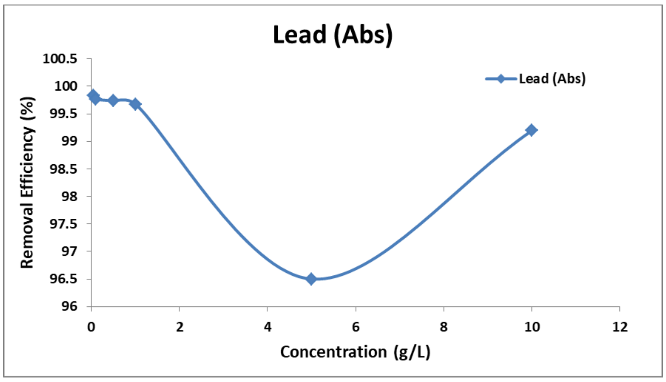

Figure 8. Effect of lead concentration on removal efficiency (%)

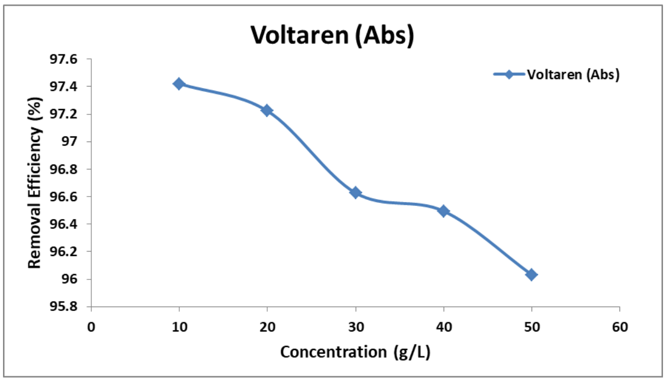

Figure 9. Effect of Voltaren concentration on removal efficiency (%)

Figure 9 depicts how the concentration of a solution of Voltaren changes as a function of its concentration in water, as measured using a spectrophotometer. Based on the findings, it appears that the absorbance increases in direct proportion to the concentration of Voltaren. Absorbance readings of 0.039 at 10 g/L show that the solution contains a negligible amount of Voltaren, since just a tiny fraction of the light reaching the sensor is absorbed. At 50 g/L, the absorbance reaches 0.06, which is a steady increase with increasing concentration. The absorption principle, which states that more molecules in a solution mean more opportunities for molecules to interact with the light travelling through it, is reflected in the fact that absorbance increases as concentration does. As the absorbance typically varies with the solute concentration in accordance with Beer-Lambert Law, this pattern is common for many compounds in solution. Assuming a constant light path length and molar absorption coefficient, the law states that absorbance is directly proportional to concentration. This is what the results demonstrate: that if we increase the concentration of Voltaren, the total absorbance increases, because then, there are more absorbing molecules in solution. The experiment is performed at a temperature of 25°C, 150 rpm, contact time 120 min, and GAC of 0.5 g, pH of lead is 6, and the pH level for Voltaren reaches 5, respectively.

According to the figure, Voltaren exhibits predictable absorbance behaviour across a variety of concentrations, and within the concentration range under study, the correlation between concentration and absorbance is linear. This finding is significant because it sheds light on the light-solvent interaction of Voltaren, which has practical uses such as sample concentration determination and the creation of spectrophotometric methods for Voltaren quantification.

4.2.3 Effect of GAC dosage on adsorption

Raising the carbon dosage from 0.1 to 1.5 grams considerably enhanced the removal of both contaminants. There was a maximum clearance rate of 1 g for diclofenac sodium and 0.8 g for lead. Specifically, the surface area and number of active sites both grew in direct proportion to the adsorbent's mass. No more than 1.5 g of carbon powder could be extracted.

Figure 9 illustrates the correlation between the levels of granular activated carbon (GAC) and the absorbance of Voltaren and lead in a water solution. The fact that the absorbances of Voltaren and lead decrease when the dosage of GAC is increased indicates that GAC is effectively removing those compounds from solution.

The adsorption amount of Voltaren and lead is still high even at a low potential dosage (0.1 mg/L) of GAC. It thus appears that fewer active sites are available for adsorption and, as a result, lower removal of both chemicals from solution can be obtained with a lower dosage of GAC. The absorbance of both GJ2C and RV decreased gradually with increasing amount of GAC dose, which implied that more adsorbates were extracted from the solution. The absorption of the proposed sorbents can be seen in the reduction of absorbance A with time, as Voltaren and lead are absorbed by GAC, showing a diminution in their concentration in the solution.

