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Adsorptive Removal of Surfactants from Laundry Wastewater Using ML Data Analysis

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ABSTRACT
The release of surfactant-loaded laundry wastewater without proper treatment is a major environmental concern as it causes foam and reduces oxygen level in aquatic bodies. Conventional methods are often not only expensive but also non-environmentally friendly. This paper explores a new bio-composite material, Graphene Oxide modified Coconut Shell Activated Carbon (GO-CSAC), for the purpose of adsorbing surfactants effectively. GO-CSAC has outstanding structural features and displays a very large surface area of 1120 m^2/g along with a pore size of 1.75 nm. It uses the natural characteristics of activated carbon along with the additional functional groups of graphene oxide to maximize adsorption sites. Various batch experiments were performed to check performance at different conditions. Results show that the GO-CSAC is capable of adsorption much more than the unmodified carbon. Under ideal conditions which are the amount of adsorbent = 1 g/L, time of contact = 6 hours, and pH value = 8, the material managed to remove 95% of surfactants. The Langmuir isotherm (R^2 = 0.995) and pseudo-second-order model (R^2 = 0.965) fit to the adsorption data shows a close correlation between theoretical and experimental results. To make the operation more efficient, a Machine Learning (ML) model was designed based on the experimental dataset to forecast the performance. This model gave very low prediction error during validation thus drastically decreasing experimental trial-and-error. Making use of this environmentally friendly bio-composite produced from waste and best-quality predictive modeling together is a very effective, intelligent solution for treating household wastewater and achieving pollution mitigation in a sustainable way.

Keywords: coconut shell activated carbon, machine learning, adsorption, laundry wastewater, surfactant

1. INTRODUCTION

Worldwide the need for better sanitation and ease has driven domestic water consumption to rise dramatically. Laundry is the main culprit by far. This problem has become even more serious in the 21st century with the wide spread use of washing machines at home and bigger facilities. Estimates say that every year laundry produces globally billions of cubic meters of wastewater; in some parts industrial laundries are responsible for even up to 10% of all urban wastewater. What makes this problem more difficult is the fact that globally around only 56% - 58% of domestic wastewater is being safely treated. So much so that this much untreated or insufficiently treated laundry wastewater has become a major environmental issue. It contains surfactants dyes organic matter and various chemical additives among other things. Putting this kind of waste into natural waters is greatly harmful to aquatic life and human health. That is why technologies for efficient and sustainable treatment are needed. Of the different ways for remediation, the method of adsorption besides the other benefits is very promising and cost-effective in removing a large number of pollutants from wastewater. The main reason for its success is the high surface area and the porous nature of adsorbent materials. Activated carbon, known for strong adsorptive power, has been extensively used in water treatment works. In the past activated carbon has been produced from a number of sources which include wood and agricultural residues. The making of activated carbon from biomass is a green and sustainable way of converting abundant and renewable materials into useful ones at the same time offering an environmentally friendly alternative to the conventional carbons which are derived from fossil fuels.Shelled coconuts are a common source of waste in many developing countries, where they are mostly discarded. However, they are also a major biomass resource that is scarcely tapped. Due to their natural characteristics, they can serve as an excellent raw material for producing activated carbon. In addition, through nanotechnology, traditional adsorbents can now be improved considerably. Graphene oxide (GO) which is derived from graphene, has a high surface area, enough oxygen-containing groups, and good chemical stability among other properties these together with reducing agent made it highly efficient. These properties are what make GO being used for developing advanced adsorbents. So, in this project, we will be studying the design of a new and improved adsorbent by modifying coconut shell derived activated carbon (CSAC) with graphene oxide (GO). This new composite (GO-CSAC) plans to combine advantages of both raw materials: The inexpensive, porous nature of CSAC together with the upsurged adsorption capacity and surface chemistry of GO. The main goal, is to check the real application of GO-CSAC to efficiently remove pollutant sin particular surfactants, dye se, and organic matter from laundry wastewater, therefore contributing to sustainable water management and environmental protection. The method to be used in the project has the potential to match specific objectives with advanced analytical techniques: After preparation of the GO-CSAC adsorbent, a comprehensive set of analytical tools will be used in this work to conduct an in-depth characterization and comparison of physicochemical, morphological, and structural features of both raw and modified materials. It almost used Scanning Electron Microscope (SEM) to observe changes in surface morphology, X-Ray Diffraction (XRD) to identify crystal structures and purity, BET to thoroughly quantify the specific surface area and pore characteristics, and FTIR for GO characterization. Next, the research will focus on performance optimization, determining the ideal batch adsorption parameters—such as pH, contact time, adsorbent dose, and initial pollutant concentration—that would maximize the treatment efficacy. UV-Vis Spectrophotometer is a highly reliable way of quantifying residual contaminants in the solution, while Chemical Oxygen Demand (COD) and Biological Organic Demand (BOD) are indicators of the total organic content that has been diminished after the treatment.

Furthermore, to give a well-rounded grasp and ensure adaptability, the study will explore the basic adhesion mechanisms by doing kinetic, isotherm, and thermodynamic modeling. Lastly, the research will wrap up with a study of the GO-CSAC adsorbent's ability to be regenerated and its stability over time in order to confirm that it is capable of being used repeatedly in a sustainable manner.

2. EXPERIMENTAL SECTION

2.1 MATERIALS AND METHODS

For activated carbon production, about 7 kg of coconut shells were collected from several sources, mainly local markets and agricultural waste sellers in Karnataka. Sodium hydroxide (NaOH) used for activating carbon chemically, was brought from Ram Shree Chemical, a well-known supplier of Bangalore. The graphene oxide (GO) which was used to change the activated carbon having a purity of 99% and a rich density of oxygen functional groups was got from ISO (International Organization Standardization), located in Bangaluru, Karnataka. The suggested structure of modified GO-CSAC composite is shown in Figure 1.

2.2 Synthesis of Graphene Oxide-Modified Coconut Shell Activated Carbon (GO-CSAC)

Preparation of Coconut Shell Activated Carbon (CSAC) At first The raw coconut shells were rinsed thoroughly with distilled water in the beginning to cleaned all the dirt and dust on the surface of the shell.. After that, the washing step was followed by drying in a hot air oven at 110°C temperature for 12 hours. The dried shells were crushed mechanically and then passed through a sieve in order to have uniform particle size of 300 to 700µm. Then the char obtained was activated chemically by soaking it in a sodium hydroxide solution with an impregnation ratio of [Ratio, e.g. 1:3 char-to-chemical] (w/w). The raw material was put in a muffle furnace for carbonization and heated up to 500°C for 1.5 hours in nitrogen atmosphere (inert gaseous atmosphere). Activated coconut shell carbon (CSAC) was prepared after Cleaning with 0.1 M HCl followed by hot distilled water until the pH of the washing liquid became neutral. The cleaned CSAC was dried overnight at 110°C and kept in a desiccator.

