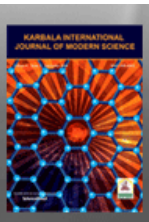

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Implementing a sustainability approach by converting plastic bottle waste from a mischievous substance to a beneficial material by means of zero residue level concept

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Abstract

Plastic waste represents a serious environmental and health hazard due to its non-biodegradability and toxic leachates. This study investigates the potential conversion of plastic waste into a sustainable raw material for producing a useful substance. This investigation focuses on repurposing PET beverage bottles—a major contributor to microplastic pollution—into high-value activated carbon (AC) for water treatment, aligning with circular economy principles. The chemical preparation method for AC using phosphoric acid as an activating agent was evaluated. Results demonstrated the successful conversion of 68% of plastic waste into AC under the following conditions: pyrolysis temperature of 700°C, pyrolysis time of 7 hours, and PET mass of 200 g. The highest surface area achieved was 590 m^2/g under optimized conditions (72-hour impregnation at a 2.5 acid ratio, followed by calcination at 600°C). The environmental applicability of the prepared AC was confirmed through its efficient adsorption of erythrosin B stain (>87% removal at pH 1, 400 rpm agitation speed, and 10 ppm concentration), a common pollutant in textile wastewater. FTIR analysis identified functional groups critical for adsorption, while SEM revealed significant surface modifications post-adsorption (surface area reduction to 161.8 m^2/g). To achieve a zero-waste solution, the spent AC was further tested as a rodenticide. Laboratory trials recorded mortality rates with an LD_{50} consistent with literature values, suggesting a potential dual-purpose application for plastic waste management and pest control. This study presents a scalable approach to addressing plastic pollution while generating value-added materials for environmental and industrial applications.

Keywords

Activated carbon, adsorption, chemical method, erythrosin B stain, PET plastic waste, and ZRL

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RESEARCH PAPER

Implementing a Sustainability Approach by Converting Plastic Bottle Waste From a Mischievous Substance to a Beneficial Material by Means of Zero Residue Level Concept

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Abstract

Plastic waste represents a serious environmental and health hazard due to its non-biodegradability and toxic leachates. This study investigates the potential conversion of plastic waste into a sustainable raw material for producing a useful substance. This investigation focuses on repurposing PET beverage bottles—a major contributor to microplastic pollution—into high-value activated carbon (AC) for water treatment, aligning with circular economy principles. The chemical preparation method for AC using phosphoric acid as an activating agent was evaluated. Results demonstrated the successful conversion of 68% of plastic waste into AC under the following conditions: pyrolysis temperature of 700 °C, pyrolysis time of 7 h, and PET mass of 200 g. The highest surface area achieved was 590 m^2/g under optimized conditions (72-h impregnation at a 2.5 acid ratio, followed by calcination at 600 °C). The environmental applicability of the prepared AC was confirmed through its efficient adsorption of erythrosin B stain (>87% removal at pH 1, 400 rpm agitation speed, and 10 ppm concentration), a common pollutant in textile wastewater. FTIR analysis identified functional groups critical for adsorption, while SEM revealed significant surface modifications post-adsorption (surface area reduction to 161.8 m^2/g). To achieve a zero-waste solution, the spent AC was further tested as a rodenticide. Laboratory trials recorded mortality rates with an LD_{50} consistent with literature values, suggesting a potential dual-purpose application for plastic waste management and pest control. This study presents a scalable approach to addressing plastic pollution while generating value-added materials for environmental and industrial applications.

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1. Introduction

Environmental pollution is considered one of the most serious challenges facing the blue planet today, as it clearly affects the ecological balance of living organisms as well as human health. Regarding pollution sources, this pollution results from two important origins: the natural source represented by earthquakes, floods, volcanoes, fires, landslides, the deterioration of the ozone layer, and other natural disasters [1]. Concerning anthropogenic impacts, the other source stems from various human activities that lead to the pollution of environmental elements. Notably, this source is broader than natural ones and often exacerbates them, significantly contributing to climate change and natural resource depletion [2].

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Considering these challenges, with increasing industrial activity and urban expansion, implementing sustainable measures to mitigate pollution and safeguard environmental integrity has become imperative to secure the future for coming generations [3]. One of the most prominent types of pollutants causing combined soil, water and air contamination is plastic product pollution, which generates widespread harm to both ecosystems and human health [4]. The durability and persistence of these synthetic materials in the environment leads to bioaccumulation across trophic levels, while their fragmentation into microplastics enables penetration into groundwater systems and atmospheric circulation patterns [5]. Currently, environmental pollution with plastic wastes has reached alarming levels. This form of pollution is the most prevalent form of contamination worldwide, among all types of environmental pollutants. Of particular concern are waste plastic bottles used for storing liquids and food, which constitute a significant portion of this pollution [6]. Polyethylene terephthalate (PET) is the base material for these bottles. It appears as a semi-crystalline glassy polyester with both mechanical and thermal properties [7]. This material consists of polyethylene terephthalate (PET) chains and has the chemical formula $C_{10}H_8O_4$. PET has many applications. It enters into the production of fibers, accounting for 60% of its production, which last a long time. Industrial applications account for 10% of its use. Transparent plastic containers, including bottles, account for 30% of its production. The most common products include carbonated soda bottles, liquid containers, and water bottles. Roughly 99% of these bottles are used domestically [8]. These bottles are disposed of in the garbage, which greatly increases municipal waste due to their size. Alternatively, they are thrown into rivers, lakes and ponds, becoming a source of insects and pathogenic microorganisms [9]. Plastic waste reduces light penetration needed by aquatic life and lowers dissolved oxygen levels, creating additional pollution beyond the toxic byproducts generated during its extremely slow decomposition, which can persist for millennia. The combined effects disrupt delicate aquatic ecosystems through multiple pathways [10]. Due to the harmful effects of this material, projects now manage these quantities through technical operations. Recycling converts these materials into new PET products like packaging containers. Materials are also reprocessed for binding and wrapping uses [11]. The concept of zero residue level represents a new perspective on waste recycling. It aims to achieve the maximum utilization with near-zero pollutant residues and environmental impact. Plastic waste can thus yield useful materials such as fuel and activated carbon [12]. Activated carbon from polyethylene terephthalate (PET) waste was developed by Yuliusman *et al.* (2017) [13] for use as an adsorbent in natural gas storage using the adsorbed natural gas (ANG) technology as a safe and effective alternative to compressed natural gas (CNG) and liquefied natural gas (LNG) technologies. The carbonization process was carried out at 400 °C, followed by physical activation using CO_2 gas at 975 °C. The results showed that the best operating conditions were at a CO_2 flow rate of 200 mL/min and an activation duration of 240 min, achieving a combustion rate of 86.69% and a surface area of 1591.72 m^2/g, indicating high adsorption efficiency. SEM and EDX analyses showed that the activated carbon had a carbon content of 83.2% with a microporous structure. Sureshkumar and Susmita (2018) [14] were keen to improve the preparation conditions of activated carbon from polyethylene terephthalate (PET) waste using the chemical activation method with sulfuric acid. The effect of impregnation ratio, activation temperature, and time on surface area and yield was studied. A central composite design (CCD) within the response surface methodology (RSM) was used to develop mathematical models that relate variables to outcomes. The results showed that the best preparation conditions were an impregnation ratio of 37.63%, a temperature of 600 °C, and an activation time of 30 min, resulting in a surface area of 537 m^2/g and a yield of 12.57%. Analyses indicated that the impregnation ratio and activation time significantly affected the surface area, while temperature had a greater impact on yield. Wang *et al.* (2020) [15] investigated the potential of converting waste polyethylene terephthalate (PET) bottles into activated carbon for carbon capture, potentially addressing two major environmental concerns: plastic pollution and carbon emissions. The environmental performance of this process was evaluated through a life cycle analysis (LCA). The results showed that using activated carbon derived from PET waste with cyclic thermal desorption