After the GAC dose approaches 1.5 mg/L, the absorbances of Voltaren and lead decrease significantly, indicating that the higher concentration of GAC has led to more active sites and more effective adsorption. We may conclude that GAC is more successful than lead at eliminating Voltaren since the absorbance of Voltaren decreases more dramatically with larger dosages of GAC.

Because a larger amount allows for more interaction with contaminants, it is normal for adsorbents like GAC to have an increasing removal efficiency with increasing doses. Voltaren and lead concentrations are reduced as the concentration of GAC is increased due to its adsorption capabilities. Findings highlight the requirement of optimizing GAC dosage to ensure effective adsorption and demonstrate that, with increasing doses, GAC can successfully remove these contaminants.

The experiment has occurred at a temperature of 25°C, rpm is 150, contact time is 120 min, GAC is 0.5 g, pH is 6 for lead, pH of Voltaren is 5, and concentration of Voltaren and lead is 10 mg/L, respectively.

As illustrated in Figure 10, the removal effectiveness of Voltaren goes up quickly when the GAC dose goes up. It starts at about 90% at a dose of 0 mg/L and goes up significantly to about 96–97% when the GAC dose reaches 0.2 mg/L. After this first spike, the removal efficiency for Voltaren levels off, with only a small rise, while the GAC dose keeps going up. This means that after a given amount of GAC, the removal efficiency for Voltaren doesn't get any better. The elimination efficiency for lead is comparable, but it starts at a higher value of about 91% and goes up more slowly than for Voltaren. At greater GAC dosages, it works at 98–99% efficiency, and after roughly 1 mg/L of GAC dose, it doesn't vary much. The lead curve demonstrates that the removal efficiency rises more slowly and steadily as the GAC dose goes higher.

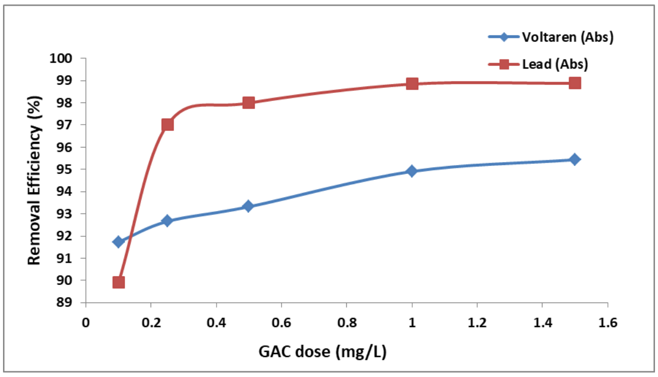

Figure 10. Effect of GAC dose on the removal efficiency (%) of Voltaren and lead

4.2.4 Influence of pH on adsorption behavior

The degree to which substances adhered to it was significantly influenced by the solution's pH. Lead had an optimal pH of 5, while diclofenac sodium had an optimal pH of 6 (a high pH removes the proton from diclofenac). The increased interaction between the GAC surface and powdered carbon is due to the electrostatic forces that attract the two. Granular carbon's removal rate increased with decreasing pH, with 3 and 4 yielding the highest rates for the two contaminants, respectively.

Figure 11 illustrates how the adsorption of lead and Voltaren onto granular activated carbon (GAC) is affected by the pH of a water solution. From 4 to 12, the graph displays the changes in the absorbance (Abs) values of lead and voltaren as a function of pH. Lead absorption gradually increases as pH rises. The absorbance begins at 0.0016 at pH 4 and rises steadily with increasing pH up to 0.00664 at pH 12. Lead is more effectively adsorbed to GAC at higher pH values. One possible explanation for the increase in absorbance at higher pH levels is a change in the chemical form of lead in solution. There are a couple of possible explanations for why lead ions are more amenable to adsorption at higher pH levels: either the GAC's surface charge interacts better with the lead ions, or both are true. Voltaren is more complex, however. Here, the absorbance is 0.073 at a pH of 4, and then it increases rapidly to 0.71 at a pH of 6. This sudden increase may indicate that GAC can adsorb more Voltaren under this pH. It falls to 0.098 only at pH 12, and decreases further up the scale of pH.

Due to this decrease, the synergistic effect between Voltaren and GAC at higher pH disappears. This may be due to alteration of the surface characters of GAC, or in the solubility or charge of Voltaren moieties.