Preparation of the GO-CSAC Composite

To prepare the novel GO-CSAC composite, we used a wet impregnation and ultrasonication technique. Briefly, 5.0 g of CSAC was suspended in 100 mL of a water-based GO solution with a GO concentration of 2.0 mg/ml. The mixture was ultrasonicated for 30 minutes to achieve an even dispersion and to allow the GO sheets to deeply penetrate the porous structure of the CSAC. Then, the sonicated suspension was magnetically stirred at 500 rpm for 12 hours at 60°C for full surface interactions and modification. Eventually, the solid composite obtained was separated by vacuum filtration, carefully rinsed with distilled water to remove any unbound GO, and dried in a vacuum oven at 80°C for 24 hours to get the final GO-CSAC adsorbent.

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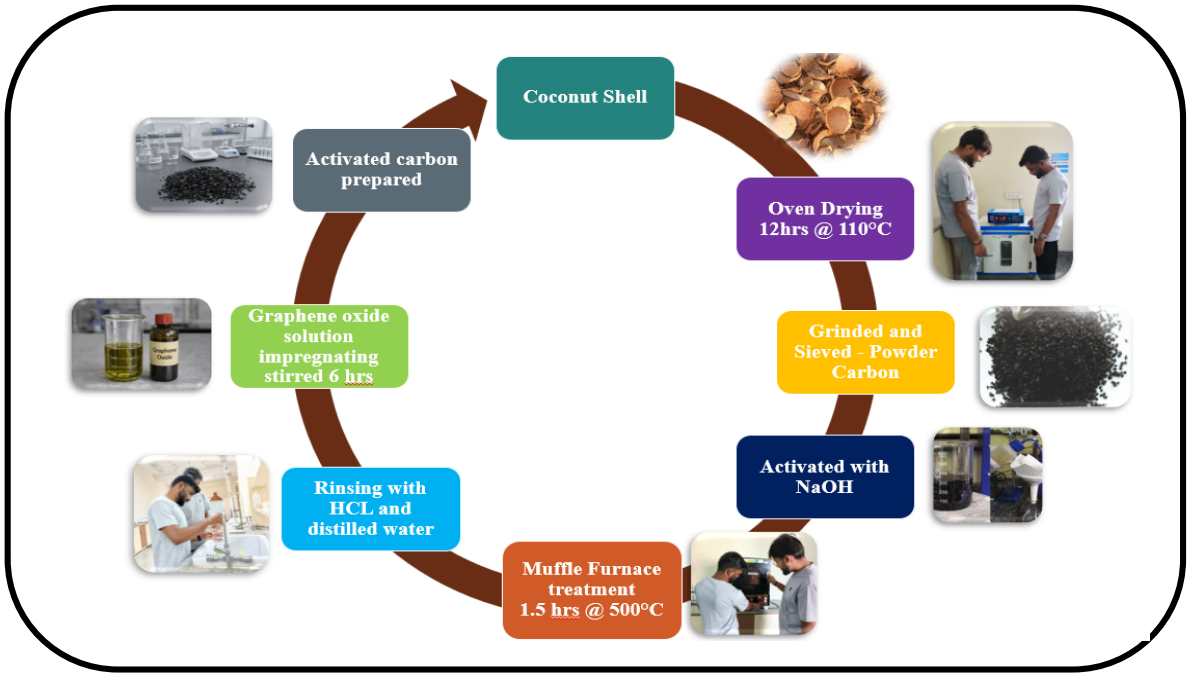

The characterization of the original activated carbon (CSAC) and the prepared graphene oxide modified composite (GO-CSAC) was achieved by a number of analytical techniques in order to confirm the successful modification and assess the material properties. Scanning Electron Microscopy (SEM) was primarily utilized for examining surface morphology, the micro-porous structure, and the dispersal of the graphene oxide sheets within the carbon matrix. FTIR spectroscopy using the KBr pellet method was carried out for the spectral range 4000-500 cm^{-1} to identify the oxygen functional groups introduced with graphene oxide. Apart from measuring the BET specific surface area and pore size distribution, the automatic surface area analyzer was employed. Nitrogen adsorption–desorption isotherms at -196°C were recorded, and BET surface area determinations were made to assess the changes in porosity after the GO modification. In addition, X-Ray Diffraction (XRD) was employed to provide structural details and confirm the alterations in the crystallographic phase of the composite. Finally, the Zeta potential characterization was done to find the surface charge of the adsorbents. These advanced characterizations taken together give a deep understanding of the physical, chemical, and structural features of the GO-CSAC composite, which is very important in assessing its composition and potential for the targeted treatment of laundry wastewater.

2.4 Experimental investigation carried out to understand the adsorption process with GO-CSAC—batch studies

Batch adsorption experiments are the backbone of our research. They support a systematic approach towards the study of essential factors to explain the adsorption of laundry wastewater pollutants. Here we summarize the main experiments, offering the background information, justification, and importance of the parameters examined. In order to carry out the experiments, simulated laundry wastewater solutions with the target pollutants (e.g. surfactants and dyes) were made by diluting the stock solution with distilled water. The method of quantifying the concentrations of pollutants in this study was the use of an Ultraviolet-Visible (UV-Vis) Spectrophotometer. The measurement of the remaining concentration of the target pollutant was done at its specific wavelength of maximum absorbance. In the course of preparing the calibration curve, the standard solutions of the target pollutant were made, and the UV-Vis technique was then used for the accurate analysis of pollutant elimination, thus opening the way for an understanding of the efficiency of the GO-CSAC removal process. The monitoring of further organic load reductions was carried out through the measurement of Chemical Oxygen Demand (COD). This research involved a detailed assessment of several major factors, including the initial pollutant concentration, the amount of the adsorbent, the duration of contact, the levels of pH, and the temperature. The parameter x1 represents the initial concentration of the adsorbate solution. This variable is quite important as it has a direct effect not only on the rate but also on the level of adsorption onto the GO-CSAC material. Changing the concentration of the adsorbate solution allows us to observe the modifications in the adsorption capacity and to collect information on the adsorption mechanisms. In the current work, the initial concentrations of the target pollutant varied from 50 to 250 mg/L, a constant dose of GO-CSAC of 0.2 mg per 100 mL solution was used, the pH was neutral, and the temperature was 25°C.

