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Reclaiming Waste: Comparative Insights into Plastic-Derived and Spent RO Filter Activated Carbons

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***Abstract*:The alarming rise in plastic waste and the growing volume of spent activated carbon from domestic and industrial reverse osmosis (RO) filters have raised serious environmental concerns. This study explores a sustainable valorization pathway by comparing activated carbon derived from pyrolyzed plastic waste with spent activated carbon recovered from used RO filters. Plastic waste, an abundant and carbon-rich resource, was thermally decomposed via pyrolysis to yield char, which was subsequently chemically activated using 1N KOH at various impregnation ratios. A series of characterizations, including CHNS elemental analysis, Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), and iodine number assessments, was conducted to evaluate the physicochemical properties and adsorption-relevant features of both materials. The aim was to assess the structural and elemental differences arising from their distinct origins and preparation routes. The study reveals key insights into the surface morphology, functional groups, and porosity development in both plastic-derived and RO-spent activated carbons. By juxtaposing the two materials, this research provides a comprehensive understanding of their comparative effectiveness and potential as alternative carbonaceous adsorbents. The findings contribute to advancing circular economy practices through waste-to-resource strategies, particularly in the development of low-cost, sustainable activated carbon materials.**

Keywords: Plastic Waste Valorization, Spent RO Filter Carbon, Activated Carbon, Chemical Activation

I. INTRODUCTION

Plastics have become indispensable in modern society due to their exceptional properties, such as durability, chemical resistance, lightweight nature, and cost-effectiveness. These attributes have led to widespread usage in numerous sectors, including packaging, electronics, automotive, construction, and household applications (Hopewell, Dvorak, and Kosior 2009; Andrady and Neal 2009). Among the various forms of plastic waste, single-use plastics (SUPs), particularly multilayer flexible packaging materials, are a growing concern due to their short lifecycle and limited recyclability. These multilayer composites often consist of an inner aluminium-metallized layer, a middle layer of low-density polyethylene (LDPE), and a biaxially oriented polypropylene (BOPP) outer layer, making mechanical recycling technically and economically unfeasible (Singh et al. 2017; Patrício Silva et al. 2021). Globally, plastic consumption continues to rise, with packaging materials alone accounting for nearly 35% of plastic demand (PlasticsEurope 2021). The persistent accumulation of plastic waste has led to widespread environmental pollution, with adverse impacts on terrestrial and aquatic ecosystems, human health, and biodiversity (Geyer, Jambeck, and Law 2017). Plastic waste includes PET, HDPE, PVC, LDPE, PP, PS, and multilayer plastics, each differing in chemical composition and recyclability. Recycling is constrained by contamination, polymer degradation, mixed-material packaging, inefficient sorting, and unfavorable economics, reducing recovery efficiency and limiting high-quality recycled material production (Hosny et al. 2016b).The challenges are further exacerbated by increasing urbanization, population growth, and industrial expansion, all contributing to greater volumes of municipal solid waste (Kaza et al. 2018). Conventional recycling technologies are inadequate to manage this diversity of plastic waste, especially for contaminated or composite plastics, and also result in secondary pollutants like wastewater (Rinku Verma et al. 2016).

Consequently, there is a critical need for sustainable alternatives that not only reduce plastic waste but also generate value-added products. Pyrolysis has emerged as an effective thermal recycling method for non-recyclable plastics,

capable of decomposing synthetic polymers into char, oil, and gaseous by-products in an oxygen-free environment (Al-Salem, Lettieri, and Baeyens 2009; Miandad et al. 2016). The char produced through pyrolysis is a carbon-rich solid that can be further processed into activated carbon a highly porous material widely recognized for its adsorption capabilities in environmental and industrial applications (Lua and Yang 2005; Ioannidou and Zabaniotou 2007). Pyrolysis temperature range (350–400 °C). At lower temperatures, incomplete decomposition of plastic polymers occurs, resulting in poor-quality char with insufficient carbonization and underdeveloped porous structures. Conversely, excessively high temperatures may lead to excessive degradation of carbonaceous materials, reducing char yield and affecting the quality of the final activated carbon. Therefore, the selected temperature range (375 °C)was optimized to achieve effective carbonization while maintaining suitable char yield and quality for subsequent activation (Ragab, Gumaah, et al. 2024a). Studies have shown that activated carbon derived from plastic waste exhibits promising surface area and porosity characteristics, making it suitable for various containment and filtration purposes (Pereira et al. 2024).