Nomenclature

C_i	Concentrations of erythrosin B stain before adsorption (ppm)
C_f	Concentrations of erythrosin B stain after adsorption (ppm)
m	Mass of activated carbon (g)
q	Adsorption capacity of activated carbon ($mg.g^{-1}$)
$\%R$	is the percentage removal of erythrosin B stain (–)
V	Volume of polluted solution used in experiment (L)
LD_{50}	Half Lethal Dose ($mg.kg^{-1}$)

technology can result in negative carbon emissions, reinforcing the concept of a "closed carbon cycle". Sensitivity analyses showed that replacing conventional heat sources with biomass sources can significantly reduce energy consumption, and the use of recycled PET flakes in PET production reduces water consumption by more than 25%. Ahangar *et al.* (2021) [16] studied the conversion of waste polyethylene terephthalate (PET) bottles into activated carbon that can be used as a catalyst in the production of green fuels from waste cooking oil (WCO) and palm oil fatty acid distillates (PFAD). PET was treated with a solution of phosphoric acid (H_3PO_4) and potassium hydroxide (KOH) to produce activated carbon with acidic and basic properties. Analysis showed that treatment with KOH increased the surface area to 261 m^2/g and basicity to 13.49 mmol/g, while treatment with H_3PO_4 increased the acidity to 18.17 mmol/g. In applied experiments, KOH-treated carbon achieved a 50% conversion of WCO to esters, while H_3PO_4-treated carbon achieved a 45% conversion of PFAD, demonstrating the effectiveness of these materials in stimulating biofuel production. Polyethylene terephthalate (PET) plastic waste, used in the manufacture of water bottles and other containers, was used as a raw material for the synthesis of activated carbon and nanoporous carbon materials, due to its high (~11%) fixed carbon content and low impurity content. Although conventional methods exist for converting this waste, poor productivity and the lack of cost-effective alternatives have limited interest in this application compared to other types of polymeric waste, such as waste tires. The study analyzed the latest chemical and thermal methods for PET activation, evaluating the performance of the resulting carbon in various applications, including contaminated water treatment, air pollutant purification, gas storage, and energy storage in supercapacitors. The results demonstrated remarkable efficiency in the adsorption of dyes and heavy metals with surface areas exceeding 600 m^2/g, opening new horizons for sustainable plastic waste management (Sharifian and Asasian-Kolur, 2022) [17]. Cho *et al.* (2023) [18] used an innovative technology to address the environmental pollution problem caused by PET plastic waste by recycling it and converting it into activated carbon (PET-blended pitch (AC-P)), which is based on incorporating it with bitumen. Results showed that the incorporation process led to a significant improvement in the physical and chemical properties of the produced material, with the surface area increasing from 1096.24 m^2/g in conventional carbon to 1969.22 m^2/g in modified carbon (AC-P). Scanning electron microscopy (SEM) and field-effect X-ray (EDX) spectroscopy analyses revealed a homogeneous distribution of micropores and an increased carbon content on the surface. Furthermore, FTIR and X-ray photoelectron spectroscopy (XPS) results showed an increase in carbon bonds and surface functional groups resulting from the polymerization process during preparation, enhancing the efficiency of material in environmental and industrial applications. Onwucha *et al.* (2023) [19] investigated the production of activated carbon from waste PET plastic bottles using an ionic thermal synthesis method as a sustainable alternative to traditional, complex, and environmentally unfriendly methods. A mixture of choline chloride and urea was used as a bio-solvent (DES) to enhance the carbonization process. The results showed that the activated carbon from the untreated sample had a higher adsorption capacity (955.95 mg g^{-1}) compared to the treated sample, which had an adsorption capacity of 549.05 mg g^{-1} at 100 ppm methylene blue. Polyethylene terephthalate (PET) waste was converted into activated carbon by Pham (2023) [20] using a physical carbon dioxide activation method. The effect of different temperatures and carbonization and activation times on the resulting surface area was studied. The process involved cutting the plastic bottles into small pieces, carbonizing them at 550 °C for 15 min, and then activating them at 850 °C for 25 min. The results showed that the resulting activated carbon had a high surface area of 703.4 m^2/g, with excellent adsorption capacity for methylene blue (MB) dye in contaminated aqueous solutions, especially at neutral or basic pH, where the adsorption efficiency exceeded 80%. Microscopic and spectroscopic analyses confirmed the presence of pores and a chemical composition suitable for the adsorption of organic pollutants, highlighting the potential of this method for treating contaminated water and converting plastic waste into materials of high environmental value. Alabi-Babalola *et al.* (2024) [21] studied the conversion of wasted polyethylene terephthalate (PET) bottle into highly efficient activated carbon for wastewater treatment via a multi-stage process. The preparation process involved carbonization at 400 °C followed by chemical activation with potassium hydroxide (KOH) at 800 °C. The results showed the surface area reached 1120 m^2/g, and high efficiency of using the prepared material as an adsorption medium in removing inorganic ions from wastewater at the following ratios: 98% for Mn^{2+}, 87% for Cr^{3+}, and 88% for Co^{2+} due to the microporosity and suitable pore distribution, which confirms the feasibility of using PET waste as a sustainable raw material for producing environmentally and economically effective activated carbon in wastewater

treatment applications. Park *et al.* (2024) [22] explored a method for preparing bitumen suitable for the production of activated carbon using concentrated catalytic cracking oil (FCC-DO) as a high-purity feedstock, focusing on the effects of adding PET waste and varying temperatures on the properties of the resulting bitumen and activated carbon. The results showed that adding PET at temperatures of 390 °C or higher resulted in the production of stable, high-surface area activated carbon (SSA) ranging from 2680 to 2740 m^2/g, without generating additional waste or negatively affecting the physical properties of the final product. This confirms the potential of this method as a practical solution for converting plastic waste into value-added materials in the activated carbon industry. Duong *et al.* (2024) [23] studied two major environmental problems: plastic waste and antibiotic-contaminated water. They developed a new composite material (PET-AC-ZFO) by integrating activated carbon derived from PET plastic bottles with $ZnFe_2O_4$ particles to remove tetracycline from water. The practical aspect involved preparing the activated carbon using KOH and analyzing it using advanced physicochemical methods, while using a central composite design (CCD) to optimize adsorption conditions. The results showed that the resulting composite material had a high surface area (1110 m^2/g) and microporosity (≈2 nm), enabling it to remove approximately 90% of tetracycline with a theoretical maximum adsorption capacity of 45.1 mg g^{-1}. The adsorption processes were governed by hydrogen bonding, π-π interactions, and pore filling. This study presents an innovative solution that simultaneously recycles plastic and purifies water contaminated with antibiotics. Galeano-Caro *et al.* (2025) [24] aimed to convert industrial polyethylene terephthalate (PET) waste into activated carbon for freshwater production via atmospheric moisture adsorption, comparing its performance with activated carbon prepared from agricultural waste (coffee and coconut residue). Results showed that untreated carbon achieved a high surface area (1313 m^2/g), while this value decreased by 65% for agricultural materials and 5% for PET after surface acid modification. Adsorption experiments were performed under humidity levels ranging from 11–84% and temperatures (293.15–313.15 K). The P800N sample (carbonized at 1073.15 K and acid-modified) recorded the highest water adsorption capacity of 1.55 mg g^{-1} at 84% humidity and 293.15 K, exhibiting a Type IV (IUPAC) adsorption curve due to the increased micropore size. Thermal analysis confirmed that the process is spontaneous and endothermic. In a pilot application in Medellín, Colombia, the solar-powered PET-derived carbon (P800N) device achieved a condensed water yield of 0.9 mg g^{-1} (dry basis) under operating conditions (80% humidity, 2.3 m/s wind speed, and 293.15 K for adsorption and 299.35 K for water release), demonstrating the feasibility of these materials as sustainable solutions for water-scarce regions. A study by Usama *et al.* (2025) [25] presented an innovative solution for disposing of plastic waste by converting it into highly efficient activated carbon for the removal of aquatic pollutants. Thirteen activated carbon samples were prepared using potassium hydroxide as an activating agent, and the effects of preparation conditions such as temperature and reactant ratios were studied. The results demonstrated that the sample prepared at a 1:1 ratio at 700 °C was superior in removing a variety of pollutants such as dyes and antibiotics. It achieved near-complete removal efficiency for doxycycline and nitazoxanide, with a maximum adsorption capacity of 324.75 mg g^{-1}. Kinetic and thermodynamic studies confirmed that the adsorption process was physical, exothermic, and based on electrostatic interactions. Theoretical analyses revealed the presence of multiple active binding sites on the surface of the activated carbon, while a life cycle study confirmed its environmental and economic feasibility, with a low carbon footprint (5.92 kg CO_2/kg) and reasonable production cost ($13.75/kg), making it a promising option for sustainable wastewater treatment and mitigation of plastic pollution. This study introduces an innovative circular economy approach to transform plastic bottle waste into high-efficiency activated carbon for erythrosin B stain removal, while pioneering a novel dual-application strategy that converts the spent adsorbent into effective rodenticides, thereby achieving complete waste valorization and addressing two critical environmental challenges simultaneously.

