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Sustainability in the Generation of Household Waste from Dishwasher Sponges for the Purpose of a New Adsorbent Material and Its Operating Costs

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Abstract: The major problems related to environmental pollution are increasingly present among us. The uncontrolled use and incorrect disposal of products means that these problems are increasing at frightening rates. In this context, a major related problem is the incorrect disposal of dishwasher sponges that are no longer useful; their material being made up of petroleum derivatives causes this problem to be leveraged in the environment. In the present work, we evaluated and carried out tests in which these dirty sponges that would be discarded were used for the purpose of developing new sustainable adsorbent materials. These materials were washed and dried, crushed and made available for use, by which they were kept in contact with a paracetamol solution, evaluating the effect of mass, pH, kinetics, equilibrium, thermodynamic parameters, and cost analyses. The results demonstrated an adsorptive capacity of approximately 40 mg g^{-1} and its cost was relatively viable, since this material would otherwise be discarded incorrectly. In conclusion, this material achieved the good removal of this studied contaminant and became an economical, viable, and ecologically viable material.

Keywords: dishwasher sponges; eco-friendly; removal; emerging pollutants; viable costs

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1. Introduction

Dishwashing sponges are a ubiquitous element in practically every kitchen around the world, where they are considered indispensable for efficiently cleaning dishes, pans, and cutlery to achieve hygiene [1]. However, what often goes unnoticed is the considerable environmental impact these sponges have on our global ecology. To this end, the widespread use of dishwashing sponges represents a significant environmental concern, as sponges are often manufactured from synthetic materials, such as polyurethane and polyethylene, which originate from petroleum. The problems associated with these materials are caused by the inefficiency of recycling, where dishwashing sponges are not easily recyclable due to the complex combination of materials, which end up in landfills or being incinerated, further increasing environmental problems, especially in regions of countries considered in development. According to the World Wide Fund for Nature (WWF) [2], Brazil is the fourth largest producer of plastic waste in the world, behind the United States, China, and India, with only 1.2% of the total recycled in 2016 second [3,4].

In response, it is necessary to look for ways to deal with the environmental impact of dishwashing sponges, aiming to transition to sustainable alternatives, which will require the active participation of consumers, manufacturers, and governments around the world [5]. Such factors must be allocated to global management, which must be representative of the renewable environment, focusing on ways to inhibit the release of microplastics and recycling inefficiency, where the challenge of dealing with the environmental impact of dishwashing sponges is far from being resolved. Therefore, the transition to sustainable alternatives requires the active participation of consumers, manufacturers, and governments around the world. Furthermore, it is essential that scientific research continues to explore new materials and technologies that can replace the harmful materials traditionally used in dishwashing sponges [6,7].

Given the applied context, polymers come from the formation of macromolecules made up of repetitions of atoms (or groups of atoms) joined by covalent bonds. However, the main raw material for their production are oil, coal, and natural gas, as well as forms of natural origin, such as starch, silk, and cellulose [8,9].

The most used materials are PE, Polypropylene (PP), Polystyrene (PS), Poly Vinyl Chloride (PVC), PU, and Poly Ethylene Terephthalate (PET), which in 2017 corresponded to 92% of global consumption. Thus, the management of solid waste as well as the recycling of materials and products are needed to address the presence of polymers and their synthesis, becoming a challenge for society, companies, and public management in general.

In relation to PU, the majority of global production, there are aims to apply flexible foams, mainly in mattresses and automotive manufacturing [10].

PU is recognized as a prominent material on the world market, among synthetic polymers, especially for applications involving flexible foams used for cleaning, upholstery, mattresses, and the automotive industry, among other global forms [11].

The presence of microplastics is massive in all oceans on different continents, resulting from degradation by controlled methods or through adverse weather conditions. To this end, the decomposition of the polymer occurs according to its chemical composition, with the presence of reactive chemical groups that favor chemical reactions as well as the breaking of its bonds [12,13].

Thus, sponges are commonly used to clean household items; however, their deterioration or fragmentation can generate microparticles and cause the release of added chemical substances. Although there is evidence of the danger of microplastics, there is little knowledge about the effects caused by these microparticles and the chemical additives leached [14].

However, pus can undergo degradation, with the ease of this process being influenced by structural characteristics such as the chemical groups present in the molecular chains, the level of crystallinity, and molecular orientation, among others [15]. According to research conducted by [16], the chemicals present in 55 polymers were identified and classified according to the environmental risk they present, where flexible PU was categorized as one of the most dangerous due to the toxicity, mutagenicity, and carcinogenicity of its monomers, catalysts, and degradation products, such as hydrogen cyanide [17–19].

Due to their physical, thermal, electrical, and chemical properties, polymeric materials have been increasingly considered to replace products traditionally manufactured with metallic and ceramic materials. With the increase in polymer production, there has been a significant effort to conduct studies that seek to balance economic viability, environmental benefits, and positive social impacts [20–22].

Adsorption comes from a physical–chemical phenomenon of surface adhesion, observed when a fluid, which can be liquid or gaseous, is transferred to the surface of a solid. It has been widely studied with the aim of developing low-cost alternative adsorbents, where the adsorbents are generally solid and with the presence of porous particles in their structure [23,24].

To this end, sustainability is one of the alternative priorities when obtaining low-cost adsorbents, especially those considered discardable such as polyurethanes, which have been attributed with a positive environmental impact and chemical and thermal resistance. These have shown promising results as they have good permeability, low density, and high porosity [25–27].