Simultaneously, another emerging waste stream is the spent activated carbon from reverse osmosis (RO) filtration units, extensively used in water purification systems. After exhaustion, these materials are often discarded despite retaining residual carbon structures. Spent activated carbon, if properly regenerated or reprocessed, can serve as a viable source for secondary activated carbon production (Ahmedna, Marshall, and Rao 2000; Daifullah and Girgis 2003). This approach not only reduces waste volume but also conserves resources by re-utilizing carbonaceous materials that would otherwise be landfilled or incinerated. Although regeneration of spent activated carbon has been widely reported, comparative investigations evaluating its performance alongside activated carbon derived from pyrolyzed plastic waste using the same activation methodology are scarce. Addressing this gap is essential for identifying sustainable and economically viable waste-derived adsorbent materials. In this context, the novelty of the present work lies in the direct comparison of activated carbons synthesized from two distinct waste streams, pyrolyzed multilayer plastic char and spent RO filter media, using a common KOH chemical activation process. Unlike previous studies that generally focus on a single precursor, this work systematically evaluates and compares the elemental composition, surface functional groups, morphology, and adsorption characteristics of both materials. Such a comparative approach provides new insights into the relative potential of these waste resources for producing low-cost activated carbon and supports integrated waste valorization within a circular economy framework.

The present study aims to explore and compare the potential of two waste-derived carbon sources: pyrolyzed plastic char and spent RO filter media. Using chemical activation (with KOH) and a series of physicochemical characterization techniques, including CHNS elemental analysis, Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), and iodine number determination, the properties of the two activated carbons are analyzed. By juxtaposing the structural, morphological, and compositional features of these materials, the study seeks to determine their comparative effectiveness as activated carbon sources.

This investigation contributes to the broader objective of waste Valorization and circular economy strategies by integrating two significant waste streams, plastic and spent RO filters, into a unified material recovery framework. The outcomes have potential implications for sustainable materials engineering, low-cost adsorbent development, and integrated waste management policies.Synthesis of process flow and possible use of Activated Carbon are illustrated in Figure 1.