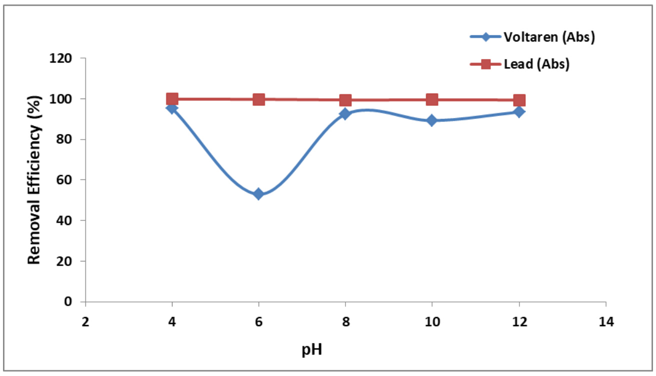

Figure 11. The effect of pH on the removal of lead and Voltaren

The difference between lead and Voltaren shows the importance of pH in the adsorption performance of GAC to different chemicals. Although adsorption of Voltaren is promoted in a slightly acidic to neutral pH range, higher values offer better channelling for lead adsorption. The adsorption decreases with increasing pH, up to a certain point at basic pH. These results underscore the importance of pH in the adsorption model for chemical compounds on waterborne surfaces. Moreover, they argue that a pH higher than X may work better in removing lead, while perhaps less so for Voltaren, and that a lower pH value might be the preferred condition for the removal of Voltaren.

The surface charge on GAC depends on pH, being positive at low pH and negative at high pH. This influences the adsorption, making electrostatic interactions more prevalent. Diclofenac is an acidic organic compound that is protonated and un-ionized at low pH. This is believed to cause the FiCAM solution to adhere to a positively charged GAC surface. But at a higher pH, diclofenac sheds its protons and takes on a negative charge. This means it is less likely to stick to your stuff due to electrostatic repulsion. Lead (Pb^{2+}), however, is a cation at low pH and adheres well to the negative surface of GAC. As the pH increases, lead forms hydroxy complexes ($PbOH^{+}$). They are unlikely to adhere to surfaces as electrostatic attraction is weaker. So these two adsorbents, one for diclofenac and lead, would be different. The adsorption of diclofenac is mainly governed by its protonation state, while the ionic form and pH value of lead are predominantly responsible for its adsorption.

The result is utilized to identify that the optimal pH with the end goal to remove the pollutants is as follows: for Voltaren, it is at values higher than 7 and lower than 5, but optimal efficiency is in the alkaline zone from 8 to 12. The level of lead removal is constant around 100% through the whole pH level range from 2 to 12, from which it is visible that pH has the least effect on lead removal level. For Voltaren, the optimal pH is sub-alkaline—from 8 to 12—while for lead, it is neutral to alkaline because removal remains over 90% effective at all pH values.

4.2.5 Effect of shaking speed on adsorption efficiency

It was found that shaking speed was a key aspect in the adsorption process. The optimal removal speed was determined to be 150 rpm. The faster the speed, the less effective the removal. This is because the boundary layer of the adsorbed particles gets thicker when the agitation level goes up. The best results were at 100 and 200 rpm. For powdered carbon, the faster the speed, the less efficient it was. The opposite happened with granular activated carbon, though. The faster the pace, the faster the removal rate. At 250 rpm, granular carbon had the highest removal rate.

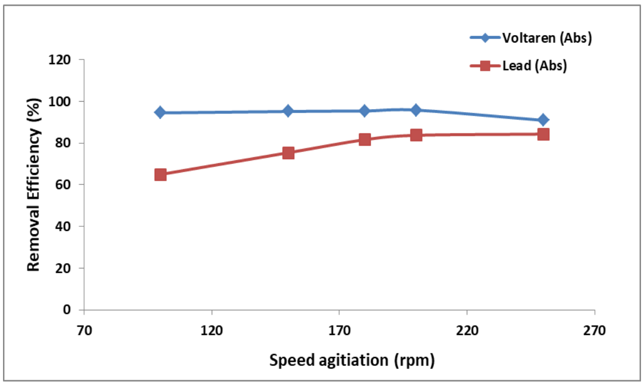

Figure 12. Effect of agitation speed on the removal efficiency of Voltaren and lead using 0.5 g GAC at 25°C (contact time: 120 min)

Figure 12 represents the impact of rotational speed (rpm) on lead and Voltaren removal efficiency in a solution. The absorbance of Volteran decreases as the rpm increases from 100 to 250, but the absorbance of lead first decreases before increasing at higher rpm values.