Thus, the adsorption process can be classified into two types according to its intensity: physical and chemical. Where, for the physical adsorption process, the bond between the surface of the adsorbent and the adsorbate is considered relatively weak, this can be attributed to Van der Walls forces. However, the chemical adsorption process involves sharing or exchanging electrons, characterized by a possible new bond, stronger in relation to the physical adsorption process [28].

Therefore, the application of PUs is intended as an adsorbent agent from various pollutants present in water, including heavy metals and volatile organic compounds (VOCs), as well as dyes. In this context, the functionalization of PUs through their functional groups increases the efficiency in removing certain pollutants present in drinking water. Thus, PUs are promising materials for chemical adsorption systems due to their high porosity, chemical versatility, good mechanical stability, and low cost [29].

Within an attribution envisioning the quantity of PUs for kinetic treatments, in Brazil, several factors influence the useful life of a sponge made up of PUs due to its conditions of use and the ways in which consumers interpret its use. Thus, the city of Maringá/PR located in Brazil, treated as a city for ecological purposes, was used as the management context for the quantification of spongy material in kilograms (kg). The city of Maringá is made up of 415 thousand inhabitants and generates an average of 300 thousand kg of waste daily. Based on this principle, the replacement of dishwashing sponges is estimated to be changed every 15 to 20 days on average [30].

Data attributed by the Brazilian Institute of Geography (IBGE), 2023, stipulate that Maringá is made up of 188,117 residences distributed in the master and urban plan. Thus, in the context described for the number of residences, when multiplied by the exchange of sponges on average every 15 days within a month, an estimated number of 376,234 units/month was obtained [31].

However, to achieve this goal, it was necessary to include teams distributed across a region within the city, divided by regions in order to meet the selective collection of the material in question. The city hall, within its collection management, assigned as a team the application of 25 direct employees, and the use of five trucks to carry out collection management throughout the territorial extension of the master plan, representing collection from Monday to Friday during a period of 10 h of daily work. The present study aimed to use the used dishwashing sponges that are discarded incorrectly in the environment for the sustainable production of a new adsorbent material and analysis of its production costs.

2. Materials and Methods

2.1. Research Development

The experiments were developed in the Laboratory of Management, Control and Environmental Preservation at the State University of Maringá. This laboratory was created to promote research and practice in the fields of environmental management, control, and preservation, and to explore the impacts of human activities on the environment. Through the laboratory, the university actively engages in initiatives to protect and preserve the environment.

2.2. Material Preparation

The methodology for preparing the sponge for use in scientific purposes involves several steps. First, the sponge was collected carefully so as to not cause any damage. Then, it was chopped into small pieces in order to facilitate further steps. Next, deionized water at 100 °C was used to remove any possible contaminants present in the sponge. This was performed for 30 min, stirring occasionally for complete removal of contaminants. Finally, the sponge was placed in an oven and dried at 105 °C for 24 h. This step allowed any residual water and contaminants to evaporate and the sponge was ready to be used for scientific purposes [32].

2.3. Material Characterization

The material was characterized in terms of its textural, structural, morphological, and chemical composition. Scanning electron microscopy (SEM) (Quanta 250 FEI) was used equipped with an EDX-type chemical analysis system with software support (Oxford Instruments Nanotechnology Tools Ltd., London, UK). The zeta potential of the surface was determined using a particle analyzer DelsaTMNanoC (Beckman Coulter) and Fourier transform infrared spectroscopy (FTIR) Vertex 70 v (Bruker) [33].

2.4. Effect of Mass and pH

To investigate the effect of the mass and pH of a sponge on the release of paracetamol, the following method was used. Between 0.01 and 0.05 g of sponge was used by varying the mass in five increments, and an initial paracetamol concentration of 60 mg L^{-1} was added and stirred at 120 rpm at room temperature for 24 h. The pH values were varied to 4, 7, and 10 to investigate the effect of pH on the release of paracetamol. The mass that gave the best result was used in the study of the effect of pH on the release of paracetamol. The release of paracetamol was measured for all the different pH levels and the results were analyzed. The results were compared to identify the effect of the mass and pH of sponge on the release of paracetamol. We also looked at any potential interactions between the mass and pH values. The results will inform us on how to best optimize the release of paracetamol from a sponge and what mass and pH values we should use for further studies on the effect of a sponge on the release of paracetamol.

2.5. Kinetic and Equilibrium Study

The kinetic and equilibrium studies of the effect of dosage (0.01 g of sponge) and pH (7) on the adsorption of paracetamol onto sponge material was investigated in a laboratory set-up. The experiments were conducted at room temperature (25 °C) in a batch reactor with 30 mL of paracetamol solution at a concentration of 60 mg L^{-1}, with a stirring speed of 120 rpm, while pH was maintained at 7. Samples were collected at specific intervals (namely from one to 1440 min) and filtered through cellulose acetate membranes, in Equation (1):

$$q_e = \frac{(C_i - C_f) \times V}{m} \tag{1}$$

The adsorption capacity was determined by measuring the amount of paracetamol adsorbed in the sponge material at equilibrium. Data obtained from the experiments were fitted to the pseudo first order and pseudo second order kinetic equations. The pseudo first order equation describes the rate of adsorption as a linear function dependent on the initial concentration of the adsorbate (C_i), while the pseudo second order equation relates the rate of adsorption to a product of the initial concentration (C_f) and the capacity of the adsorbent (q_e).