2. Methodology

2.1. Raw material (plastic bottles)

Pellucid plastic containers specifically for bottling water and beverages (recycling code 1), were collected from household waste.

Colored containers or those previously containing fatty beverages were excluded to ensure the consistency and purity of the raw material. Visual inspection was conducted to ensure that the containers met the following criteria: transparency, complete absence of organic impurities, and integrity of the plastic structure. Any container showing signs of damage or contamination was excluded. The lids, labels and any adhesive residue were

removed completely and carefully, and the containers were washed using running tap water with dishwashing liquid (pH 7.0 ± 0.5) up to three times, as required. To dry, the clean and washed containers were exposed to direct sunlight in summer conditions (42-45 °C) and relative humidity (<25%) for 12 h in a clean environment until completely dry. Using scissors (20.3 cm blade) (KS-010, Kitchen Shears, Stainless Steel, Multipurpose, Felix Solingen - Germany), the containers were cut into irregular pieces (3-6 mm), as in Fig. 1, to reflect the natural variations due to different container thicknesses depending on the brand. Before using, cut pieces were manually shaken intermittently (5 min/h) for 4 h in amber glass jars (500 mL) to ensure uniform distribution. All procedures were performed in a fully equipped laboratory, adhering to safety regulations (gloves, face masks, goggles, lab coat, head cap, etc.), and all surfaces and tools were cleaned with 70% ethyl alcohol before each use.

2.2. Preparation of activated carbon

The batch method was used to prepare activated carbon by placing a precise amount (100-250 ± 0.01) g of PET rectangular pieces into reusable heavy duty test tubes (Borosil®) closed at the top side with a glass stopper with a capacity of 100 cm^3 capacity and dimensions ($\phi = 34$ mm and $L = 120$ mm). The glass test tubes were put in a sealed titanium pot (Vargo) of 1000 cm^3 capacity ($\phi = 105$ mm and $L = 160$ mm) prefilled with lab-prepared alumina powder (>99% purity, <50 μm particle size) prepared as described in Ref. [26]. The setup was heated in a programmable muffle furnace (M104 Thermo Scientific ™, USA) from 25 °C to 700 °C (optimal temperature) at 10 °C/min, with a controlled N_2 flow (125 ± 5 mL/min, 99.99% purity) using a calibrated flow meter (AO-32211-50, Cole-Parmer®-USA). Heating durations varied (2-8 h) before cooling to 25 °C. After cooling to 25 °C, the tubes were opened and the carbonized material was immediately weighed using analytical balance ±0.001 g (Mettler Toledo, Switzerland) and stored in 1000 cm^3 amber glass jar of (GL 80, Paul Marienfeld-Czech) until activation.

Fig. 1. Preparation of plastic bottles.

2.3. Activation process

The carbonized plastic obtained from the pyrolysis (previous step) was activated via chemical method using strong acid. Exactly 5 g of resulting carbonized material was immersed in 85% industrial technical grade phosphoric acid (H_3PO_4, IndiaMART). The acid-to-carbon ratio and impregnation time were carefully controlled throughout the activation process ranged between 0.5 and 3.5 cm^3/g and 12-72 h, respectively. The mixture was then filtered using Whatman Qualitative Filter Paper No. 41(Fisher Scientific) prior to drying in a vacuum oven (Thermo Scientific Heraeus VT6025) at 75 °C for 3 h. Calcination was subsequently carried out at high temperatures ranging from 400 to 700 °C in a muffle furnaces (M104 Thermo Scientific ™, USA) for 4-8 h. The surface area of the resulting activated carbon samples was evaluated using the BET analysis (Qsurf 9600, Thermo Finnegan Co., USA), based on nitrogen (N_2) gas adsorption at 77 K.

2.4. Preparation of erythrosin B stain stock solution

In order to apply the safety principle and avoid any interference from other potential contaminants, erythrosin B stain removal experiments were conducted using pre-prepared aqueous solutions. To achieve this goal, a stock solution of known concentration was prepared and then diluted to obtain the solutions used in the adsorption experiments. The preparation process included dissolving 1000 mg of the erythrosin B stain (supplied by the Sigma-Aldrich company-USA) in a certain volume of double distilled water, and the mixture was manually shaken continuously until all the erythrosin B stain dissolved. The solution was then diluted to a final volume of 1 L to obtain a 1000 ppm erythrosin B solution. All working solutions used in laboratory experiments were prepared by further diluting the stock solution to the desired concentrations using double-distilled water.

2.5. Erythrosin B stain calibration curve

To determine the concentration of erythrosin B stain in the aqueous solutions treated with the activated carbon prepared in this study, a colorimetric method was applied using a UV-VIS spectrophotometer (UV-1900i - Shimadzu Corporation, Japan) at a wavelength of 537 nm. A calibration curve was established by preparing a series of

standard solutions with known concentrations and measuring the corresponding absorbance values.

Based on the plotted data, the calibration curve for erythrosin B stain was obtained and is presented in Fig. 2 [27].

2.6. Unit of adsorption

The activated carbon sample with the highest surface area was selected for further testing. Its efficiency in adsorbing erythrosin B stain was evaluated as a practical application. A batch adsorption unit was employed, consisting of a water bath shaker (Thermo Scientific MaxQ™ 7000 SHKE7000) in which flasks containing solutions of erythrosin B stain were mixed with increasing amounts of the prepared adsorbent (i.e., activated carbon). Experiments were conducted at varying agitation speeds and contact times. Prior to the experiments, the pH of the erythrosin B solution was measured using a pH meter (7110 WTW, Xylem Analytics - Germany) and adjusted using either 0.1 N sodium hydroxide (NaOH, 98%, HEMEDIA, India) or 0.1 N hydrochloric acid (HCl, 3 to 38% THOMAS BAKER, India). The adsorption experiments were performed by placing 100 cm^3 of erythrosin B solution (with a predefined concentration and pH), and a specific amount of activated carbon, into a 250 cm^3 flask. The shaker was set to the required agitation speed, and the adsorption process was allowed to proceed until the designated treatment time was reached. Adsorption was tested under various conditions, including different pH levels, agitation speeds (100-450 rpm), and contact times (10-150 min) at a laboratory temperature of 28 ± 2 °C, using 10 ppm of erythrosin B and 1 g of the prepared activated carbon. Afterward, the activated carbon was separated from the solution using a vacuum filtration kit (EIS-CH200501, CP LabSafety, USA), and the sample was analyzed using a spectrophotometer and the established calibration curve to determine adsorption efficiency. All experimental measurements were performed in triplicate or quintuplicate under identical conditions. The values reported in the Results section represent the mean of triplicate measurements to ensure the reliability of the reported findings. Using Equation 1, and the concentration of the remaining unadsorbed erythrosin B during treatment can be determined, while the amount of adsorbed stain per gram of activated carbon is determined from Equation 2 [28]:

$$\%R = \left(\frac{C_i - C_f}{C_i}\right) \times 100 \quad (1)$$

$$q = \frac{V(C_i - C_f)}{m} \quad (2)$$

3. Results and Discussion

3.1. Preparation of carbonic material from plastic waste

3.1.1. Influence of PET plastic amount

Fig. 3 illustrates the effect of varying the amount of PET plastic used as a raw material on the quantity of carbon produced. The experimental results indicate that increasing the mass of PET raw material leads to a greater yield of carbon from the pyrolysis process, with a clear direct relationship observed between 100 and 200 g of plastic mass, assuming other design factors are held at their optimum values. This result can be attributed to the fact that a greater amount of raw material increases the extent of bond