The parameter x2 represents the amount or mass of the GO-CSAC adsorbent used in the experiment. It is the adsorbent dosage, the most critical factor, that determines the number of active sites and functional groups available for adsorption, and hence the overall efficiency of the process. Besides figuring out which amount works best, testing different dosages also helps in understanding the capacity of the adsorbent under various conditions. Here, we used dosages of 0.1, 0.2, ... 1 mg of GO-CSAC at pH=7, 25°C, 12 h, C0=50 mg/L, V=100 ml. In our study, the parameter x3 refers to the contact time or how long the adsorption process is conducted. The duration of contact is essential in influencing the kinetics of adsorption., i.e. the rate at which GO-CSAC is adsorbed to equilibrium with the pollutants from the laundry wastewater. By thoroughly analysing the influence of contact time, we will be capable of assessing the time needed to reach the highest level of adsorption effect. We have engaged in experiments with contact time lasting from 1 hour to 12 hours, under the conditions of pH=7, temperature 25°C, GO-CSAC dosage 50 mg/100 mL, and initial LAS concentration at 50 mg/L. The variable x4 indicates different pH levels that can considerably affect adsorption, for example, by altering the surface charge of GO-CSAC and ionization of the pollutants. The experiments pH range (5 to 9) was controlled by 0.1M HCl or NaOH, contact time - 6 hours, C0=50 mg/L LAS, 1 mg GO-CSAC, and T=25°C. Furthermore, the x5 factor is the temperature at which the reaction occurs. By changing temperature, besides assessing the potential practical application of GO-CSAC, it is one way to determine experimentally whether an adsorption process is exothermic or endothermic. We conducted this experiment changing the temperature from 25°C to 50°C, while the pollutant concentration was 50 mg/L, the GO-CSAC dosage was 1 mg per 100 mL, the pH was 8, and the contact time was fixed at 6 hours. In brief, through stepwise variations of these parameters (x1 x2 x3 x4 x5) in our batch adsorption experiments, we will be able to delineate the treatment process, comprehend the complicated interactions during adsorption of graphene oxide and activated carbon, and prepare the groundwork for the further enhancement of the performance of the GO-CSAC composite in the purification of laundry wastewater.

2.4.1 Laundry Effluent Analysis

In order to test the GO-CSAC composite's effectiveness in a real environment following the lab synthesis of the adsorbent, laundry wastewater was the medium of trial. The samples were directly taken from the commercial laundry facility of Jain University Bangalore with careful consideration of the standard sampling protocols and Central Pollution Control Board (CPCB) guidelines for effluent analysis. This test was to check the real-time potential and overall effectiveness of the GO-CSAC composite in handling the complete, multi-component of laundry effluents under the actual conditions.

2.4.2 Adsorption Kinetic Models

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In order to comprehend the mechanism of pollutant adsorption on GO-CSAC composite, two types of kinetic models, i.e. pseudo-first-order (PFO) and pseudo-second-order (PSO) were used. These provide significant information about adsorption at non-equilibrium conditions which help in a thorough explanation of the associated kinetics. The chosen models were used on the basis of their power to fit mathematically the experimental data obtained during batch studies.

Pseudo-First-Order (PFO) Kinetics

The common model for studying a solid 'resorbs' to liquid from air is called kinetic (pronounced perfluoro ethylene; "one product of probability below one numerical answer)), and determines solute removal rate of any given substance depends on that both concentration at saturation level discus by each country's clear plasticity mass through the addition of particles as substances: The PFO model introduced today may refer variously into mathematics including: the ratios of pollutants present in the solid-liquid mixture mixture, with emphasis upon: first solvent factors; released in challenging components, while the PTO coefficient remains relevant

$$\log(q_e - q_t) = \log q_e - \frac{K_1}{2.303}$$

In this context, Qe (mg/g) and Qt (mg/g) are used to denote the mass of the contaminant adsorbed at equilibrium and at any time t (min). K1 (1/min) is the rate constant for the PFO adsorption process. The value of Qe and K1 can be obtained from the intercept and the gradient of the plot of ln (Qe - Qt) against t.

Pseudo-Second-Order (PSO) Kinetics

Through this process we normally use of a pseudo-second order model to describe the several phenol adsorption systems in which the rate-determining step of the overall process of conversion of reactant to products is included chemisorption. as the valency forces through sharing or transfer the electrons mechanism constituting the interaction between. The linear form of PSO is expressed as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}\, t$$

In this context, K_2 (g/mg-min) represents a constant that correlates with the speed of PSO adsorption. The initial rate of adsorption, referred to as V0, is roughly equivalent to K_2Qe^2 as t approaches 0. The equilibrium capacity, Qe, along with the rate constant k2, can be ascertained from the slope and intercept of the linear graph plotting t/Qt against t, respectively. Adsorption Isotherms

In order to gain insight into the equilibrium distribution of the pollutants between the liquid and the solid phases of GO-CSAC, two familiar adsorption isotherm models (Langmuir and Freundlich isotherm) were adopted.

Langmuir Isotherm

The Langmuir isotherm describes the adsorption of a substance to a surface occurs in equilibrium when: adsorption proceeds in a monolayer, on a surface with all adsorption sites being equal, there are no interactions between adsorbed molecules. In its linear form the isotherm is:

$$\frac{C_e}{q_e} = \frac{1}{q_{m.K_l}} + \frac{C_o}{Q_e} \qquad (3)$$

In this context, Ce (mg/L) is the concentration of the pollutant in the solution at equilibrium. Qe (mg/g) is the quantity of pollutant adsorbed at equilibrium. Qm (mg/g) is the maximum amount available for monolayer adsorption, and K1 (L/mg) is the Langmuir constant related to the availability of the binding site and the energies associated with adsorption. From the graph of Ce/Qe as a function of Ce, Qm and K1 are obtained by the slope and intercept of the line.

Freundlich Isotherm

The Freundlich model considers adsorption to occur in multi-molecular layer (multilayer) form on heterogeneous surfaces. In addition, it proposes a decrease in binding energy as more sites are filled. The following linear form of the equation is

$$lnq_e = (lnK_f) + \left(\frac{lnC_e}{n}\right) \qquad (4)$$

K_F ((mg/g) (L/mg)1/n) is a constant from the Freundlich isotherm that indicates the estimated adsorption capacity, while 1/n is an empirical constant associated with the intensity of adsorption or the heterogeneity of the surface. If 1/n is between 0 and 1 then adsorption is favourable. The constants K and n are calculated by plotting values of 'ln(Qe) against ln(Ce) then obtaining the intercept and slope respectively.

.3. RESULTS AND DISCUSSION

3.1 Characterization of CSAC

Before properly using CSAC for wastewater treatment, the physical, chemical, and adsorptive properties of this material should be characterized. Pore structure and surface morphology of CSAC are frequently analysed via SEM. SEM images revealed that the surface was highly porous and irregular, which made the surface excellent for adsorption. BET analysis is a method that helps determine the surface area and pore size distribution of materials, which can indicate the presence of active sites capable of capturing pollutants. Functional groups present on the surface can be determined using FTIR. In addition, this method helps to identify how adsorbents and contaminants interact with each other. The degree of crystallinity or amorphousness is determined through XRD. Furthermore, proximate analysis is conducted to determine the levels of moisture content, ash content, volatile matter, and fixed carbon, all of which influence adsorption capacity. Additionally, the pH and point of zero charge (pHpzc) are assessed to understand the variations in surface charge under various conditions. Collectively, these characterization techniques provide comprehensive insights into the suitability and efficiency of CSAC for the elimination of pollutants from laundry wastewater.