The pseudo first order equation is given by $q_t = q_e\ [1 - e^{-k_1 t}]$, where qt is the adsorbed amount of paracetamol at any time 't', q_e is the adsorbed paracetamol at equilibrium, and k is the rate constant. The constant can be determined by plotting a graph of qt against t (time) providing a linear link between them. The pseudo second order equation is given by $q_t = \frac{k_2 q_e^t t}{1+k_2 q_e t}$ where k is the rate constant and Co is the initial concentration of paracetamol. By plotting q_t against t (time), a linear relationship is obtained and the pseudo second order equation can be applied. The linear plots generated from the kinetic equations are used to calculate the rate constants (k) which are then used to determine the adsorption capacities expressed in terms of mg g^{-1}. The data obtained from the experiments can thus be used to calculate the adsorption capacity (q_e) and the rate constants (k) for pseudo first and pseudo second order equations. This in turn enables one to modify the existing conditions in order to increase the adsorption capacity or reduce the rate constant, as required.

2.6. Adsorption Isotherms

The adsorption isotherm experiments were conducted at three different temperatures 298, 308, and 318 K C using 30 mL paracetamol solution with varying concentrations from 10 to 250 mg L^{-1} in contact with 0.01 g in adsorbent pH 7 under stirring at 120 rpm for

720 min. From the calculations of the adsorption capacity, the most classic models of adsorption isotherms were evaluated, i.e., Langmuir and Freundlich.

The Langmuir isotherm is based on the assumption that there is a defined number of active sites with no competition between them, assuming that adsorption occurs in a location independent of the adjacent active sites occupied, and is presented in Equation (2).

$$q_{eq} = \frac{q_m b_L C_e}{1 + b_L C_e} \tag{2}$$

where b_L is the Langmuir isotherm (L mg^{-1}) constant. The Freundlich model is applied to heterogeneous surface models, and therefore, does not provide assumptions about the adsorption capacity of a monolayer, and assumes that there is an interaction between the adsorbed molecules, and is presented in Equation (3):

$$q_{eq} = k_F C_e^{1/n} \tag{3}$$

where k_F is the Freundlich isotherm constant (mg L^{-1}) (L g^{-1})$^{1/n}$. After applying the adsorption isotherm models, equilibrium data were used to calculate the thermodynamic parameters: enthalpy (ΔH), entropy (ΔS), K_c equilibrium constant, and Gibbs free energy (ΔG).

2.7. Cost Analysis Involving the Use of Dish Sponge

Cost can be interpreted as different concepts depending on the format in which the analyst interprets this function. Here, the study included the purchasing of raw materials, which must be aligned with production costs, especially due to their final composition, which will be the final product. Thus, the cost analysis was studied for both adsorbents in order to report all expenses involved in the production of the materials, that is, the financial outflows related to production and final costs attributed to the application of the adsorptive agent.

3. Results and Discussion

3.1. Material Characterization

Scanning electron microscopy was performed, as shown in Figure 1:

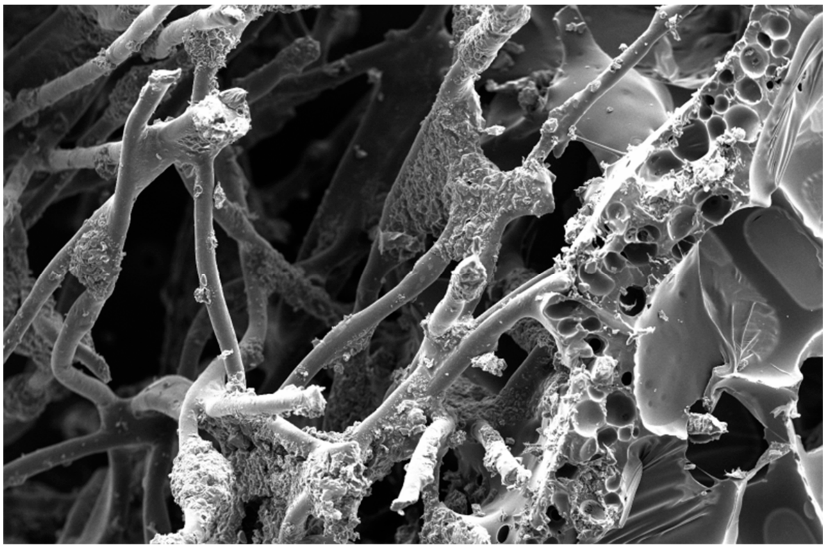

Figure 1. Dish sponge residue SEM.

The dish sponge super-elastic material (SEM) is a novel adsorbent material developed for water treatment and eco-friendly devices. It is composed of a combination of organic and inorganic lattices which form a three-dimensional super-elastic structure. This structure is able to deform and recover its original shape during the adsorption of contaminants, providing a high-performance capacity. The dish sponge SEM has a larger surface area and a strong adsorption capacity compared with traditional adsorbents, enabling it to adsorb a wide range of contaminants. It is also capable of regeneration, allowing for the reusability of this material for successive adsorption runs. This feature helps to reduce the cost of operation and the environmental footprint associated with adsorption operations.

The Zeta potential was performed to obtain the isoelectric potential of the material, as shown in Figure 2.