As the rpm increases, the residual concentration of lead in solution decreased, reaching 0.188 mg/L at 250 rpm, from 0.42 mg/L at 100 rpm. Because of this, the faster the mixing, the less lead there will be in the solution because the material can absorb it better. The decrease in absorbance indicates that the adsorbent is more effective at removing lead from the solution when the rpm is increased. The increased contact between the adsorbent and the lead ions is likely to be to blame. At 100 rpm, the absorbance is 0.083, and at 200 rpm, it drops to 0.063, indicating that the concentration of Voltaren in the solution decreases with increasing rpm. However, the absorbance increases to 0.137mg/L at 250 rpm. This means that at extremely high rpms, the effectiveness of Voltaren's adsorption can decrease or perhaps reach a point where it becomes ineffective at removing the drug. Possible causes include excessive mixing, which impedes the adsorption process or prevents the adsorbent from achieving greater rates of Voltaren attachment.

Based on the results, the maximum for efficient lead adsorption was obtained at a larger rpm, with the absorbance decreasing steadily. The rpm-versus-adsorption efficiency relationship of Voltaren is more complicated. At 200 rpm, absorbances decrease and then increase at higher speeds (250 rpm).

The efficiency of light-absorbing lead and Voltaren dictates the best adsorption %.

The minimal value of the lead absorption is achieved at 250 rpm (0.188), while it decreases with increasing rpm. Being that higher rpms enhance lead removal from solutions, 250 rpm is a suitable speed for lead adsorption. Improved removal of lead by the adsorbent is achieved with increasing mixing speed, as shown by the decrease in absorbance over time.

As its absorbance, diminished from 0.083 at 100 rpm to

0.063 at 200 rpm, is increased to 0.137 at 250 rpm by Voltaren. Because Voltaren absorbs the most at 200 rpm, that's probably when its performance is optimal. At 200 rpm, the maximum Voltaren can be taken up by the system. Subsequently, the adsorption exhibits a weak impact as rpms increase.

For depuration at both tide speeds, pollutant loads and temperatures, no less than 97% and up to more than 100% of Voltaren were detected. As a result, Voltaren is rapidly removed in the material used to remove it, independent of stirring velocity and initial pollutant concentration. Temperature and agitation speed snap do not affect removal much. Voltaren is desorbed from the solution upon contacting the adsorbent. Another evidence is that the efficiency does not depend on concentration.

But speed, movement, and temperature have a greater effect on lead expulsion. Lead is initially removed at an efficiency of 60–70% and the process improves with GI rate and concentration. The efficiency of removal is 80% even at high agitation speeds and temperatures. Stirring can remove some lead, but not completely, in the experimental conditions. Lead adsorption is highly dependent on adsorbent dosage and temperature. The time and agitation enhance the lead removal percentages, but more efficient work is achieved at higher adsorbent dosage and temperatures.

4.2.6 Temperature dependence of adsorption

Experiments have shown that increasing temperature does not affect the adsorption process for powdered activated carbon, but it does increase the adsorption capacity for granular activated carbon.

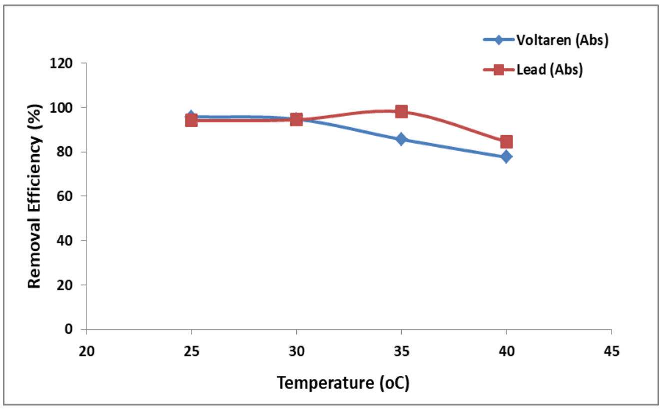

Figure 13. The relation between temperature and removal efficiency (%) for Voltaren and lead at GAC is 0.5 g, 150 rpm, contact time is 120 min, respectively

Figure 13 illustrates the relationship between temperature and the change in absorbance of lead and Voltaren. It achieves this by taking readings of the absorbance at four different temperatures: 25, 30, 35, and 40 degrees Celsius. Both compounds adsorb differently depending on the temperature. Because lead is less soluble in water at higher temperatures, the concentration of lead in the solution increases. However, a significant increase to 0.184 is observed at 40°C. This further evidence indicates that high temperature could enhance lead adsorption as a result of higher activity or availability of the adsorption sites. This trend suggests that the lead-adsorbent interaction becomes stronger at a temperature of ~ 40°C, which is considered as optimum temperature for the adsorption of lead.