3.1.1 Scanning Electron Microscopy (SEM)

SEM is an excellent analytical technique to reveal surface features and microstructure of Coconut Shell Activated Carbon (CSAC). SEM works by scanning a concentrated beam of high-energy electrons across the surface of the sample generating detailed images resulting from electron-sample interaction. The SEM images of CSAC usually depict a highly porous, rough, and irregular surface with deep cavities and channels that are well-developed due to the activation process. These pores are essential in adsorption because they provide a large surface area and a high number of active sites for pollutants. The method is also used to analyze pore distribution, particle size, and structural

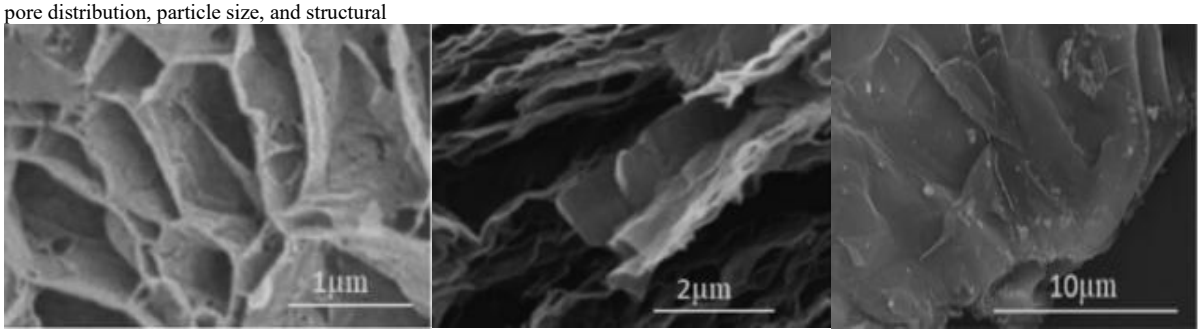

FIGURE 2 SEM micrographs of samples: (a), (b) and (c) of prepared coconut shell activated carbon at 750 °C of activation temperature, and NaOH activating agent

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SEM at 1 µm (micrometre) scale offers an extremely enlarged image of the CSAC surface and thus fine pores and microstructure can be seen clearly. These pores are mainly responsible for the adsorption of very small molecules such as surfactants and dissolved pollutants which is a characteristic of micropores and mesopores. At this scale, surface roughness and active sites can be observed in detail. At 2 µm scale, the image presents features that are a little bit bigger. One can notice the pores' distribution and their connectivity. Micropores and mesopores can still be seen here, but they are presented in a broad way that helps to understand how the pores are linked together and how the pollutants diffuse through the structure. SEM at 10 µm scale allows one to have a more general idea of the surface morphology. One can see the large pores (macropores), cracks, and the overall texture of the carbon material. This scale is suitable for understanding the structural framework and organization of the pore network that influences the fluid flow and adsorption site accessibility.

3.1.2 X-ray Diffraction (XRD)

XRD is the analytical technique that tells us whether a material is crystalline or amorphous. It can be employed for coconut shell activated carbon (CSAC) as well. An XRD pattern of CSAC generally consists of broad and diffused peaks, reflecting a material that is mostly amorphous in nature with very little crystallinity. To elaborate, the XRD profile of CSAC reveals one broad peak at about $2\theta \approx 20°–30°$ which relates to the (002) plane of disordered graphite-like carbon, while another weak and broad peak may be observed at around $2\theta \approx 40°–45°$ which is related to the (100) plane and confirms the existence of turbotrain (randomly oriented) carbon layers. These are all signs that carbon atoms are organized in an irregular, non-uniform lattice instead of a well-defined crystalline structure. Since no sharp diffraction peaks are seen, it means that the majority of the inorganic components and the crystalline impurities have been removed successfully by the activation process (chemical or thermal activation). This helps the material to be amorphous, which in turn helps the pores and the surface area to increase.

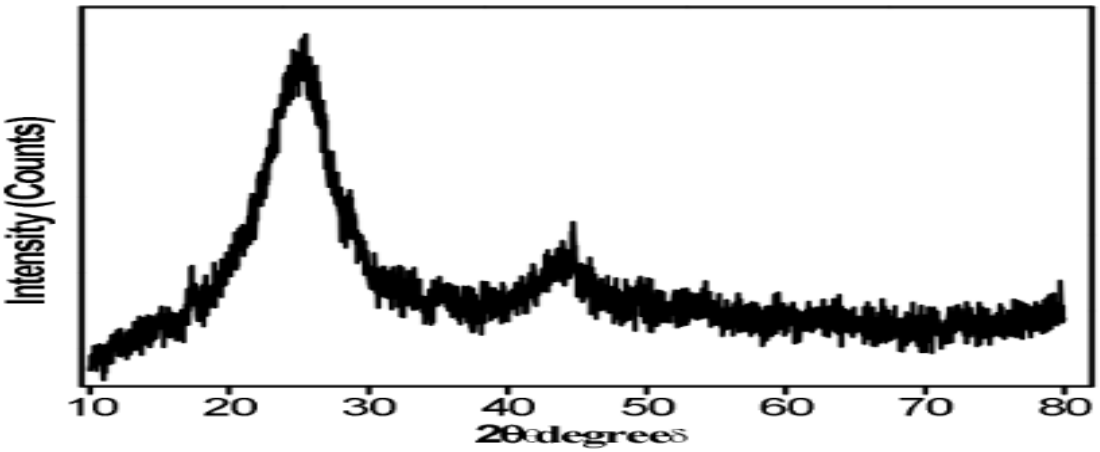

FIGURE 2.4 XRD patterns of GO-CSAC prepared at 500°C (XRD: X-ray diffraction)

These two factors, in fact, are the main reasons for the high adsorption capacity of CSAC. To wrap things up, XRD results are in line with the fact that the main component of coconut shell activated carbon is amorphous carbon with localized microcrystalline graphitic areas, thus turning it into a very effective material for wastewater treatment, pollutant adsorption, and filtration applications.

3.1.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is a technique that helps to know the types of functional groups present on the surface of CSAC. These surface groups greatly influence how the material adsorbs and reacts chemically. The typical FTIR spectrum of CSAC reveals several characteristic absorption bands that correspond to different functional groups: A broad peak at around 1000-1500 cm^{-1} represents O–H stretching vibrations and it is an indication of hydroxyl groups (alcohols or phenols) and adsorbed water. Peaks at around 1000–1250 cm^{-1} are related to C–H stretching vibrations of aliphatic compounds. The first peak at around 1700–1750 cm^{-1} is linked to C=O stretching and shows the presence of carbonyl or carboxylic groups. Bands near 1580–1650 cm^{-1} result from C=C stretching in aromatic rings, thus confirming the carbonaceous structure. Peaks in the 1000–1300 cm^{-1} range are the consequence of C–O stretching vibrations, and correspond to such functional groups as alcohols, ethers, or esters. Oxygen-containing functional groups such as –OH, –COOH, and C=O are capable to improve the adsorption capacity of CSAC because they act as active binding sites to pollutants like heavy metals and organic contaminants.