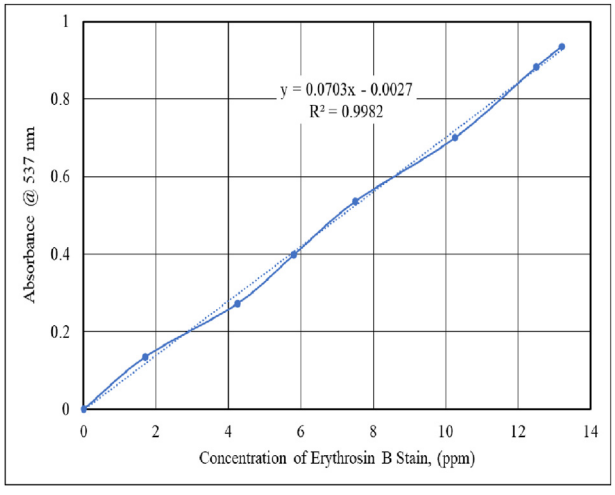

Fig. 2. UV-Vis Calibration curve of erythrosin B stain used in this study.

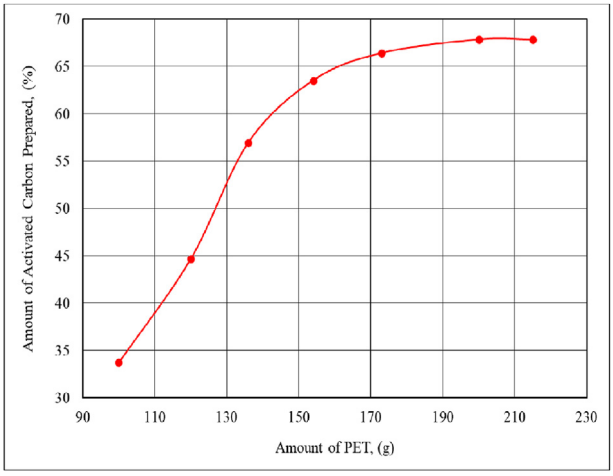

Fig. 3. Effect of PET amount on % mass of activated carbon produced @ pyrolysis temperature = 700 °C and pyrolysis time = 7 h.

breakage in the plastic during the pyrolysis process, which enhances the transformation process in the oxygen-free environment, thereby increasing carbon production [29]. However, the figure shows that beyond 200 g of PET, the mass of carbon produced remains constant, despite the increased raw material input. This may be attributed to the system's geometry, fixed volume, and other operational constraints. Alternatively, the accumulated carbon may act as an insulating layer, reducing heat transfer and thereby limiting further transformation of the material, which may hinder the continued conversion of the plastic into carbon. Consequently, the efficiency of the pyrolysis process decreases, and the carbon yield plateaus under constant temperature and pyrolysis duration [30].

3.1.2. Influence of temperature on plastic pyrolysis process

Carbon can only be produced from plastic waste by pyrolysis material. Therefore, the temperature of pyrolysis is an operational factor with a decisive and fundamental influence in determining the mass of the prepared carbon. Fig. 4 shows the practical results of changing the amount of carbon as a result of changing the temperature of the pyrolysis process.

It is obvious that the temperature is clearly related to the amount of carbon prepared from PET plastic wastes. Since the relationship between the two variables is direct, increasing the temperature leads to an increase in the amount of the prepared carbon in the temperature range of 500-700 °C by 52.55%. The reason for this result is that increasing the pyrolysis temperature of the plastic wastes enhances PET dissociation, facilitating combustion and carbon conversion. Generally, higher temperatures increase reaction rates [31]. Although it is well-established that increasing the temperature typically reduces carbon yields-*due to greater thermal degradation in most biomass-based systems*-these findings present a notable exception. This deviation arises from the distinct pyrolysis behavior of PET. Unlike biomass, PET undergoes chain scission and aromatization near 700 °C, forming a stable carbon structure resistant to further degradation. Additionally, phosphoric acid stabilizes the material via phosphate cross-linking and the formation of C–O–P bond, reducing mass loss during pyrolysis [32]. Together, these factors contribute to the observed increase in yield with temperature, as shown in Fig. 4.

3.1.3. Influence of pyrolysis time

The relationship between the time of the pyrolysis process and the amount of carbon is illustrated in Fig. 5. The increase in the mass of carbon is associated with an increase in the time of the pyrolysis process, keeping other designing variables constant at their optimum values. When the residence time of PET plastic waste in the pyrolysis vessel increases, the chance of oxidation of a greater number of plastic particles also increases, leading to greater transformation of raw material into activated carbon compared to shorter durations. Seven hours appears to be the optimal time to convert the maximum amount of PET plastic into 64.833% carbon, and after increasing the pyrolysis time beyond 7 h, no further change in carbon yield was observed; the amount remained constant. This is because the pyrolysis process reached its maximum efficiency, influenced by other conditions as well as by the size and shape of the vessel. The surface area of the prepared samples remained nearly constant, meaning the carbon produced at different times had similar properties [33].

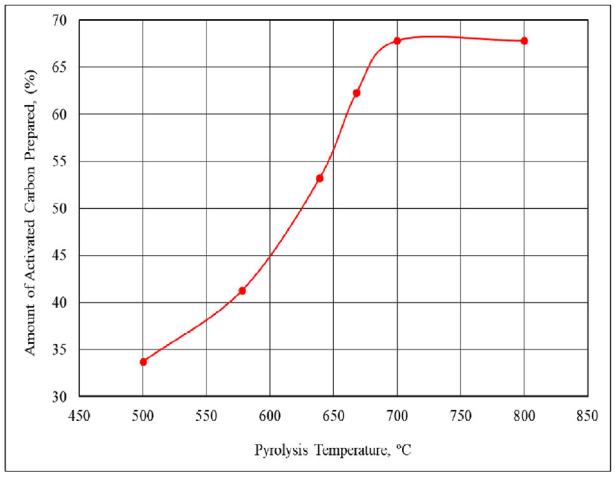

Fig. 4. Effect of pyrolysis temperature on % mass of activated carbon produced @ PET mass = 200 g and pyrolysis time = 7 h.

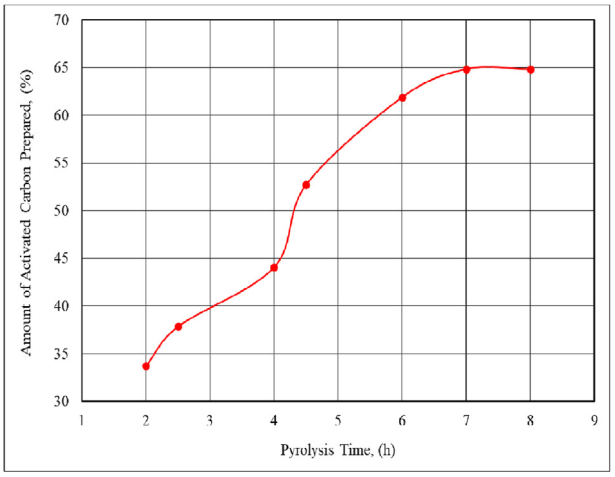

Fig. 5. Effect of pyrolysis time on % mass of activated carbon produced @ pyrolysis temperature = 700 °C and PET mass = 200 g.