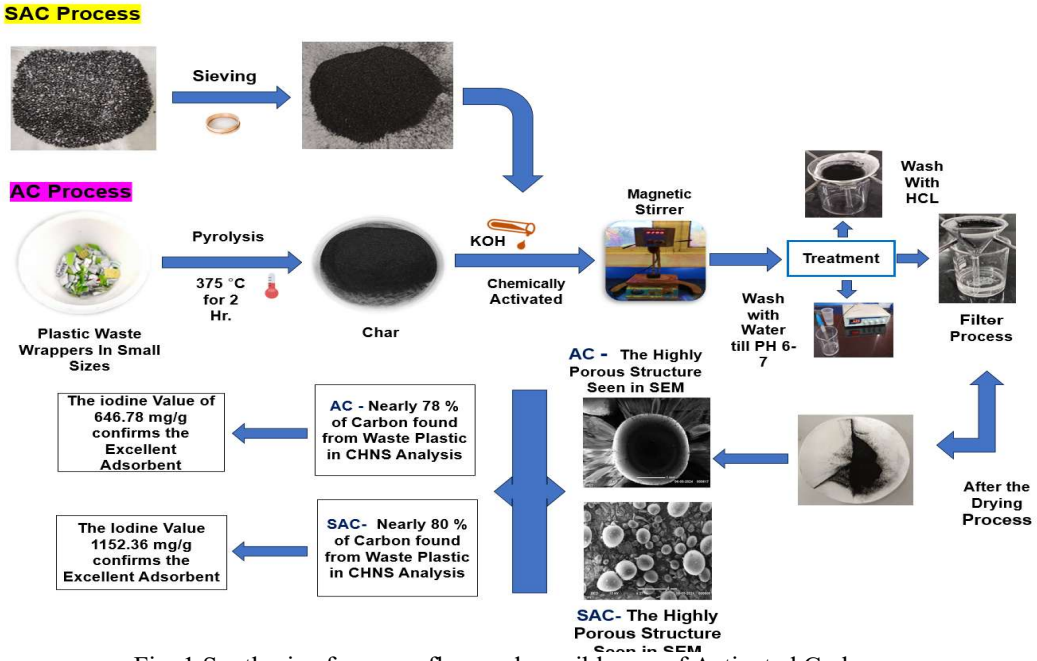


Fig. 1 Synthesis of process flow and possible use of Activated Carbon

Brief description of ActivatedCarbon

AC is a microcrystalline material with a high surface area and porosity, making it highly effective as an adsorbent (Heidarinejad et al. 2020). It is a solid, black, porous sponge or bead made from waste plastic materials, including PET, LDPE, PVC, BOPP, and PP etc. The preparation process involves specific temperatures and atmospheric conditions. The type of raw materials utilized will surely result in variations. The surface area of the carbon that is activated can also differ based on the raw ingredients, temperature, and type of activation applied (Nugraha et al. 2022). Low-temperature carbonization is ideal for producing efficient activated carbon, as it promotes the development of a porous structure (Zhu et al. 2021). The raw materials are subjected to the appropriate activation agent, such as zinc oxide, potassium permanganate, potassium hydroxide, ammonium persulfate, sulfuric acid, hydrogen peroxide, phosphoric acid, or others, to create activated carbon. Hydrochloric acid is one of the best activating agents, as it modifies the graphite structure, resulting in high adsorption capacity (Ademiluyi and David-West 2012). Chemical and physical activation are two unique approaches for generating activated carbon, primarily differing in their processing steps, operating conditions, and the properties of the resulting material.

The process of chemical activation involves a single step where a precursor, such as biomass or polymers, is treated with a chemical activating agent like KOH, H_3PO_4, $ZnCl_2$, or NaOH. This is then followed by carbonization at moderate temperatures ranging from 350 to 700°C in an inert atmosphere. The activating agent facilitates dehydration and oxidation, reducing tar formation and improving carbon yield. This approach successfully produces micro- and mesoporous structures featuring adjustable pore size distribution and a wealth of surface functional groups. It additionally presents benefits like reduced energy usage, decreased processing duration, and enhanced carbon yield in comparison to physical activation. Nonetheless, it necessitates thorough washing to eliminate leftover chemicals and can produce chemical waste, presenting environmental issues (Shahcheragh, Bagheri Mohagheghi, and Shirpay 2023). In contrast, physical activation involves a two-step process: the initial carbonization of the raw material in an inert environment to create charcoal, followed by gasification with oxidizing gases (CO_2, steam, or air) at elevated temperatures (800–1000°C). This approach eliminates the use of chemical agents, ensuring it is environmentally sustainable and more feasible for industrial scaling. The activated carbon produced primarily showcases microporous structures, making it ideal for applications in adsorption and purification. However, physical activation typically results in reduced carbon recovery, requires greater energy input, and provides less control over pore development when compared to chemical activation. In general, chemical activation is preferred for achieving high-performance porous carbons (Oraby et al. 2025; Bergna et al. 2018). Activated carbon is an affordable, eco-friendly adsorbent with a broad range of uses across the globe. The content of AC is dependent on the source material and processing method utilized (Hui and Zaini 2015).

Types of Activated Carbon

The feed material and processing technique define the types of activated carbon. It can be challenging to classify activated carbon based on surface characteristics, behavior, and other fundamental criteria. There are three main types of activated carbon (Ravi Verma 2025). They are categorized according to their size, method used for preparation, and industrial applications. Each type of activated carbon has unique properties that make it appropriate for specific uses. (Ganjoo et al. 2023). Three types of well-known activated carbon are as follows (Roquia, khalfan hamed Alhashmi, and hamed Abdullah alhasmi 2021).

a. Powdered Activated Carbon



Fig. 2PowderedActivatedCarbon

It is the main type of AC that is found in every time when we make activated carbon (Figure 2). Out of the total production of AC, powdered activated carbon consists ofabout 50%.Therangeofpowdered activated carbon particle size is between 5 to 15 A^0. Powdered activated carbon is mainly used in liquid–phaseadsorption,and itprovidesflexibilityinoperationsas wellasreducesthecostsof processing (Mubarak, Khedr, and El Sharkawy 2024). The major applications of powdered activated carbons are in the industrial sector, such as the food industry and the pharmaceutical industry, and most of it is used these days in water treatment (wastewater purification)(Egirani et al. 2021).