Its absorbance increases directly proportional to temperature for Voltaren. It starts at 0.063 when you reach 25°C and goes up to 0.079 when reaching 30°C, then it increases again to arrive at 0.217 going to 35°C, and it peaks at a value of 0.339 with temperature around the number of Celsius degrees equal to that between zero and forty. Since more medicament binds to a certain material as this has its higher temperature, we can conclude that higher temperatures favor the adhesion process of Voltaren gel on any solid surface. Adsorption of Voltaren is best at 40°C, hence it is the optimum temperature for this mechanism.

Lead and Voltaren both absorb most effectively around 40°C. The particular temperature at which adsorption becomes more effective can vary for different compounds, although generally speaking, higher temperatures improve its performance.

The adsorption of diclofenac and lead onto GAC exhibited temperature dependence, with adsorption increasing concomitantly with rising temperature. This means that the process is affected by more than one thing. There are several ways that diclofenac and lead might stick to GAC. GAC has functional groups like -OH and -COOH that interact with diclofenac by hydrogen bonding and electrostatic interactions, especially at lower pH levels. Lead, on the other hand, is coordinated with oxygen-containing groups on GAC. Also, pore filling happens in GAC's micropores and mesopores, where lead is physically confined, and diclofenac mostly sticks to the surface or inside the micropores. The π-π interactions between the aromatic rings of diclofenac and the GAC surface make adsorption even better.

The maximal efficiency toward Voltaren and lead is 95% and 85%, respectively. This demonstrates that agitation, adsorbent dosage, and temperature all contribute, but efficacy plateaus. Granular activated carbon is great for Voltaren, but a bit too wide-strung for lead. It had an adsorption efficiency of 1.9 mg/g for Voltaren (diclofenac), with a removal rate of 95%, proving to be quite effective. It revealed a percentage of 85% of leads were removed, which is the adsorption capacity of 1.7 mg/g. This is slightly less efficient because it was pointed to take off.

Our results represent the removal efficiency of both Voltaren and lead. Our results are in line with Antunes et al. [1], Espina de Franco et al. [2], and Thi Minh Tam et al. [3], who found that the Voltaren removal is affected using adsorbents such as GAC and others. Our results demonstrate the removal of lead, and it is in line with Jaber et al. [30].

4.2.7 The Langmuir and the Freundlich isotherms

Figure 14 shows how the amount of lead adsorbed per unit of adsorbent (Ce/qe) in g/L relates to the equilibrium concentration (Ce) of lead in mg/L. The dots on the graph show the results of an experiment that tests how well a certain adsorbent material can hold lead at varying concentrations.

The fitted line, which is a dotted line, shows the linear equation: $y = 337.88 X - 0.9542$. Where y is the lead adsorption capacity (Ce/qe), and x is the equilibrium concentration (Ce) of lead in mg/L. The equation shows that the amount of lead adsorbed by the material goes up in a straight line as the equilibrium concentration of lead goes up.

The coefficient $R^2 = 0.9619$ indicates that the plot of experimental data and the linear regression model are well-fitted. That's the data being very well fit to the model.

Finally, it can be seen from the figure that at a lower concentration of lead (Ce), the adsorption capacity increases slowly, but when the level of lead gets higher, the adsorption capacity increases rapidly. This graph is typical of an adsorption isotherm, which illustrates how the concentration of the pollutant in solution influences a material's capacity to adsorb it.