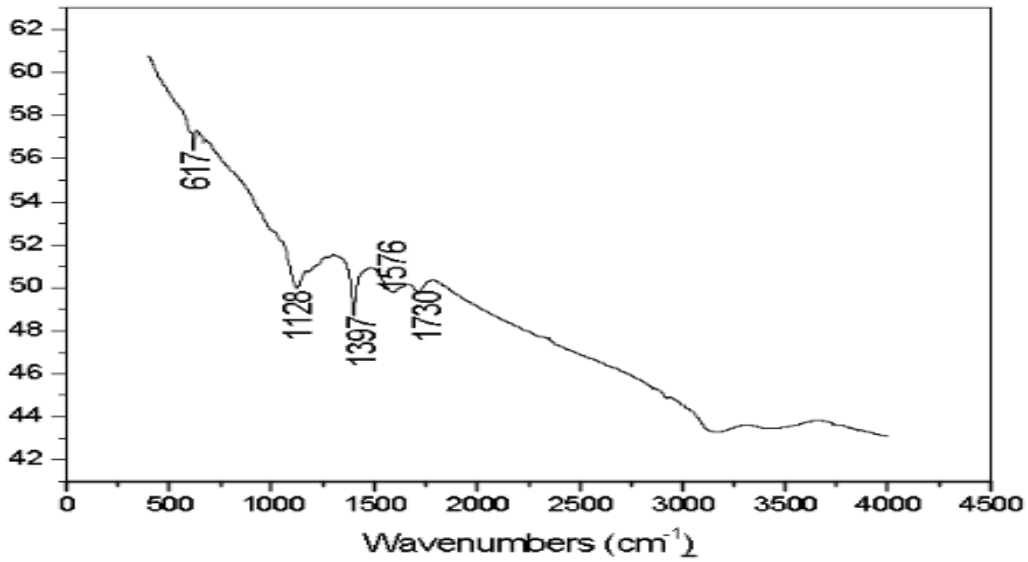

FIGURE 2.5 FT-IR spectra of GO-CSAC using NaOH

In brief, FTIR study verifying that coconut shell activated carbon contains various types of functional groups, which play an important role in the efficiency of the material in wastewater treatment and adsorption.

3.1.4 Brunauer-Emmett-Teller (BET)

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BET is used to determine the specific surface area, pore volume and pore size distribution of CSAC. This process is based on nitrogen adsorption–desorption isotherm measurement at liquid nitrogen temperature (77K). Usually, the CSAC surface is a type I isotherm representing the microporous nature of the activated carbon. A rapid increase in nitrogen adsorption at a low relative pressure (P/P < 0.1) indicates a significant number of micropores (< 2 nm) while a small hysteresis loop at high relative pressure indicates the presence of some mesopores (2–50 nm). The specific surface area of CSAC is within a range of 500 to 1500 m2/g with depend on activation process, whether the physical or chemical.. Chemically activated varieties frequently demonstrate higher surface areas due to enhanced pore development. The total pore volume generally falls between 0.3 and 0.8 cm^3/g, with micropores primarily contributing to this volume. The extensive surface area and extremely porous microstructure of CSAC serve as the main factors for providing a large number of active sites for adsorption, which is one of the reasons why it is so effective in removing organic pollutants, dyes, and heavy metals from wastewater. Also, the pore size distribution ensures the proper diffusion and trapping of the contaminants in the carbon matrix.

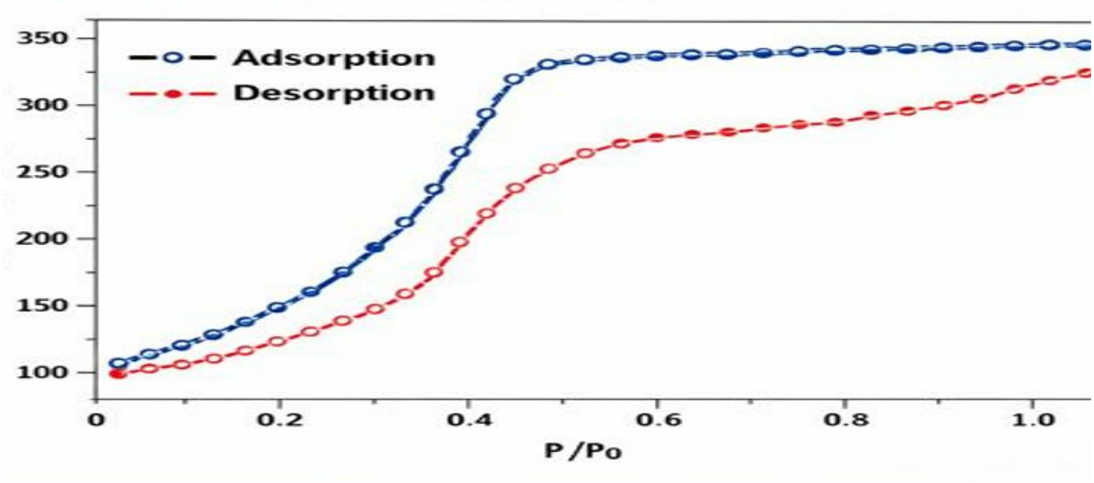

FIGURE 2.6 A graph plotting Incremental Pore Volume (in cm^3/g) versus Pore Diameter (in Ångströms, Å)

In summary, BET analysis verifies that activated carbon derived from coconut shells has a highly porous structure and a large surface area, which is the primary factor contributing to its remarkable adsorption properties in a range of environmental and industrial uses.

3.2 Adsorption Studies

Based on the comprehensive characterization conducted on the synthesized GO-CSAC composite, it is evident that this novel material possesses the structural and chemical properties required of a highly effective adsorbent. The subsequent experimental analysis relies on systematic batch studies designed to evaluate various critical operational parameters. Ultimately, the results from these studies will enable us to fully understand the underlying adsorption mechanisms and validate the practical potential of the GO-CSAC composite for the targeted remediation of complex laundry wastewater.

3.2.1 Impact of adsorbent dosage on LAS

Coconut shell activated carbon (CSAC) dosage is a very crucial factor affecting adsorption performance. Initially, a rise in contaminant removal efficiency happens when CSAC dose increases, simply because there are more active sites for adsorption and a larger surface area. However, beyond a certain dosage, the effectiveness either remains the same or slightly decreases due to particle overlapping or aggregation, which reduces effective surface area and prevents adsorption. The results of our studies indicated that 1 g/L CSAC yields the best removal efficiency. At this level, there is a perfect balance between the number of free adsorption sites and the amount of contaminants in the solution. On the contrary, if the dose is less than 1 g/L, the removal efficiency has to be lower because of the insufficient number of active sites.