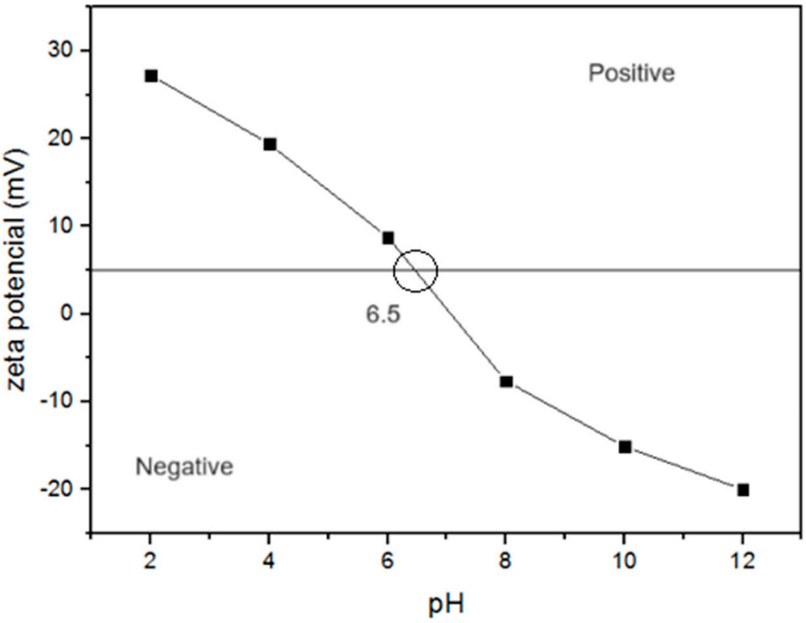

Figure 2. Zeta potential dish sponge residue.

The zeta potential of the dish sponge residue with an isoelectric charge of 6.5 refers to the charge of the dish sponge residue particles at an interface between the particles and the surrounding liquid. The zeta potential of a particle is determined by the polarization of electrical double layers around the particles. In the case of the dish sponge residue, the isoelectric charge of 6.5 indicates that the zeta potential of the particle is zero due to the equal amount of positive and negative charges [34]. This neutral state is known as the isoelectric point where the repulsion between particles is at its maximum. At this point, the particles cease to be attracted/repelled by each other and form a stable colloidal suspension.

In order to understand the chemical bonds of the material, the FTIR was analyzed, as shown in Figure 3.

The dishwashing sponge FTIR is a type of contact-mode Fourier-Transform Infrared Spectrometry (FTIR), which is used to measure the absorption of infrared radiation by a sample's molecular bonds. With an instrumental bandwidth between 3678 and 3482 cm^{-11}, this instrument is able to make conclusions about the various molecular bonds in the sample based on how much energy is being absorbed. At 2887 cm^{-11}, we can observe a vibration in the spectra, most likely due to the stretching of a single bound between two atoms-OH stretching in a water molecule, for example in [35]. This would indicate the presence of hydrogen-bonded OH groups in the sample. Peaks located at 1650, 1107, and 948 cm^{-1} would indicate the presence of C-H vibrations, C-O vibrations, and C-C vibrations alike. These chemical features impart different information about the sample, which can help the researcher conclude prevailing properties about the sample. For example, the CH peak would indicate the presence of aliphatic hydrocarbons and the C-O peak could indicate the presence of esters, alcohols, or ketones. Oftentimes, more than one annotation can be made from a single peak, which may require further research or confirmation. The C-C peak could reveal the presence of aliphatic or aromatic carbons, which could suggest the presence of a particular type of hydrocarbon [36]. In sum, the dishwashing sponge FTIR provides a temporal snapshot of the molecular interactions in the sample. The various peaks can then be parsed to determine the prevailing molecular connections, inspiring further inquiry into the sample's properties.

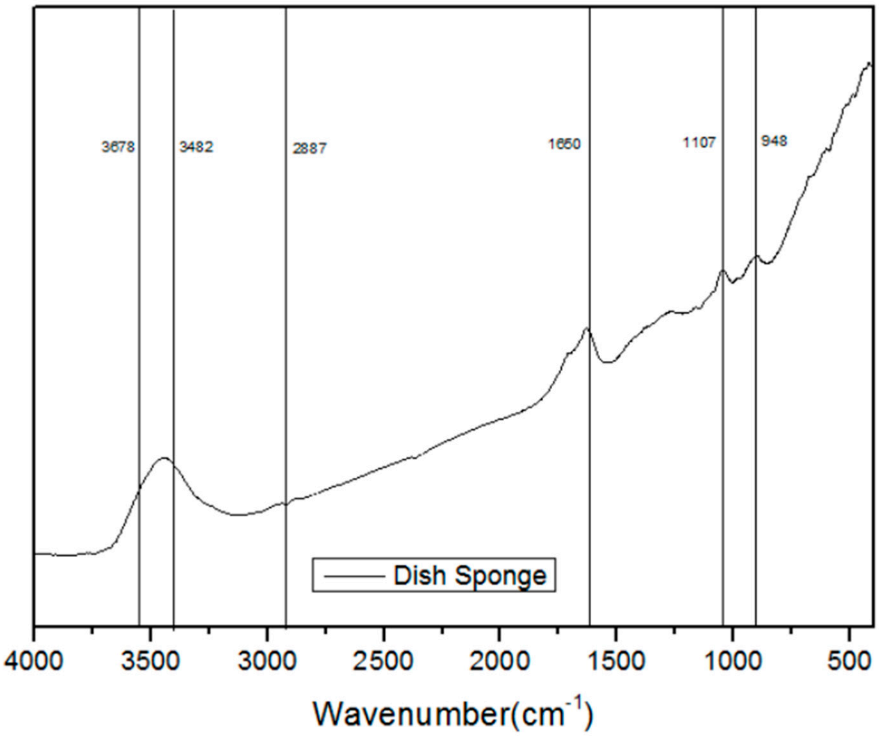

Figure 3. FTIR of dish sponge.