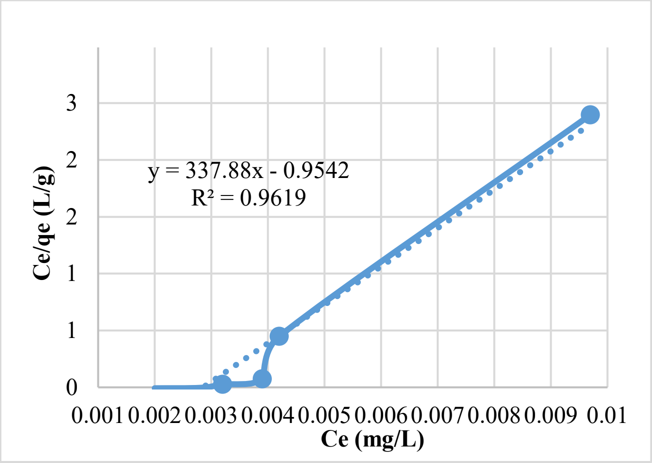

Figure 14. The relation between Ce/qe (L/g) and the Ce (mg/L) for lead

4.2.8 Langmuir isotherm for Voltaren adsorption on GAC

The Langmuir Isotherm describing how Voltaren (a pharmaceutical pollutant) adheres to GAC is illustrated in Figure 15. The model demonstrates how molecules (Voltaren) compete with each other and adsorbents (GAC), which have a finite amount of uniform binding sites. This ratio is a retrofit to the Langmuir equation that converts the data linearity. How well the data fits the Langmuir model can be determined by plotting this ratio against Ce and obtaining a line. Straight is good, and it looks like the Langmuir Isotherm works nicely for how Voltaren adheres to GAC. From this linear fit, we obtain essential Langmuir constants (qmax and KL).

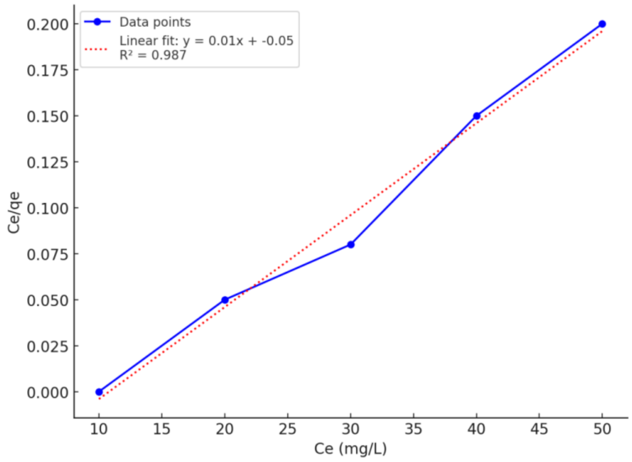

Figure 15. The relation between Ce/qe (L/g) and Ce (mg/L) for Voltaren

The qmax is the maximum concentration of Voltaren that can be adsorbed on a unit mass of GAC. The adsorption increases as Ce increases, but it decreases when the GAC surface becomes full of Voltaren. The red line hits the y-axis at that point, which corresponds to GAC's maximum capacity, meaning how much it can hold here.

KL is the Langmuir constant that indicates the degree of adsorption. These higher values of KL indicate that not only is there a better interaction between Voltaren and GAC, but also that the adsorption capacity for Voltaren is higher at low concentrations of it.

The solid lines demonstrate that the Langmuir model fits the data well. The latter model assumes adsorption in one layer on the activated carbon, i.e., at any given point, there is no other adsorbate molecule other than a single Voltaren molecule occupying an available active site on the GAC. This is a very significant aspect of Langmuir adsorption. With an increasing Ce, additional Voltaren molecules occupy the adsorption sites of GAC. But eventually, the surface gets congested and adsorption attains a maximum. This is indicated by the plateau in the curve.

The adsorption isotherm can be well fitted to a linear curve, as shown in Figure 15. It can be seen from the high R^2 value (close to 1) that the data fit to Langmuir model quite well. It implies that adsorption occurs in the manner of monolayer adsorption on a completely smooth surface. The better fit of the Langmuir isotherm to data will be obtained when R^2 approaches 1.

The higher the dose of Voltaren (Ce), the more Voltaren is bound to GAC, but as soon as the sitting capacity of GAC had been reached, this increase flattened. This is a typical mode for saturation in adsorption. At low concentration, the increase in adsorption is significant because there are still plenty of places where it can occur. But when there are many Voltaren molecules, there is not as much room for them to bond with, which slows adsorption, and the pace of healing speeds up. The Langmuir isotherm is a mathematical model that describes the adsorption of systems, and this can be confirmed from the above plot that the settlement of Voltaren on GAC follows the Langmuir model quite efficiently.

The Langmuir qmax, and when the graph is constructed (qe versus Ce), the slope from which the Langmuir constant KL can be calculated. These data give us an indication of how much Voltaren can be eliminated from the solution by GAC and what is the intensity of adsorption.

It can have a practical value in the design of water treatment/fluxion systems or GAC-based adsorption processes for pollutant removal, such as Voltaren from aqueous solutions.

The linear fit of the plot and the high R^2 value indicate that adsorption of Voltaren by GAC is very effective and it closely follows the Langmuir model, which implies monolayer adsorption. This renders GAC an excellent material for the removal of Voltaren from wastewaters and solutions.