b. Granular Activated Carbon



Fig. 3 Granular Activated Carbon

Generally, the particle sizes of the granular activated carbon range between 0.2 mm to 0.5 mm (Ganjoo et al. 2023). Granular-activated carbonscan be used in liquid and gasphase applications. Granular activated carbon is much more popularthanpowdered activated carbon because it tends to last longer and offers clean handling (Figure 3). Granular activated carbon (GAC) provides remarkable mechanical strength, reusability, and ease of handling, rendering it highly suitable for continuous-flow industrial systems like water and air purification. The relatively large particle size guarantees a low-pressure drop and promotes regeneration via thermal or chemical methods, thereby improving cost efficiency (El-Sawaf, Nassar, et al. 2024a).GAC demonstrates a strong capability for the adsorption of organic pollutants and residual chlorine. Nonetheless, the restricted surface area in

comparison to powdered activated carbon leads to decreased adsorption rates for minor or low-concentration pollutants. Furthermore, regeneration may result in a decrease in activity and necessitate energy-demanding processes, presenting obstacles for sustainable large-scale implementations(Muttil et al. 2023).The granular activated carbon classification and its applications. The discussion now distinguishes between unshaped granular activated carbon with irregular particle morphology and shaped granular activated carbon with defined geometries, such as cylindrical forms. Additionally, the potential applications of granular activated carbon in gas masks, gas separation, gas purification, and other adsorption-based processes have been incorporated to provide a broader context (Elfiky et al. 2024).

c. Extruded Activated Carbon

Extruded activated carbon is one of the major forms of activated carbon, produced by extrusion or pelletization of activated carbon powder with suitable binders, resulting in cylindrical pellets with improved mechanical strength and lower pressure drop compared with powdered activated carbon. The particle size of extruded activated carbon typically ranges from approximately 0.8 mm to 130 mm, depending on the intended application and manufacturing process. In addition to shape and particle size, recent classifications of activated carbon emphasize textural properties, particularly pore structure, which strongly influences adsorption performance (El-Sawaf, Nassar, et al. 2024b). Extruded activated carbons generally exhibit a combination of micropores and mesopores, enabling effective adsorption of both small molecules and larger organic compounds. Their tailored particle size, pore structure, and mechanical stability make them suitable for applications such as gas purification, solvent recovery, water treatment, and catalytic support.(Ganjoo et al. 2023).



Fig. 4 Extruded Activated Carbon

PropertyofActivatedCarbon

ACadsorbentshave a specificporouscarbonstructure,whichissimilartothegraphite structure. Carbon adsorbent contains a small amount of ash content (mineral matter) and heteroatoms such as hydrogen and oxygen. The Ash content amount is very low and is good for a better adsorbent. The physical properties of the activated carbon are mostlydependent onporousstructureand size.According to the IUPAC the pore size is divided into (Figure 5) three groups(Gabr et al. 2023).

(i) Macro pores, size is bigger than the 50 nm diameter.
(ii) Meso pores, size ranging between 2-50 nm diameters
(iii) Micropore, size less than 2 nm diameter

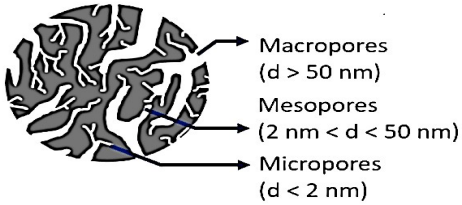


Fig. 5 Graphical representation of different types of pore structures of activated carbon (Ang et al. 2019).

Hardness provides good mechanical strength and structural stability during handling, transportation, and adsorption processes. The mechanical properties of activated carbon are commonly evaluated through hardness and abrasion resistance tests, which indicate the ability of carbon particles to withstand attrition and particle breakdown during operation. High hardness is particularly important for granular and extruded activated carbon used in fixed-bed adsorption systems, where mechanical degradation can increase pressure drop and reduce service life. Activated carbon derived from coconut shells generally exhibits exceptionally high hardness due to the dense lignocellulosic structure and high carbon content of the precursor material(Yusufu M. I. 2012).This superior mechanical strength makes coconut shell-based activated carbon suitable for applications requiring repeated regeneration and long-term operation.