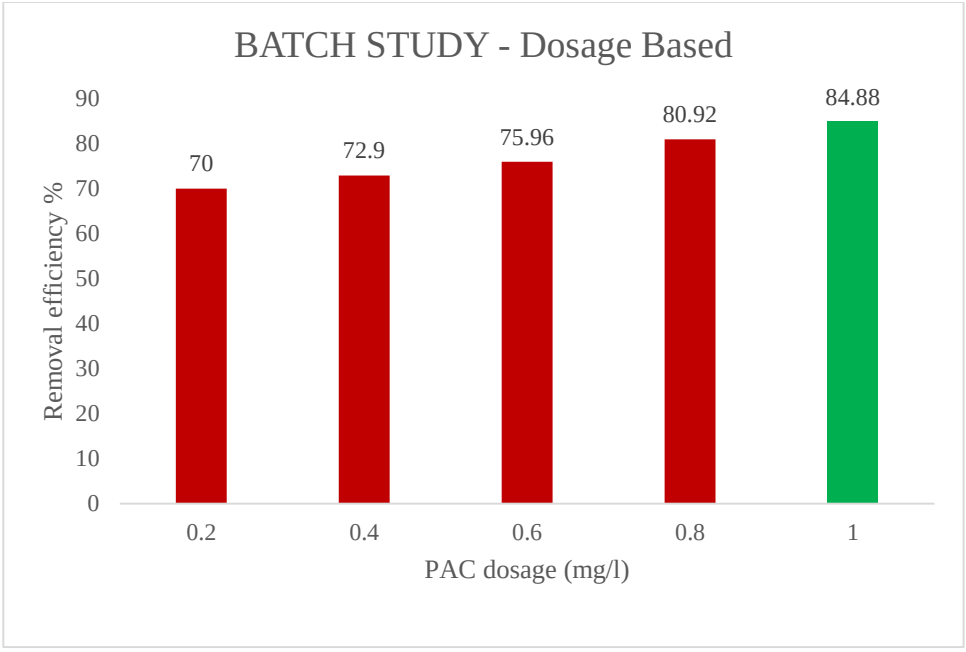

FIGURE 3.1 Graphical depiction of the impact of Adsorbent Dosage on adsorption efficiency

In contrast, beyond this point, no considerable increase is obtained, and so additional dosage becomes economically wasteful. Consequently, 1 g/L as the quantity of adsorbent is the optimum choice, capable of achieving maximum removal of pollutants while using the adsorbent most efficiently. This is an important factor for economical wastewater treatment.

3.2.2 Impact of contact time on LAS

One of the main reasons significantly affects the adsorption capacity of coconut shell activated carbon (CSAC) is possibly time. The longer contact time is achieved, the increase in purification efficiency. This is due to the existence of a large number of active sites on the surface of the adsorbent which can be used. During the first stage, the pollution substances are drawn and bonded to the outer surface of CSAC so quick that the speed of adsorption becomes high. However, as the time goes on, the adsorption speed decreases little by little because the available active sites for adsorption are getting fewer and the major mechanism is also moving toward intraparticle diffusion and attainment of equilibrium. However, at last, a stage comes when the value of removal doesn't increase significantly, which means the adsorption equilibrium is established.

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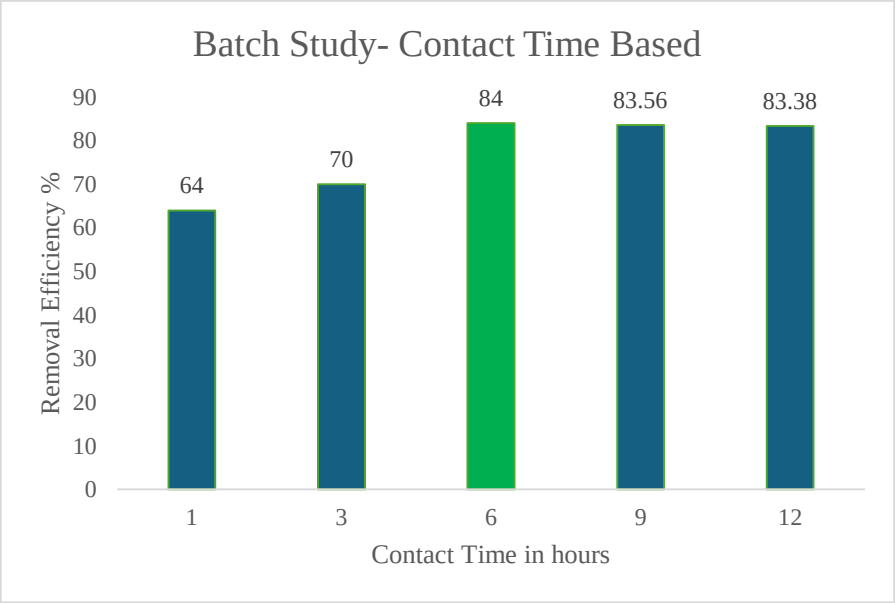
FIGURE 3.2 Graphical depiction of the impact of contact duration on adsorption effectiveness

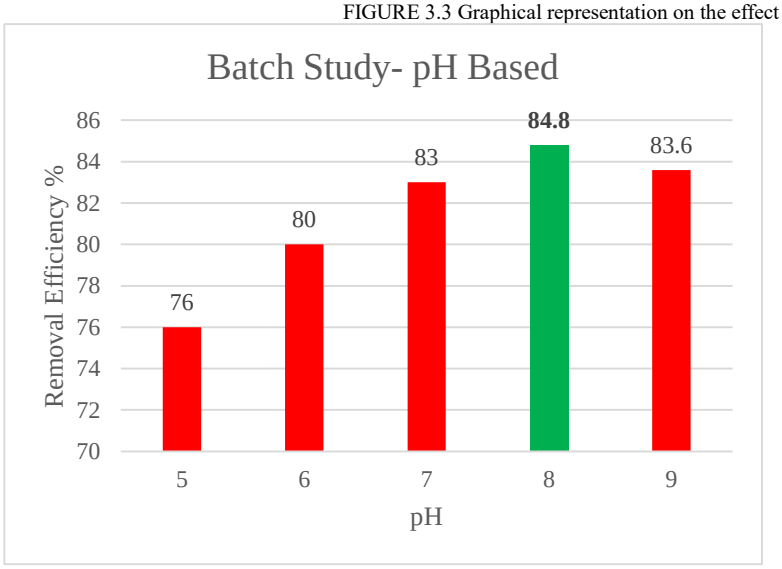
The present work revealed that the contact time of 6 hours was the most effective time to get the maximum removal efficiency. In fact, after this time, the adsorption will not get better so that it does not make sense to stay longer and furthermore it will be less economical. Hence, the period of 6 hours is deemed as the best contact time to have an effective pollutant removal with using CSAC in the wastewater treatment process.



3.2.3 Impact of pH on LAS

The pH of a solution is very important for determining how well coconut shell activated carbon (CSAC) can adsorb different substances. This is because pH not only changes the surface charge of the adsorbent but also the chemical form of the pollutants. By changing the pH, we can either increase or decrease the interactions between CSAC and the contaminants, which ultimately results in different levels of removal efficiencies. We discovered that a pH range of 8–10 was best, with pH 8 leading to the results that we were most happy with. When it is just a bit alkaline, a CSAC surface offers a much better arena for adsorption reactions to take place due to stronger electrostatic attractions with the adsorbate and changes in adsorbate species, especially for organic and negatively charged ones. At lower pHs (acidic conditions), there are too many hydrogen ions (H^+) which directly compete for these same surface sites with the pollutant molecules, causing the adsorption process to slow down. On the other hand, if the pH is raised again (above 10), the adsorption performance will see almost no improvement and sometimes even get slightly worse due to repulsion or saturation effects.