Freundlich isotherm model for Voltaren adsorption

Figure 16 shows the log-log plot for the Freundlich Isotherm of Voltaren's adsorption onto GAC. The figure shows the logarithm of the equilibrium concentration of Voltaren in the solution (Ce), and the figure shows the logarithm of the amount of GAC that is adsorbed per unit mass at equilibrium. We linearize the Freundlich model, which explains how things stick to a surface that isn't smooth, by showing these logarithmic numbers. The red dotted line on the plot is a linear fit to the data that follows the Freundlich equation. The slope of the line is -0.87, which shows how strong the adsorption process is. The equation for the line is $\ln(qe) = -0.87\ln(Ce) + 8.76$. A slope less than 1 suggests that the adsorption process is good but not straight, which is how many real-world adsorption processes work. The intercept of 8.76 shows how much Voltaren can be adsorbed per unit mass of GAC under the specified conditions. This is the adsorption capacity.

The R^2 value of 0.93 reveals that there is a strong linear relationship between ln (qe) and ln (Ce), which means that the Freundlich model fits the data well. This means that the GAC is good at adsorbing Voltaren, but as the concentration goes up, the adsorption efficiency goes down a little, which is what the Freundlich Isotherm says should happen.

Figure 16 shows that Voltaren adsorption on GAC follows a heterogeneous surface adsorption model. This means that the process gets less effective at increasing concentrations, but it still favors adsorption because of the surface's properties and the strength of the adsorption sites.

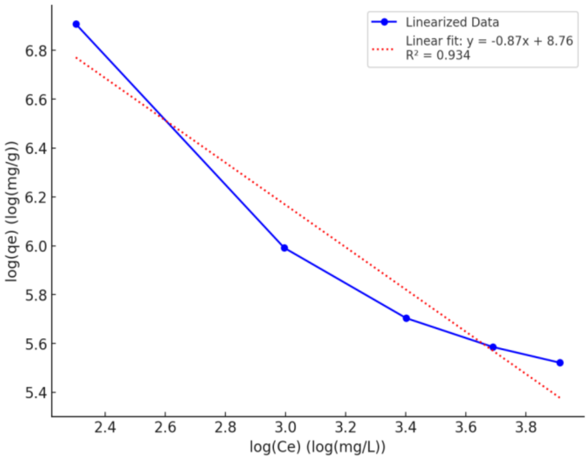

Figure 16. The Freundlich isotherm of Voltaren adsorption onto GAC

Freundlich isotherm model for lead adsorption

The effect of the quantity of lead (Pb) in a solution on the quantity of lead adsorbed by granular activated carbon (GAC), during the process of adsorption, is demonstrated in Figure 17. The logarithm of the lead adsorbed per unit mass of GAC at equilibrium (qe) is plotted against the logarithm of equilibrium lead concentration in solution (Ce) on the y-axis and x-axis, respectively. This experimental result is represented in the figure that demonstrates how much lead has been removed from the solution as a function of the GAC loaded. The red dashed line is a best-fit relation as a function of the logarithm of qe and Ce. This line was calculated through linear regression, indicating that if the data is converted to a log-log scale, it behaves according to some kind of linear relation. That is the equation of the line that best fits:

$$\log{(q_e)} = -3.20\log{(C_e)} - 19.73$$

The negative slope of the line indicates that as more lead is in the solution, less lead sticks to GAC, but at a diminishing rate. This is how adsorption processes look when they are according to the Freundlich isotherm. This is the description of how objects stick to surfaces with different species of adsorption sites that have not only different sites, but also different energies. It fit the data very well with an R^2 value of 0.985 for the Freundlich model. This, in its turn, suggests that the relationship between the quantity of lead in solution and the area on which this is adsorbed can be correctly described by a logarithmic equation. In summary, the data indicate that lead adsorption on GAC occurs in terms of the Freundlich Isotherm. This implies that with increasing concentration, the lead adsorbed decreases. The log Ce and Δx have a linear relationship.