The possible adsorption mechanisms in this study can occur in three types: electrostatic bonds, π-π bonds, and hydrogen bonds. Electrostatic bonds can occur due to differences in existing charges (cationic and anionic) in the contaminant and the adsorbent, facilitating and assisting these possible interactions. Hydrogen bonds can occur due to the paracetamol molecule having an extended chain and the bonds that form the structure of the dish sponge, enabling the possible adsorption of the material, and finally the π-π bonds are the types of covalent bonds that are present in atoms capable of making two or more chemical bonds which can enable greater interaction between the material studied and the contaminant evaluated.

3.2. Study of Adsorption

Effect of Mass and pH

The study of the effect of mass and pH were evaluated and demonstrated as shown in Figure 4:

In Figure 4A, the mass effect in this experiment varied from 0.01 to 0.05 and the adsorptive capacities for each mass were 50.02, 33.09, 22.34, 16.02, and 10.03 mg g^{-1}, correspondingly. The amount of mass removed from each of these masses was greater than 85%. With increasing mass, the adsorptive capacity was decreased. This decrease in adsorptive capacity is likely due to an increase in the number of sites available for adsorption, as well as the increased size of the particles, which reduces the surface area available for adsorption [37]. The particles also become harder to move, creating more resistance, which further reduces the adsorptive capacity. At all mass levels, the removal of particles was greater than 85%, indicating that adsorption was effective. The increased mass may have increased the surface area and the number of potential adsorption sites that became available, hence the increased removal. Overall, this experiment demonstrates that an increase in mass decreases the adsorptive capacity, while still providing an effective removal of particles from the solution. It is also possible that different particle sizes and different types of particles may respond to increased mass differently and require further testing to determine the optimal conditions for each type.

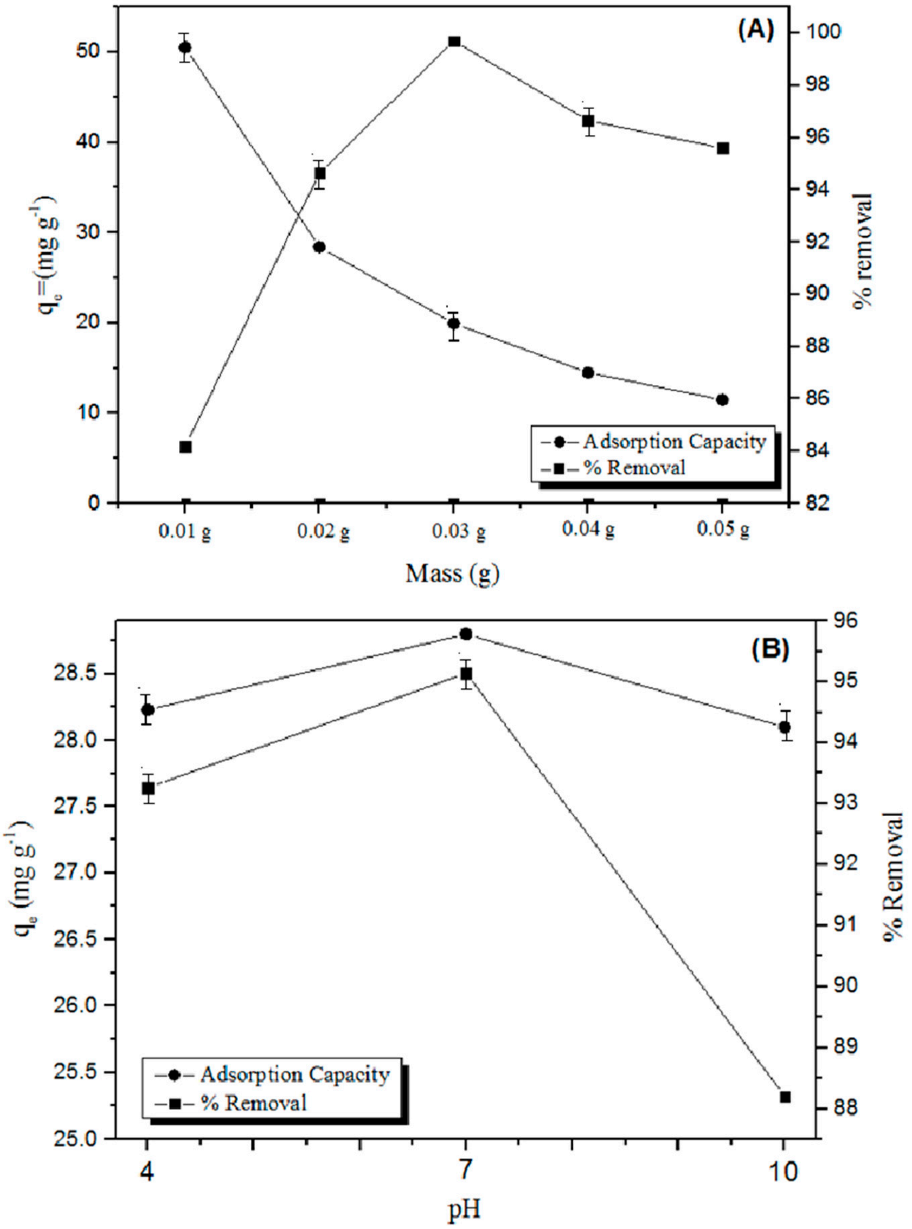

Figure 4. (**A**) effect of mass and (**B**) effect of pH.