3.2. Activation of produced activated carbon from pyrolysis step

3.2.1. Effect of impregnation ratio

Fig. 6 shows the relationship between the impregnation ratio of phosphoric acid and the surface area of activated carbon from PET waste. As shown in Fig. 6, the surface area increases with an increase in the impregnation ratio, which means that the relationship between the two variables is direct in the range 0.5-2.5, beyond this range, the surface area decreases as the impregnation ratio increases. There are two ways to activate carbon, the first is physical and depends on heating the carbon in an oxygen-free environment and the presence of an inert gas, while the other method is chemical in which acids or salts are used to obtain activated carbon [34]. The chemical method depends on the acid impregnation ratio, as this operational factor is considered the most important in determining the surface area of activated carbon [29]. One of the most important properties of phosphoric acid is that it contributes to increasing pyrolytic decomposition by inducing chemical changes in the precursor material, which facilitates the formation of activated carbon and at the same time enhances the cross-linked structure formation of the resulting material [35].

However, phosphoric acid allows the development of both type pores: mesopores and micropores of the prepared activated carbon. After reaching the highest value of 589.48 m^2/g at 2.5 impregnation ratio, the surface area of the prepared activated carbon decreases to 588.65 m^2/g with an increasing the impregnation ratio to 3.5. This result can be explained by the fact that phosphoric acid begins to affect the internal structure of the activated carbon, leading to pore overlap, causing the pores to widen while decreasing in number. This means larger pores with higher surface area form, but in fewer numbers, thus reducing the surface area, adsorption capacity and efficiency of the activated carbon [36].

3.2.2. Effect of impregnation time

Regarding the acid treatment time, Fig. 7 shows that the surface area increases as the treatment time increases within the range of 12-66 h, after which it begins to decrease. This result may be attributed to the fact that the time required for the acid to affect the raw material and the pyrolytic decomposition process has exceeded the optimum duration, which will lead to changes in the pores and the internal structure due to a reaction between the acid and carbon. This, in turn, leads to the breakdown of some activated carbon particles and leads to pore overlap, which affects resulting in a decrease in surface area. This finding is consistent with the results reported in Ref. [37].

3.2.3. Effect of calcination temperature

The calcination temperature of the prepared activated carbon is considered one of the significant design factors in accelerating the pyrolytic decomposition of the raw material (PET) and increasing the volatilization of lighter materials from the plastic waste.

This process increases the surface area and enhances pore formation in the internal structure of carbon in the presence of the activating agent (phosphoric acid). Fig. 8 illustrates the relationship between the calcination temperature and the surface area of the activated carbon produced in this study, where it is found that raising the calcination

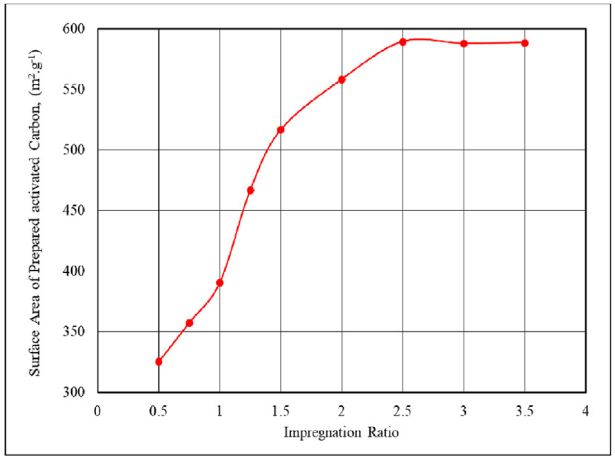

Fig. 6. Effect of phosphoric acid impregnation ratio on the surface area of prepared activated carbon @ impregnation time = 72 h and calcination temperature = 600 °C.

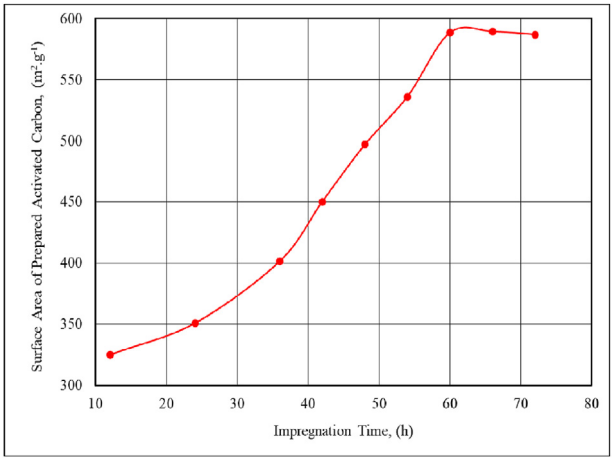

Fig. 7. Effect of impregnation time on the surface area of prepared activated carbon @ impregnation ratio = 2.5 and calcination temperature = 600 °C.

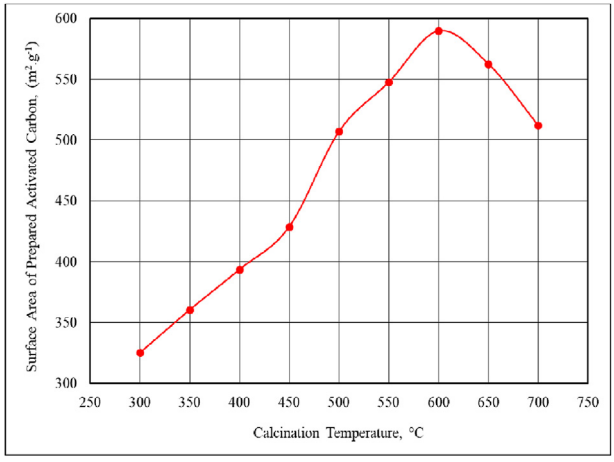

Fig. 8. Effect of calcination temperature on the surface area of prepared activated carbon @ impregnation time = 72 h and impregnation ratio = 2.5.

temperature from 300 to 600 °C increases the surface area from 325.2 to 589.6 m^2/g, respectively. However, increasing the temperature to 650 °C and then to 700 °C causes a decrease in the surface area to 562.42 and 511.96 m^2/g, respectively. This result may be attributed to the breakdown of the internal structure caused by the increased calcination temperature, which caused merging of adjacent pores and thus reducing the surface area of the activated carbon [38].

3.3. Performance of prepared activated carbon as an adsorbent of erythrosin B stain (C.I. 45430)

3.3.1. Point of zero charge (pH_{pzc})

The point of zero charge results shown in Fig. 9 represent the behavior of activated carbon prepared from plastic bottle waste in aqueous solutions over a wide range of pH values, between 1 and 14. The pH value at the point of zero charge reflects the value at which the surface of a material becomes electrically neutral, i.e., the net charge on the surface is zero. The data show that the point of zero charge value of the prepared activated carbon gradually increases with the increase in the pH value, being negative at low pH and becoming positive at high pH values, indicating that the surface of the activated carbon is negatively charged in acidic environments and positively charged in basic environments. At pH values lower than the point of zero charge, the surface of the prepared carbon material is positively charged due to the protonation of hydroxyl groups, amino groups, or other reactive sites on the surface of the activated carbon, which enhances the attraction of negative ions such as anionic dyes via electrostatic interactions. Conversely, at pH values higher than the point of zero charge, the surface loses protons and becomes negatively charged, which results in the repulsion of negative ions and the promotion of adsorption of positive ions such as cationic dyes [38]. From Fig. 9, it can be seen that the point of zero charge is 9.56, indicating that the prepared activated carbon retains a negative charge under most acidic and neutral conditions, which suggests its effectiveness in adsorption of positive molecules. Since erythrosine B is an anionic stain, the adsorption process will be more efficient at a pH lower than the point of zero charge where the prepared activated carbon surface is positively charged.