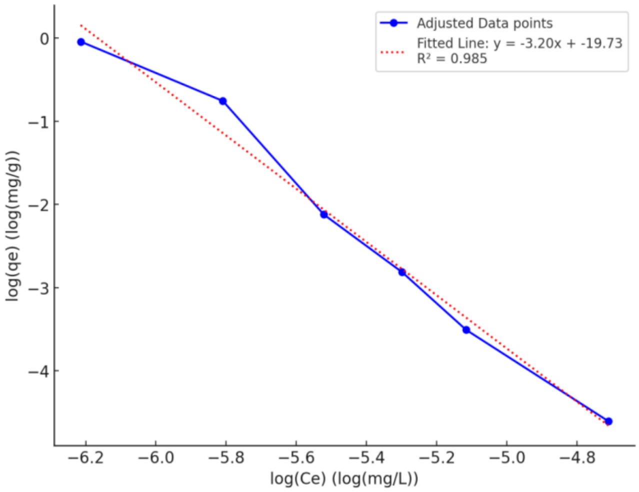

Figure 17. The Freundlich isotherm of lead adsorption onto GAC

5. CONCLUSION

Overall, this study looked at the adsorption kinetics of the two key pollutants, lead and diclofenac sodium, from aqueous solutions. Based on the results, the following can be concluded about the adsorption mechanisms, operating conditions, adsorption capacities, and efficiency. GAC adsorbed lead and diclofenac through different mechanisms. While diclofenac primarily involved electric adsorption, lead was removed through both cation exchange and electric adsorption. The difference in operation mechanisms is reflected in the optimal conditions for either type of pollutant. The highest removal for lead was at 40°C and 250 rpm, whereas the removal for diclofenac was at 40°C and 200 rpm. In terms of the increase in the GAC dosage, lead's adsorption capacity increased proportionally as removal efficiency increased, whereas the adsorption capacity of diclofenac decreased while the removal efficiency increased. While the maximal efficiency was at 95% for diclofenac and 85% for lead, diclofenac's adsorption capacity was at 1.9 mg/g with 95% removal efficiency. For lead, the adsorption capacity was 1.7 mg/g. The biggest challenge was absorbing lead rather than diclofenac, with the GAC performing well. Results revealed that the optimal conditions for the removal of the pollutants were 40°C temperature and the highest for lead and diclofenac at 250 and 200 rpm, respectively. Furthermore, higher GAC dosages resulted in higher adsorption capacities for both pollutants, and 1.5 mg/L was found to be the optimal diclofenac concentration. Consequently, the conditions facilitated the efficiency of 85% removal of lead and 95% for diclofenac. For Voltaren, the optimal pH is sub-alkaline—from 8 to 12—while for lead, it is neutral to alkaline because removal remains over 90% effective at all pH values.

Finally, this study clarifies the adsorption mechanism of GAC, enhancing its use in environmental cleaning, particularly for water treatment to remove heavy metals and pharmaceuticals. Future research could focus on improving GAC's regeneration over multiple cycles. Diclofenac and lead adsorb differently on GAC: diclofenac primarily through electric adsorption, while lead involves cation exchange and electric adsorption. Lead blocks GAC sites, making diclofenac removal harder. Adsorption is also influenced by pH, highlighting GAC's difficulty in handling complex pollutant mixtures. Therefore, improving GAC or developing new adsorbents for multiple contaminants is essential. Voltaren (diclofenac) and lead adsorption efficiencies reach 95% and 85%, respectively, with adsorption capacities of 1.9 mg/g for diclofenac and 1.7 mg/g for lead.

SEM photos show the absorption and reaction of lead by GAC. Surface morphology from rough to smooth indicates the lead-AC reaction occurs at various moments. This is essential in both air and water cleansing. They demonstrate how Voltaren and GAC bind to alter surface morphology. The morphology can help to show the ability of adsorption of Voltaren for GAC. This disruption means that drugs for controlled release can be employed with medicine and the environment.

6. LIMITATIONS AND RECOMMENDATIONS

6.1 Limitations

The following limitations were noted during the conduction of the research, such as pollutant interactions. Since lead and diclofenac were adsorbed simultaneously, it was challenging to complete this task. Lead can occupy the GAC adsorption sites, meaning that other substances cannot be removed. Therefore, it is evident that more complicated systems are required to address multiple pollutants simultaneously. The complexity in the adsorption at high rpm should also be considered since the adsorption in the case of diclofenac began decreasing at rates higher than 200 rpm. Since the tendency is not linear, it can be considered that the GAC may operate differently depending on the operational speed above a certain limit. Lead removal is another major issue since GAC demonstrated relatively poor efficiency in removing this metal. Since the washing procedure was difficult, the regeneration method needed to be improved.

6.2 Recommendations and future work

Granular activated carbon (GAC) can be effectively used to remove diclofenac sodium and lead from water. Further enhancement of this process involves investigation of less expensive GAC regeneration technologies, performance comparisons between different types of GAC, and the potential influence of actual water quality conditions on adsorption efficiency. Performance review over a long period of time and testing strategy for bigger systems are important. It may well be that, from a cost-benefit perspective, such comparisons should consider a combination of GAC with other substances to reduce costs as an alternative. Research on the environmental impacts of GAC and other substitutes is needed in order to improve their water filtration effectiveness.

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