In Figure 4B, pH is a measure of hydrogen ion concentration and is an important factor in the adsorption of particles onto a surface. Specifically, higher pH values indicate a higher concentration of hydrogen ions in the solution, and this higher ionic strength can lead to higher rates of adsorption. When pH is equal to or less than 4, particles tend to become more hydrophilic (water-loving) and, therefore, less prone to adsorption. On the other hand, when pH is equal to or greater than 7, particles tend to become more hydrophobic (water-repellent) and, thereby, more prone to adsorption. In this case, the adsorptive capacities at pH 4, 7, and 10 were 28, 29, and 27.5 mg g^{-1}, respectively. Since the capacity at pH 7 was the highest, we can conclude that this pH value provided the most favorable conditions for adsorption onto the surface [38]. The lower capacity at pH 4 and 10 may reflect either an unfavorable hydrophobicity/hydrophilicity ratio or a lower concentration of hydrogen ions.

3.3. Study Kinetic

The kinetic and equilibrium study for the adsorption process is very important, as it is through them that the equilibrium and other parameters are determined, as shown in Figure 5.

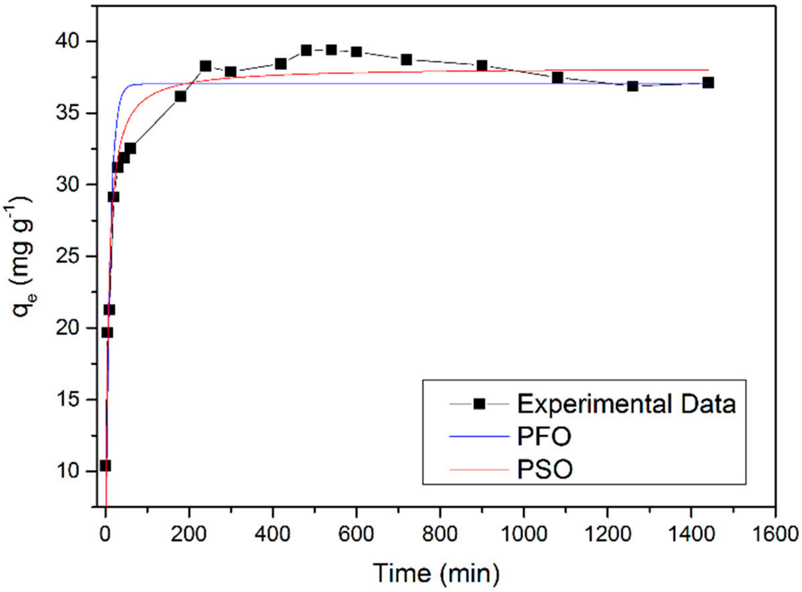

Figure 5. Kinetic of dish sponge for removal diclofenac.

In Figure 5, dishwashing sponges have become widely used for water pollution control, as they have a high ability to adsorb and remove pollutants such as heavy metals and organic compounds. To test the adsorption efficacy of dishwashing sponges for the specific removal of diclofenac, a kinetic and equilibrium study was conducted. At the start of the experiment, it was observed that there was a good interaction between the dishwashing sponge and the diclofenac. The experiment was conducted at various doses of diclofenac and the adsorption rate was examined over a period of time. It was found that the equilibrium was achieved within 400 min at room temperature [39]. The maximum adsorbed capacity of diclofenac by the dishwashing sponge was determined to be 39.02 mg g^{-1}. This suggests that the dishwashing sponge can effectively adsorb and hold diclofenac. The experimental results were analyzed and it was found that the data fit the pseudo first order mathematical model. This model takes into account the effects of homogeneous and heterogeneous adsorption phenomena. The pseudo first order model assists in understanding the adsorption kinetics of the diclofenac from the dishwashing sponge and aids in determining the magnitude of the adsorption process.

Overall, the kinetic and equilibrium study of dishwashing sponges for diclofenac removal produced very promising results. The dishwashing sponge was found to have a maximum adsorbed capacity of 39.02 mg g^{-1} indicating that it could be used for effective water pollution control [40]. Furthermore, the pseudo first order model revealed that the adsorption kinetics of the diclofenac was successfully carried out. The experimental data of the models are in Table 1.

Due to the need to compare the present studied material, Table 2 shows the comparison between other adsorbent materials for diclofenac removal, comparing the removal of contaminants with their adsorption capacity, pH, and type of material, among others.

Table 1. Models of PFO and PSO using dish sponge for removal diclofenac.

Models	Parameters	Dish Sponge
Pseudo first order	qe (mg g^{-1})	37.02
	k1 (min^{-1})	0.096
	R^2	0.846
	χ^2	9.985
Pseudo second order	qe (mg g^{-1})	38.18
	k2 (g mg^{-1} min^{-1})	0.004
	R^2	0.940
	χ^2	3.43

Table 2. Comparison of different adsorbent materials for diclofenac removal.

Type of Adsorbent Material	Capacity Adsorption (mg g^{-1})	pH	Temperature (K)	Reference
Activated Carbon and Silica	167.00	3	298	[41]
Activated carbon prepared from *Cannabis sativum Hemp*	16.18	5.5	308	[42]
CNT-COOH/MnO_2/Fe_3O_4 nanocomposite	114.2	7.2	298	[43]
N-doped activated carbon derived from coconut shell	39.9	6.4	298	[44]
Magnetic Sol–Gel Encapsulated Horseradish Peroxidase and Lignin Peroxidase Composites	24.7	7.0	323	[45]
Argan Paste Cake by KOH Activation	20.28	5.6	298	[46]
Moringa oleifera Seed Pod-based Adsorbent	21.34	3	298	[47]
Present Study	208.06	6.5	318	_

3.4. Adsorption Isotherm

Adsorption isotherms were studied to assess contaminant removal at various concentrations at temperatures of 288, 298, and 308 K, as shown in Figure 6.