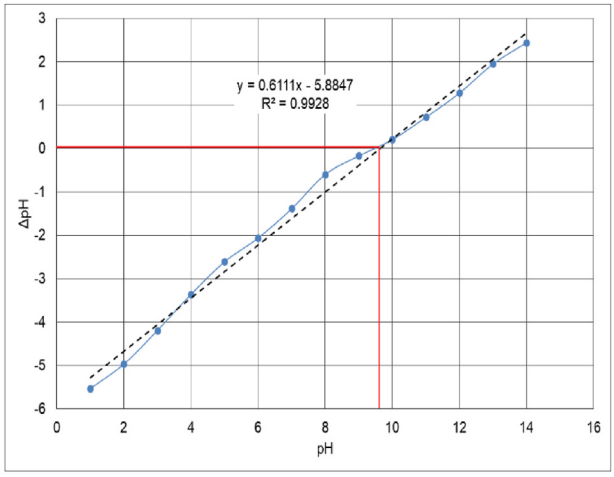

Fig. 9. Point of zero charge (pH_{pzc}) of prepared activated carbon @ room temperature.

In addition, other interactions such as hydrogen bonding, van der Waals interactions, coordination interactions, and (π−π) interactions may contribute to the adsorption process, especially since activated carbon contains active sites capable of interacting with molecules of the biological stain erythrosin B [39].

3.3.2. Effect of acidic function (pH)

The acidity represented by pH is an important factor in each adsorption experiment, as it affects both the adsorbate and the adsorbent. Varying pH may change the ionization of the polluted solution (adsorbate), at the same time, it may modify the properties of adsorbent surface, ultimately impacting the overall adsorption process. By varying the pH values between 1 and 9, Fig. 10 explains the removal efficiency of 10 ppm erythrosin B stain, keeping the values of other operating conditions constant at optimum conditions. It's clear that the relation between the removal efficiency and pH is an inverse relationship, and the maximum removal of erythrosin B occurred at pH = 1. Erythrosin B

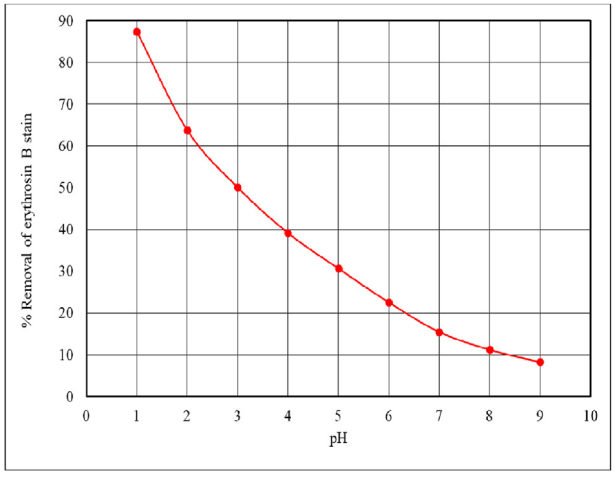

Fig. 10. Effect of pH on the removal of erythrosin B stain using prepared activated carbon @ concentration of stain = 10 ppm, agitation speed = 400 rpm, and contact time = 120 min.

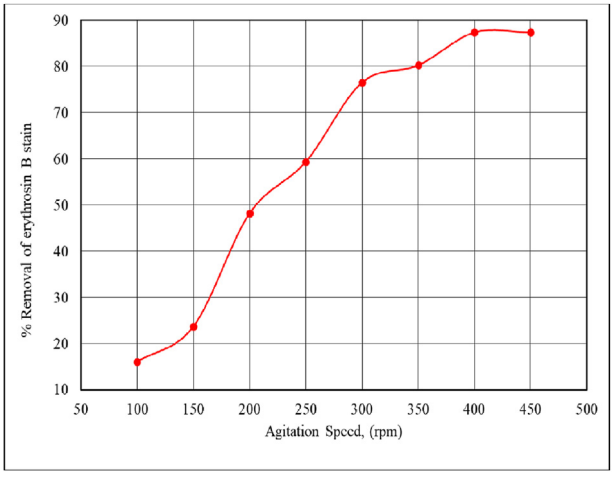

Fig. 11. Effect of agitation speed on the removal of erythrosin B stain using prepared activated carbon @ concentration of stain = 10 ppm, pH = 1, and contact time = 20 min.

with the chemical formula $C_{20}H_6I_4Na_2O_5$, can be classified as an anionic stain with a dipolar molecular structure, while activated carbon contains nucleophilic surface groups, such as carboxylic, carbonyl, and phenolic groups. At lower pH, the adsorption of ionized erythrosin B molecules onto activated carbon increases, leading to maximum removal efficiency at pH = 1. However, as pH rises, the adsorption rate decreases because the stain molecules become less nucleophilic, causing repulsion with the nucleophilic groups on the activated carbon surface [40]. The higher adsorption capacity at low pH is attributed to electrostatic interactions between the negative charge stain and the protonated groups on the adsorbent surface in acidic conditions (due to the presence of hydrogen ions).

As the pH increases, hydroxide ions compete with the stain for active sites on the adsorbent surface, reducing adsorption efficiency and leaving more stain molecules free in solution, which reduces the overall adsorption rate [41].

3.3.3. Effect of agitation speed

The agitation speed of solutions is considered a significant factor in adsorption processes, predominantly in batch mode procedures. It impacts the diffusion process and rate of transferring the molecules or ions, as well as their ability to overcome various forces such as attraction, repulsion, viscosity, and bonding, within the solution. Fig. 11 illustrates the effect of agitation speed on the adsorption efficiency of activated carbon for removing 10 ppm of erythrosin B stain. As the agitation speed increases, adsorption capacity also increases while other conditions are kept constant. This can be attributed to the improved diffusivity of particles in the solution, which promotes the chance of erythrosin B stain to reach and bind with the functional groups dispersed on the surface of activated carbon. Thus, the molecules of biological stain in the solution will decrease, leading to enhanced adsorption efficiency [42].

3.3.4. Effect of contact time

The factor of contact time in the water treatment process, particularly in adsorption techniques, plays a crucial role in determining the reaction rate and establishing the required time for the adsorption process to reach equilibrium. As demonstrated in Fig. 12, the efficiency of removing 10 ppm erythrosin B stain improves as contact time increases, while other variables remain at their optimal levels.

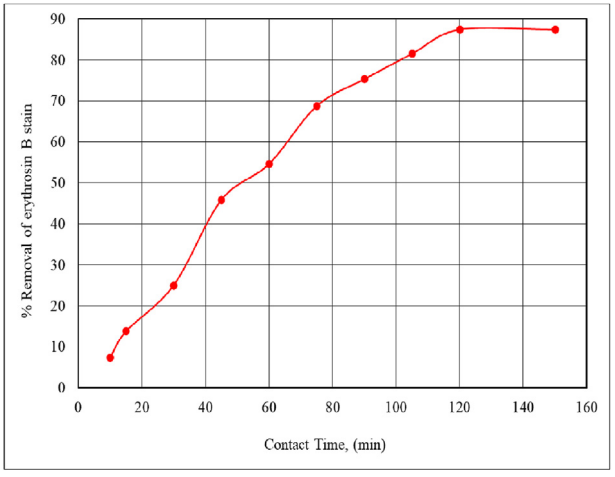

Fig. 12. Effect of contact time on the removal of erythrosin B stain using prepared activated carbon @ concentration of stain=10 ppm, agitation speed = 400 rpm, and pH = 1.