FIGURE 3.3 Graphical representation on the effect of pH on adsorption efficiency



Hence, it is best to keep the solution pH at 8, which not only helps to achieve the maximum adsorption capacity but also ensures stable and effective treatment of wastewater through CSAC.

3.2.4 Effect of Pollutant Concentration on LAS

Initial concentration of pollutant is a key factor which influences the adsorption capacity of CSAC. With an increase in pollutant concentration, the mass transfer is also strengthened naturally because of the higher driving force, so the adsorbate gets more chances to come in contact with the adsorbent. At lower concentration levels, the adsorbent's surface contains a good number of free active sites for pollutant molecules to be adhered which leads to the efficient removal of the pollutants. On the other hand, as the pollutant concentration rises, the adsorbent's active sites will be getting occupied, and consequently, the removal efficiency will decrease. This is because one constant amount of the adsorbent could only hold the fixed amounts of the contaminants. In this research, whereas the highest adsorption efficiency was recorded, optimum pollutant concentration was set at 50 g/L. At this pollutant level, the quantity of pollutant molecules and the adsorption sites are both available in sufficient amount and thus perfectly complement each other. Further increase in pollutant concentration usually stagnates and sometimes leads to decrease in removal efficiency due to saturation of the adsorption sites and restricted adsorption capacity.

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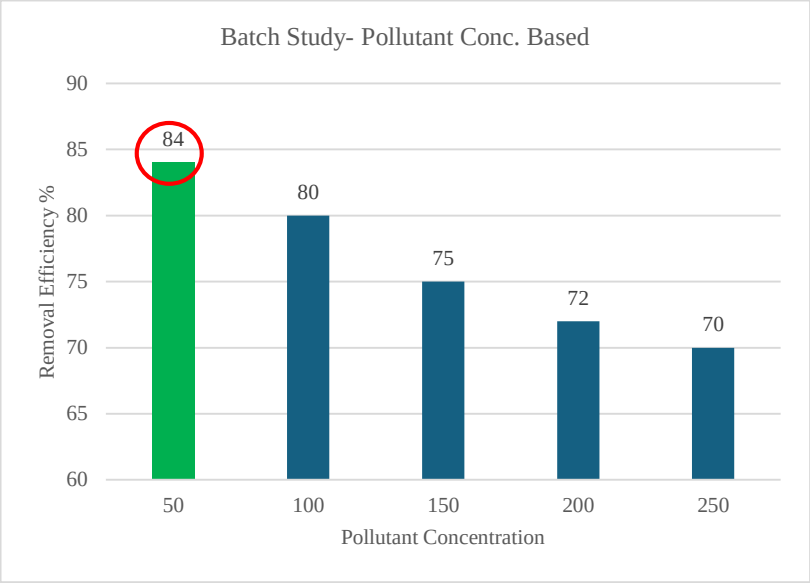

FIGURE 3.4 Graphical representation on the effect of Pollutant concentration on adsorption efficiency

On that account, the initial pollutant concentration of 50 g/L is the most suitable one when CSAC is the adsorbent because it allows the removal efficiency to reach its maximum while the other factors are kept constant.

3.2.5 Effect of Temperature on LAS

Adsorbent temperature is a key factor in determining the efficiency of a coconut shell derived activated carbon (CSAC) in removing pollutants. It is through changes in molecular kinetic energy and adsorption interactions that temperature exerts its influence on the process. As temperatures rise, the movement or diffusion of pollutant molecules toward the adsorbent surface increases, which supports a faster rate of adsorption. However, since the adsorption of activated carbon is an exothermic reaction, raising the temperature may result in a loss of adsorption capacity from the weakening of the forces that hold the adsorbate on the adsorbent. Besides, at higher temperatures, some of the molecules that had been adsorbed may be released back into the solution, which decreases the removal efficiency. In the case of this research, 25°C was the best temperature, which caused the highest adsorption efficiency to be reached. Here, molecular movement and adsorptive forces productively co-exist. Lower temperatures may lead to a slower process because of a reduction in molecular activity while temperatures over 25°C cause a drop in efficiency due to the exothermic nature of adsorption.

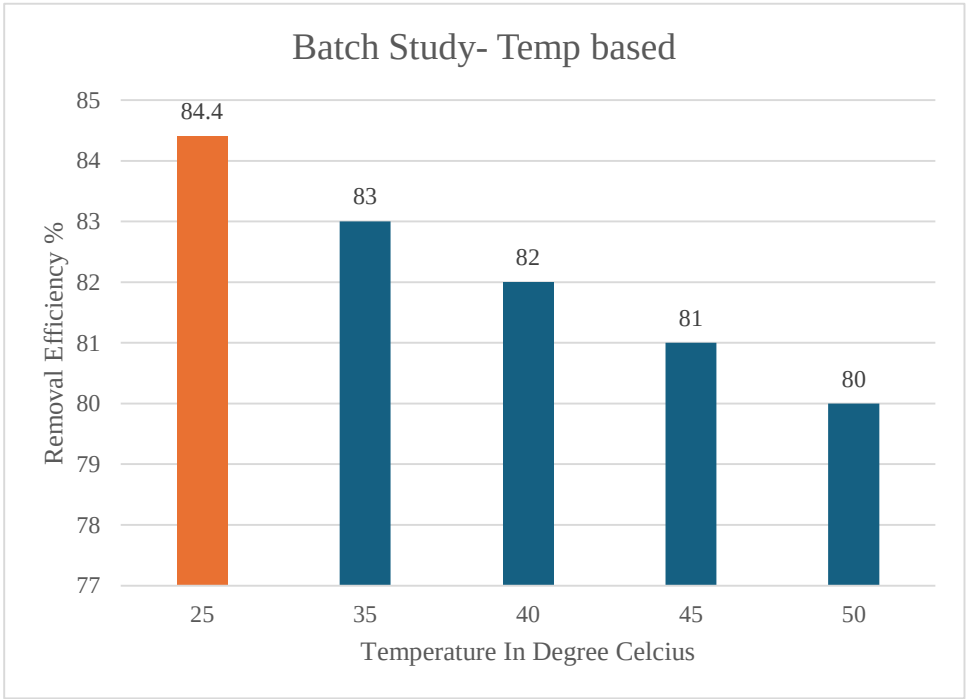

FIGURE 3.5 Graphical representation on the effect of Temperature on adsorption efficiency

Thus, 25 degrees Celsius is recognized as the best temperature for efficient adsorption with CSAC and the procedure is environmentally friendly since it does not require additional heating. This enhances the potential of CSAC in effective wastewater treatment.