An adsorption isotherm is a plot of the quantity of adsorbed material versus the equilibrium pressure of the adsorbing gas or vapor. It is used to predict how different adsorbents interact with gas or vapor molecules over different temperatures. In this case study, the best fit model was Langmuir with a correlation factor of 0.979. At a temperature of 288 K, the maximum adsorption capacity was 172.81 mg g^{-1}. At this temperature, the adsorbent material saturated with the adsorbing gas at a lower pressure than at other temperatures. This lower equilibrium pressure indicates that the strength of the interaction between the adsorbent material and the adsorbing gas was weaker at 288 K [46].

At a temperature of 298 K, the maximum adsorption capacity was 159.67 mg g^{-1}. The equilibrium pressure for adsorption was higher at this temperature than at lower temperatures. This indicates that the interaction between the adsorbent material and the adsorbing gas was stronger at 298 K than at lower temperatures. At a temperature of 308 K, the maximum adsorption capacity was 208.06 mg g^{-1}. This is the highest value among the three temperatures. The equilibrium pressure for adsorption was even higher than for the other two temperatures, indicating that the strength of the interaction between the adsorbent material and the adsorbing gas was the strongest at 308 K [48].

It can be seen that the adsorption capacity increases with increasing temperature, indicating that with increasing temperature, there is a better adsorption of the material. This is because higher temperatures increase the kinetic energy of the adsorbing gas units, which results in stronger forces of attraction between the adsorbing gas and the adsorbent material. Table 3 shows the values obtained.

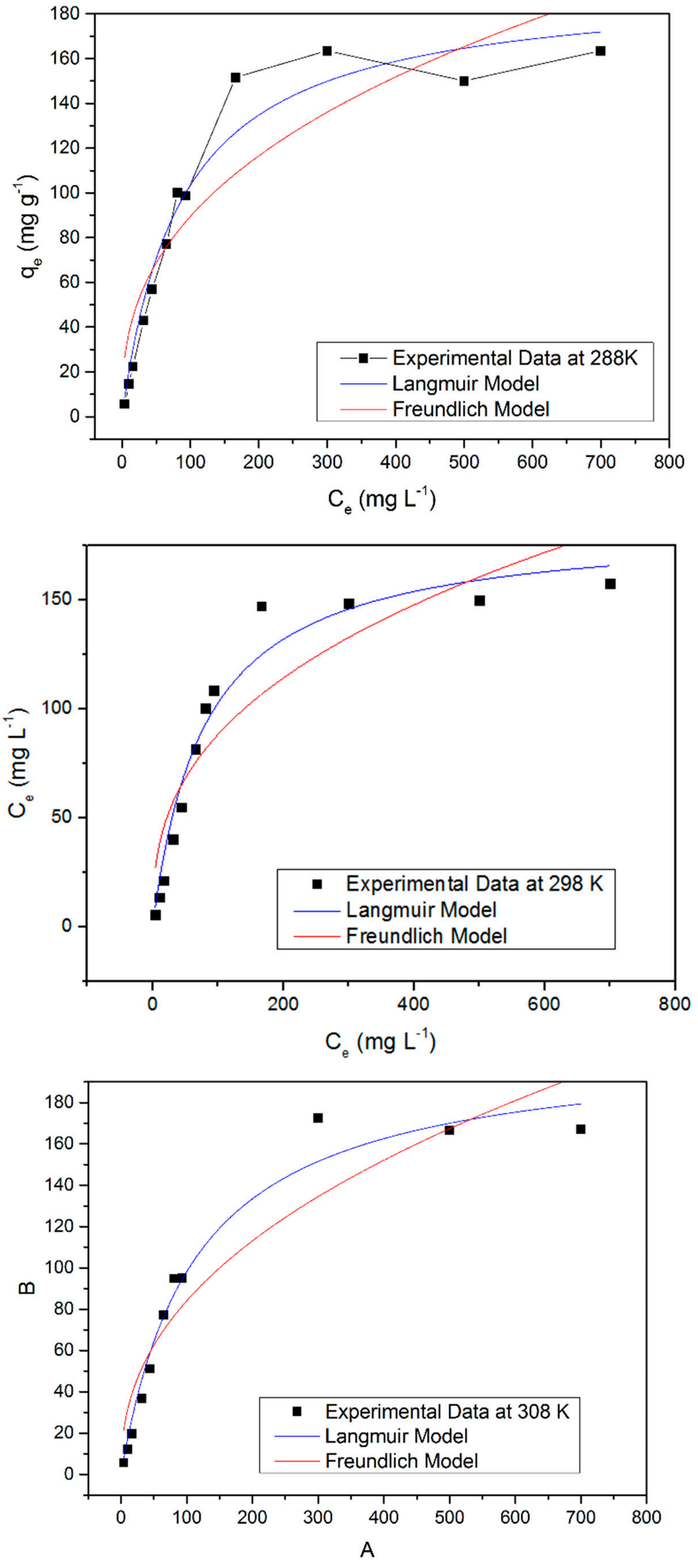

Figure 6. Diclofenac adsorption isotherms.

Table 3. Parameters of equilibrium isotherms models in temperature 288, 298, and 308.

Models	**Parameters**	**288 K**	**298 K**	**308 K**
Langmuir	qmáx (mg g^{-1})	173.22	184.59	208.06
	K_L (L mg^{-1})	0.011	0.009	0.006
	R^2	0.960	0.962	0.979
Freundlich	KF (mg g^{-1})/(mg $L^{-1})^{nF}$	15.43	14.91	11.69
	n_F	1.432	1.010	0.635
	R^2	0.841	0.834	0.890

Thermodynamic Parameters

The Gibbs free energy values (ΔG), enthalpy (ΔH), and entropy (ΔS) calculated from the equilibrium data are presented in Table 4.