With a constant agitation speed, extending the contact time enhances the likelihood of erythrosin B molecules in the solution interacting with the adsorbent. This allows the molecules to spend more time on the adsorption surface, increasing the probability of binding to the active sites. As a result, the material's capacity to adsorb erythrosin B progressively rises, and the active sites become saturated with the stain molecules, reaching equilibrium approximately 2 h after the process begins. This conclusion matches that of [43].

3.4. Characterization of prepared activated carbon before and after adsorption of erythrosin B stain

3.4.1. BET surface area

This important property was measured for the prepared activated carbon using Quantachrome, Qsurf 9600 device (Thermo Finnegan Co., USA), based on physical adsorption-desorption for nitrogen gas at a constant temperature at the boiling point of liquid N_2 (77K). The BET surface area of the activated carbon prepared from plastic bottle waste, which was used as an adsorbent for erythrosin B stain was investigated before and after adsorption, as shown in Fig. 13, which illustrates the adsorption-desorption isotherm of the prepared carbon medium. The results showed that the virgin activated carbon particles had a surface area of 589.48 m^2/g. The high surface area of the adsorbent in this study can be attributed to several factors including the porous structure, chemical composition and physical properties which result from the complex structure of carbon atoms, and most importantly the precise chemical preparation process. After the adsorption of the biological stain, it was observed that the area decreased by approximately 72.5% to 161.8 m^2/g.

This result clearly indicates fundamental changes in the adsorption surface structure and pore distribution as a result of the interaction with the target molecules of biological stain. This suggests that the adsorbate partially occupied the active sites, as the surface area was not fully depleted, which greatly reduced the surface adsorption capacity. This significant decrease confirms that the stain molecules occupied the available active sites on the carbon surface of the prepared activated carbon by the molecules of stain, indicating the high efficiency of this prepared material in adsorbing the target molecules. This change can be attributed to pore blockage by erythrosin B stain molecules, progressively reducing the available adsorption area [38].

3.4.2. Fourier transform infrared spectroscopy (FTIR) analysis

Fig. 14 represents the Fourier transform infrared (FT-IR) spectrum of activated carbon prepared from plastic bottle waste before and after adsorption of biological stain erythrosin B, which was measured using IRPrestige-2 (Shimadzu, Japan) device. The spectrum before adsorption (shown in blue) reflects the original chemical structure of the material, while the spectrum after adsorption (red) shows the changes resulting from the interaction of the prepared activated carbon with the adsorbed biological stain. It is evident that the broad vibration band between 3800 and 3000 cm^{-1}, which is attributed to the vibrations of hydroxyl (-OH) or amine (-NH) groups, has undergone a significant decrease in intensity with a slight shift, indicating that these groups are attached to erythrosin B molecules via

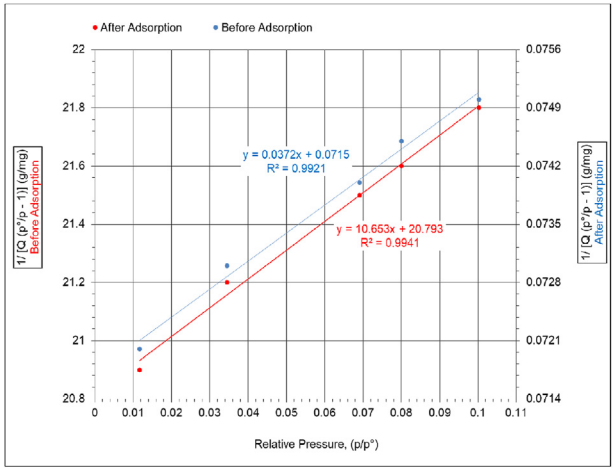

Fig. 13. Fitting curve of N_2 adsorption desorption isotherm BET surface area of prepared activated carbon, before and after adsorption of erythrosin B stain.

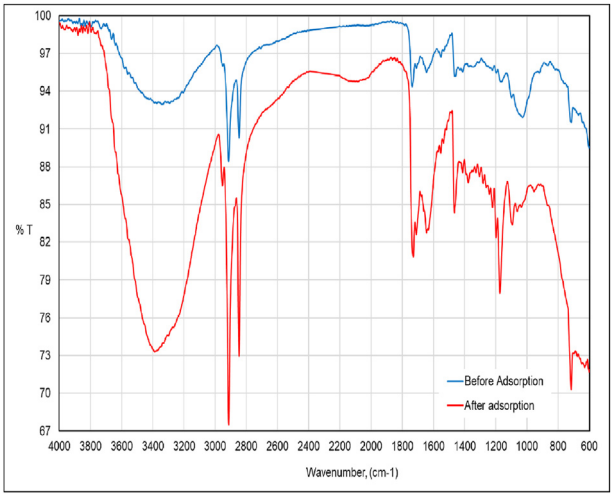

Fig. 14. FT-IR spectrum of prepared activated carbon, before and after adsorption of erythrosin B stain.

hydrogen bonds or electrostatic interactions [34]. Weak absorption peaks are also observed in the range between 2950 and 2700 cm^{-1}, belonging to the vibrations of the hydrocarbon C-H bonds, which may have increased in intensity or changed their positions due to the presence of hydrogen − containing compounds within the structure of the adsorbed biological stain. In addition, the absorption band between 1800 and 1550 cm^{-1}, associated with the stretching vibrations of carbonyl groups (C═O), shows changes in peak intensity or shifts after adsorption, indicating the formation of covalent or electrostatic bonds between the particles of prepared activated carbon and the ions of the biological stain erythrosin B [44]. Prominent peaks are also observed in the range between 1600 and 1000 cm^{-1}, which are due to the vibrations of carbon-carbon bonds (C═C), carbon-oxygen bonds (C-O), or carbon-nitrogen bonds (C-N) in aromatic structures, carboxyl groups, or ethers, in organic compounds, respectively. The adsorption resulted in the appearance of new peaks or increased the intensity of some original peaks, clearly indicating the interaction of the biological stain molecules with the prepared activated carbon via different mechanisms such as covalent interactions, ion exchange, or interactions between aromatic structures. Moreover, in the range between 1000 and 600 cm^{-1}, changes in the absorption intensity appeared, which may reflect vibrations of carbon bonds with halogens (specifically iodine present in the biological stain erythrosin B) as a result of the interaction of the adsorbent with the molecules of stain or changes in the structural composition of the prepared activated carbon after adsorption [39]. Spectroscopic analysis indicates that the adsorption process occurs through several interconnected mechanisms, including hydrogen bonding between hydroxyl groups on the surface of the prepared activated carbon and the biological stain molecules, electrostatic interactions between surface charges, and coordination bonds or molecular exchange in the presence of active sites on the surface capable of interacting with the stain. Interactions may also occur between the aromatic structures in the biological stain and the adsorbent via (π−π) interactions, which enhances the adsorption process. Based on these observed spectral changes, it can be concluded that the prepared carbonaceous material shows high efficiency in capturing erythrosin B stain molecules from the solution.