3.3 Adsorption Mechanism of the GO-CSAC Composite

The adsorption process explains the very complex and multi-layered interactions between complex pollutants in laundry wastewater (mainly surfactants and dyes) with the GO-CSAC adsorbent. FTIR results, BET surface area results, and pollutant removal efficiency changes with pH altogether indicate that adsorption on the GO-CSAC composite involves mainly four mechanisms: pore filling, hydrogen bonding, electrostatic interactions, and π–π stacking interactions. Physical Adsorption and Pore Filling The adsorption process mainly depends to a very large extent on the physical properties of the coconut shell activated carbon (CSAC). The BET analysis has revealed a very well-developed micro- and mesoporous network. Constituents of the laundry effluent physically diffuse into these pores and become hence structurally entrapped within the carbon matrix. The presence of graphene oxide (GO) changes the surface features of the composite by increasing the interlayer space that can hold bigger organic molecules, such as complex dye structures and long-chain surfactants. Hydrogen Bonding Chemical changes have a great impact on the ability of the composite to adsorb. From the FTIR spectrum of GO-CSAC, a very large number of oxygen-containing groups such as hydroxyl (–OH), epoxy (C–O–C), and carboxyl (–COOH) groups have been identified, which are mainly introduced by the graphene oxide modification. These oxygen-containing groups are strong hydrogen bond donors and acceptors. As a result, they make strong hydrogen bonds with the electronegative atoms (like nitrogen, oxygen, and sulfur) found in the molecular structures of synthetic dyes and anionic/non-ionic surfactants in laundry wastewater.

Electrostatic interactions are the dominant types of interactions in the adsorption kinetics and are highly pH dependent. The charge on the surface of GO-CSAC composite is determined by the degree of protonation/deprotonation of the surface functional groups. In low p H, the surface functional groups are protonated and for GO-CSAC composite the surface would be positively charged and it would attract the negatively charged pollutants strongly (e.g. linear alkylbenzene sulfonates, the most common laundry surfactant). On the other hand, when the pH rises and the solution turns alkaline, the carboxylic and phenolic groups on the GO sheets

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lose their protons, making the adsorbent surface very electronegative. Therefore, the GO-CSAC composite surface can easily attract cationic dyes and positively charged organic matter through electrostatic force, while at the same time it will repel anionic species. This explains why the removal efficiency changes at different pH values.

Lastly, π–π electron donor-acceptor interactions dominate because of the molecular structure of both the adsorbent and the adsorbates. Graphene oxide still consists of isolated regions of unoxidized, sp^2-hybridized carbon chains, which are well matched with the graphitic, aromatic segments of the underlying CSAC structure. Since various laundry wastewater pollutants, especially synthetic dyes and aromatic surfactants, have benzene rings in their chemical structures, substantial π–π intertwining takes place between the aromatic ring of the pollutants and the basal planes of the GO-CSAC composite. Taken together, this combination of high porosity, oxygen-containing functional groups in large quantities, and a solid graphitic backbone gives the GO-CSAC composite multiple binding mechanisms that it can use simultaneously, leading to high-efficiency treatment of complex laundry effluents.

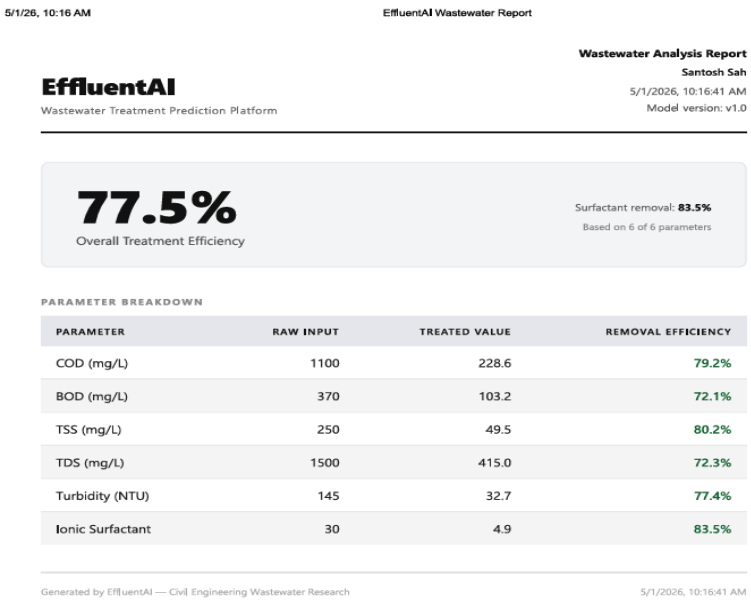
3.4 ML Integration

Besides carrying out experimentations, a machine learning (ML) data analysis model was also designed that could predict the removal efficiency of graphene oxide modified coconut shell activated carbon (GO–CSAC) system depending on different operating conditions. To train the model, different factors such as adsorbent dosage (1 g/L), contact time (6 hours), pH (8), pollutant concentration (50 mg/L), and temperature (25°C) which were the result of the experiments were taken as the inputs. The ML model developed showed excellent predictive capability, which means that the absorbance efficiency is closely linked with the input variables. It was also found that the predicted data is very similar to the experimental results which demonstrate the trustworthiness and the strength of the model. In fact, this accuracy level is a strong indication that the model is efficient in representing the complex relationships between the adsorption parameters and hence, it can be used for the performance prediction and optimization. Also, the introduction of ML model cuts down on the extensive experimental work thus, saving time and resources, besides affording quick and accurate predictions. So, the combining of machine learning with the experimental work unveils the best approach for further improvement in the efficiency and scale-up of wastewater treatment processes using GO–CSAC.

FIGURE 3.6 Laundry Wastewater Treatment Report

CONCLUSION

We report graphene oxide modified coconut shell activated carbon (GO-CSAC) preparation in this research. GO-CSAC was employed as a very good adsorbent to remove pollutants from wastewater. Besides enhanced surface area, more functional groups and higher adsorption capacity, the addition of graphene oxide also leads to higher pollutant removal emission by the starting activated carbon. The study through experiments demonstrated that the adsorption is highly dependent on operational parameters. Among them, the best set of parameters include a dose of 1 g/L of adsorbent, 6 hours of contact time, pH 8, 50 mg/L of pollutant concentration, and 25°C temperature. The adsorbent reached top removal efficiency at these parameters, which suggests a good adsorbent-pollutant molecule interaction. Besides, adsorption at ambient temperature appears quite feasible here, a nice thing making things energy-saving and thus more practical. The alkali-look, a little, pH has, in fact, favored the adsorption, owing to better surface interactions; besides, properly carried out dosage and contact time ensure that the available active sites have been, more or less, fully utilized. Besides experiment, a machine learning (ML) model was built to forecast the removal efficiency. The model performed with a very high level of accuracy which was an indication of the model's good ability to capture the link between process parameters and adsorption performance. This points to the prospect of combining data-driven methods and experimental work for optimizing wastewater treatment systems. In brief, this paper has proven that GO–CSAC is a very effective, affordable, and eco-friendly adsorbent, and the application of machine learning has opened up even more possibilities of GO–CSAC being used for predictive modeling and process optimization in modern wastewater treatment technologies.



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