Table 4. Thermodynamic Parameters.

T (°C)	**T (K)**	**(ΔG) (KJ mol^{-1})**	**(ΔH) (KJ mol^{-1})**	**(ΔS) (KJ mol^{-1})**
15	288	−31.28	−22.72	0.07
25	298	−33.54		
25	308	−35.87		

The thermodynamic parameters of the three temperatures 288 K, 298 K, and 308 K were negative for all of them. At 288 K, the Gibbs free energy was −31.28 kJ mol^{-1} indicating that the process is spontaneous. The negative enthalpy value of −22.72 kJ mol^{-1} also indicates that the reaction was exothermic. The entropy value of 0.07 was quite low which implies that the process is reversible. At 298 K, the Gibbs free energy was −33.54 kJ mol^{-1}, the enthalpy was −22.72 kJ mol^{-1}, and the entropy was 0.07. This indicates again that the process is exothermic and reversible, which also confirms the previous results at 288 K [49].

Finally, at 309K the Gibbs free energy was −35.87 kJ mol^{-1}, the enthalpy was −22.72 kJ mol^{-1}, and the entropy was 0.07. This also suggests that the process is exothermic and reversible. Overall, these results suggest that the thermodynamic parameters were negative for all three temperatures and the process is exothermic and reversible.

3.5. Costs Attributed to Adsorbent Collection and Production Management

When introducing costs and their direct relationships to industrial production, it is necessary to objectively and directly identify the product to be obtained. Therefore, the need for criteria focused on apportionment (sectors involved) must be allocated to the products manufactured or services provided. Thus, all resources used exclusively by a given product represent direct financial costs [50].

Therefore, to judge the costs involved for the application focused on collecting dish sponges, direct and indirect costs must be made according to the needs of the target audience, aiming for clarity, organization, and ease of analysis of information as shown in Table 5 representing the costs and forms attributed by this study.

Table 5. Monthly expenses obtained by direct and indirect costs for the selective collection and adsorbent manufacturing process.

VARIABLE Expenses	**US$**	**FIXED Expenses**	**US$**
Transport of dish sponge (raw material)	14,150.34	Rent of the administrative building and factory	2264.15
Costs of other raw materials for adsorbent production	94.33	Electric power factory	377.35
Laboratory equipment maintenance	93.80	Insurance and surveillance	56.60
Employee salaries	17,688.67		
Total	32,027.14		2698.10
Total Expenses	34,725.24		

When we attribute adsorption costing, it is an appropriation of all production costs of manufactured goods, where the expenses related to the manufacturing effort are distributed throughout the production context involving its production costs, such as fixed costs or variables, considered in calculating the cost of the product. Thus, non-manufacturing expenses are excluded from this calculation, where adsorption costing is a cost calculation process, aimed at apportioning all elements used in each phase of production [51].

For our study, adsorption costing is a method of calculating unit costs where we involve the criteria of the quantity of dish sponges that can be collected, which only considers the expenses incurred in the production process as shown in Table 1.

However, Table 6 is the representation of the costs attributed throughout the processes carried out by the collecting body, as well as the inclusion of the adsorbent proposal related to the investigative context of the relationship between the total cost and units collected as reported, aiming to obtain a unit cost.

Table 6. Adsorption costing using the selective collection procedure.

Adsorption Costing	**US$**
Total costs	34,725.24
Monthly production (units)	376,234
Cost per units-(adsorption)	0.09

Sustainability is achieved through procedures attributed to obtaining raw materials that can be treated, avoiding new contamination, should it occur, and its release into the environment. Thus, an enterprise uses a cost for production that must be treated as a fixed and variable cost as shown in Table 5. However, the dilution of costs is measured by controlling the quantity of dish sponges and their application as an efficient adsorbent for decontaminating chemical contaminants present in water and soil, among other applications.

In this sense, the global unit cost was US$0.09 for dish sponges, for the scenarios involved in collection logistics attributed to employees, equipment, selection, storage, and adsorptive preparation. Given the context, the cost of collection and preparations involving the adsorptive profile with the dish sponge is attributed to the selective collection actions of recycled materials in Brazil. Recycling actions in Brazil are rare because they involve public resources from city halls that do not allocate sufficient resources for such collection actions.

Based on this context, the costs attributed to the collection of dishwashing sponges do not result in an increase in costs for managers and organizers of municipal selective collection, with only an increase in the item, which complements Federal Law 12,305 of August 2010 [52], which is attributed the National Solid Waste Policy and is based on rigor and responsibility when disposing of waste (producers, importers, distributors, traders and consumers). Thus, this study's approach is focused on the management of an environmentally harmful waste being applied as an adsorbent for the purpose of reducing emerging contaminants, with low operational costs, aiming to meet national requirements, including the reuse, recycling, and treatment of solid waste and the environmentally correct disposal of waste.

4. Conclusions

In view of this study carried out with dishwasher sponges used as an adsorbent to remove diclofenac present in water, it is observed that due to its characterizations, the material is suitable for use as an adsorbent, as it has characteristics that help in the removal of these contaminants. Studies related to kinetics showed that there was a maximum adsorptive capacity of approximately 40 mg g^{-1}, proving the optimal relationship between diclofenac and the new material developed. The cost list for this material also proved that the production of this material on an industrial scale is completely viable, its fixed and variable costs are within what is expected within the scope of production engineering. And with this, it can be concluded that the material is sustainable, ecologically correct, and viable, contributing to a better society, economy, and environment.

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