3.4.3. Scanning electron microscopy (SEM)

In this study, SEM images were measured using FEI Nova Nano SEM-450 (Thermo Fisher Scientific, USA). Fig. 15a and b show the SEM images of activated carbon prepared from waste from PET plastic bottles before and after adsorption, respectively. Fig. 15a shows the activated carbon prepared prior to adsorption of the erythrosin B stain. It can be seen from the figures that the particle sizes are irregular, randomly distributed and dispersed across layer on the surface, indicating that the activated carbon particles vary widely in size and shape. Additionally, the activated carbon surface is very rough, with particles compactly arranged like a loose sponge [44]. Fig. 15b shows the activated carbon after

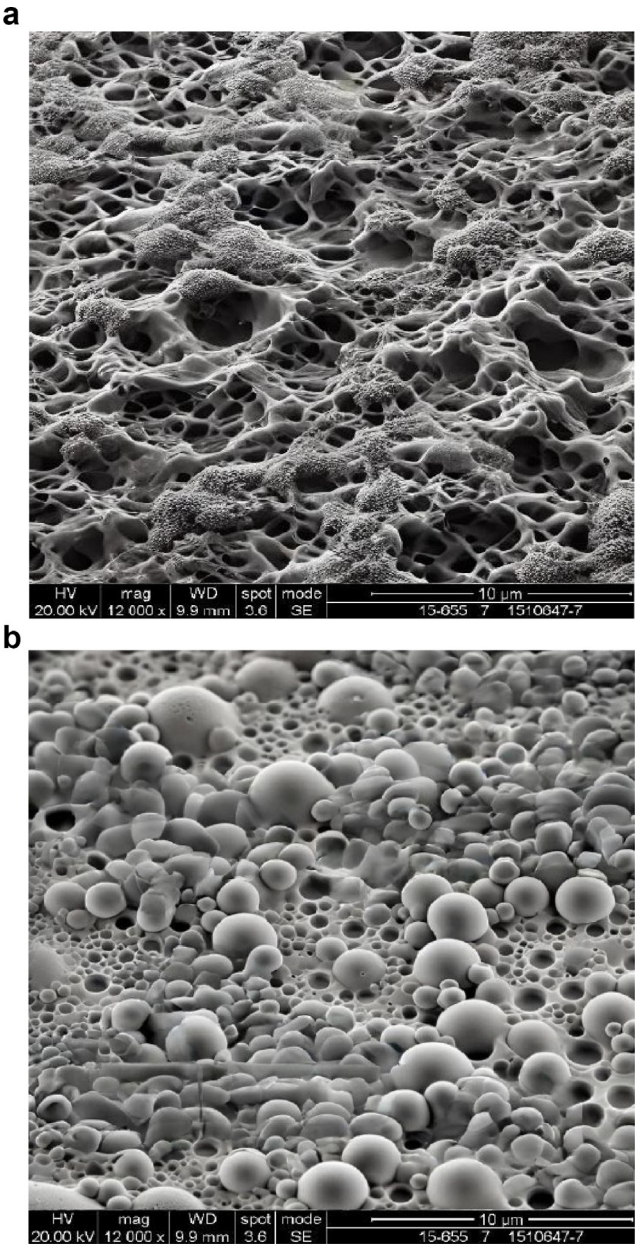

Fig. 15. (a) SEM of prepared activated carbon before adsorption of the erythrosin B stain. (b) SEM of prepared activated carbon after adsorption of the erythrosin B stain.

Table 1. Half Lethal Dose (LD_{50}) of Rodenticide Prepared from erythrosin B stain -Activated Carbon Residue.

Type of Food Consumed by Rats	Half Lethal Dose (LD_{50}) Calculated, ($mg.kg^{-1}$)		
	Males	Females	Literature
Group 1: Control Food: Normal Provender	No deaths	No deaths	–
Group 2: Experimental Food: Activated Carbon Residues Loaded with erythrosin B stain	1888	1900	1840 [47]

adsorption of the biological stain. A complete change in the surface morphology of the material is observed after adsorption, with the stain's effect clearly visible, as the surface becomes smoother, and pores with larger diameters appeared due to swelling. While conventional activated carbon systems typically maintain rigid structural integrity during dye adsorption processes [41], the current study reveals noticeable swelling phenomena under strongly acidic conditions (pH 1.0). This observation suggests that extreme protonation of oxygen-containing surface functional groups could induce temporary increases in interlayer spacing at the carbon interface. Importantly, such morphological changes appear limited to surface regions and do not significantly affect the overall structural stability or adsorption capacity of the material, as evidenced by FTIR spectra and surface area characteristics after adsorption. The swelling behavior may be attributed to electrostatic repulsion between protonated functional groups combined with hydration effects under acidic conditions, similar to phenomena reported in certain modified carbon systems.

These results indicate a reduction in the number of small pores by merging and combining with each other to form transitional or large pores in some areas. This will reduces the surface area of activated carbon. These results are consistent with the findings of [43].

4. Preparation of rodenticide from the residues of adsorption process

The activated carbon residues, after being utilized as an adsorbent for erythrosin B stain from simulated aqueous solutions, were collected and prepared for evaluation as a cost-effective and simple rodenticide. In this study, 20 groups (10 male and 10 female) of albino rats from the outbred multipurpose breed (Sprague Dawley), scientifically known as (*Rattus norvegicus*), were used to assess its effectiveness. Each cage housed five rats, weighing 250-300 g and aged 6-10 months. Additionally, a separate control group, designated as group 1, consisted of male and female rats, with each gender housed separately, which were fed a natural feed to serve as a baseline for comparison with the experimental results [45]. Before the experiments commenced, all rats were housed in clean cages under suitable living conditions for one week. The temperature was maintained at approximately 25 ± 2 °C, with an average of 14 h of light each day provided by a standard 50-W light bulb. The rats were given clean water and standard feed to ensure their health and prevent diseases that might affect the results. This acclimatization period allowed the rats to adjust to their environment and diet before the experiments began [46]. Following their acclimatization to the environment and diet, the rats were treated daily for 7 days. At the conclusion of the week, the rats were fed activated carbon residues containing absorbed erythrosin B stain, mixed directly into their feed. This mixture was combined with their feed along with a small amount of sweet-tasting food to entice the rats to consume it. Sweeteners were varied regularly to maintain palatability. The findings indicated that there were fatalities among both male and female rats across all cages, except for the control group 1. The mortality rate and time of death varied with the ingested dose stain-loaded activated carbon. The half lethal dose (LD_{50}) was determined and the calculated results are shown in Table 1. Table 1 reveals that the calculated LD_{50} of the prepared rodenticide matched the literature-reported LD_{50} [48]. This method is an effective way to simultaneously dispose of various hazardous pollutants, using a cost-effective, simple, and eco-friendly approach aligned with the Zero Residual Level (ZRL) concept.

5. Conclusions

This study shows the innovative approach of recycling PET plastic bottle wastes into activated carbon through an effective thermal decomposition process performed at different temperatures, followed by treatment with phosphoric acid as a chemical activation agent. The optimal conditions recorded for preparation is 67.833% yield of activated carbon when using 200 g of PET plastic waste, pyrolysis at 700 °C for 7 h. The prepared activated carbon showed a good adsorption ability, reaching 87.42% removal efficiency for erythrosin B stain from

simulated aqueous solutions, under the following conditions: 10 ppm initial stain concentration, pH 1, 400 rpm agitation speed, and 120 min contact time. The prepared activated carbon possesses various functional groups that are responsible for its adsorption capacity, according to FTIR analysis. While SEM examination indicated that the material suffered from clear changes in its surface structure as a result of stain treatment, and that its surface area decreased from 589.48 m^2/g to 161.8 m^2/g after adsorption. Moreover, the residues from the adsorption process demonstrate effectiveness as a rodenticide when tested on laboratory rats (*Rattus norvegicus*), with a calculated half-lethal dose (LD_{50}) closely aligning with existing literature. It should be noted that this study focused specifically on erythrosin B stain removal under a range of operating conditions, and the applicability to other contaminants ranges requires further investigation. Additionally, while the zero-residue approach was successfully demonstrated, large-scale economic feasibility remains to be evaluated. An important deduction drawn from this study is the effective reuse of PET plastic waste (as a type of municipal refuse) as a raw material in a useful, straightforward, environmentally sustainable, and economically beneficial while minimizing residual waste. This indicates that the study's approach aligns with the concept of zero residue level, promoting a clean and safe environment despite the presence of various waste types resulting from human activities and preserving commercial, industrial, agricultural, and recreational operations.

Ethics information

Ethical approval for this study was obtained from the "Code of Ethics in Research", the Ministry of Health of the Republic of Iraq, 2018.

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Conflict of interest

The authors have no conflicts of interest to disclose.

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