The adsorptive property is one of the most important and unique characteristics of activated carbon, which determines its effectiveness as an adsorbent for removing contaminants from liquid and gaseous streams. Adsorption is a surface phenomenon in which molecules from gases or solutions accumulate on the surface of a solid material due to attractive forces between the adsorbate and the carbon surface. The adsorption process is generally classified into two mechanisms: physical adsorption (physisorption), which occurs through weak van der Waals forces and is usually reversible, and chemical adsorption (chemisorption), which involves stronger interactions such as covalent bonding or electron transfer between the adsorbate and functional groups present on the carbon surface (Mahmood Aljamali and Obaid Alfatlawi 2021).The impregnation process is a critical step in chemical activation because it controls the interaction between the activating agent and the carbon precursor, thereby influencing the development of porosity and surface functional groups. During impregnation, the activating species gradually diffuse into the precursor matrix, promoting dehydration, depolymerization, and subsequent pore formation during carbonization. Therefore, impregnation time must be optimized to achieve sufficient penetration of the activating agent while avoiding excessive chemical interaction that may cause pore widening or structural degradation.

In the present study, an impregnation time of 23 h was selected to ensure effective diffusion and uniform distribution of the activating agent throughout the precursor material. A prolonged stirring period allows equilibrium between the activating solution and precursor surface, improving contact efficiency and enhancing the formation of accessible micropores and mesopores during activation. Recent studies

have demonstrated that impregnation duration significantly affects the adsorption properties of activated carbon, with optimized activation time improving surface area, pore volume, and adsorption capacity (Ragab, Gumaah, et al. 2024b). where controlled impregnation conditions were shown to influence the extent of chemical activation and the resulting pore structure. The optimization of impregnation time involves balancing sufficient activation with preservation of the carbon framework. Short impregnation periods may result in incomplete penetration of activating agents and limited pore development, whereas excessively long treatment can lead to over-activation, pore collapse, or unnecessary chemical consumption. Thus, the selected 23 h impregnation period provides adequate interaction between the precursor and activating agent, contributing to the formation of a well-developed porous structure and improved adsorption performance.

The adsorption capacity of activated carbon depends strongly on its BET surface area, pore size distribution, surface functional groups, and chemical properties. Micropores mainly contribute to adsorption capacity, whereas mesopores and macropores facilitate diffusion and transport of adsorbate molecules (El-Sawaf, El-Dakkony, et al. 2024). Activated carbon has a strong affinity for iodine molecules, and the iodine adsorption capacity is widely used as an indicator of the degree of activation and micropore development. The iodine value (or iodine number), expressed as milligrams of iodine adsorbed per gram of activated carbon (mg g^{-1}), is an important quality-control parameter used to evaluate the adsorption activity of newly produced and regenerated activated carbons. A higher iodine value generally indicates a greater micropore volume and higher adsorption capacity for small molecules. Ash content represents the inorganic mineral fraction remaining after carbonization and activation. Although excessive ash content can reduce adsorption capacity by blocking pores and altering surface chemistry, a small amount of mineral matter can be beneficial by influencing surface polarity, catalytic activity, and adsorption interactions during the manufacturing process. Therefore, controlling ash content is essential to achieve an appropriate balance between surface chemistry and adsorption performance (Lutfi et al. 2021).

Materials, Methods, And Experimental Work

Thematerial selected for the present research work and the methods for preparing the samplesare discussed in the current chapter.

Chemicals used

The chemicals utilized in this study are listed below. Thesourcesofthesechemicalsandacronyms usedaregiveninTable1.Activatedcarbon,which was prepared in the lab.

TABLE1
List ofChemicalsusedandtheirSources

CHEMICALS NAME	Plastic Waste Wrapper	Potassium Hydroxide	Hydrochloric acid	Potassium iodide	Iodine	Potassium iodate	Starch solution	Sodium thiosulphate
ACRONYM	PWW	KOH	HCl	KI	I	KIO_3	$(C_6H_{10}O_5)_n$	$Na_2S_2O_3$
SOURCES	Domestic Scrap/Waste	Central Drug House, New Delhi	Loba Chemie Pvt Ltd	Loba Chemie Pvt Ltd	Central Drug House, New Delhi	Thermo Fisher Scientific India Pvt Ltd	SD Fine Chemicals (SDFCL)	Loba Chemie Pvt Ltd

(A) PreparationofActivatedCarbon

Therawmaterialusedfor the preparationofAC isplasticwaste wrappers.

Rawmaterialcollection

Plasticwaste wrappersas arawmaterialcollectedfromsomelocalshops, dustbins, garbage areas, anddomestic Scrap/waste. Allwrapper waste was stored in bags.

Washingofplastic waste wrapper

The wastewrapperwaswashedwith detergent and tapwatermanytimes on both sides.Itisnecessarytoremove the oily inner surfaces from the wrapper. Gentlywashing the waste wrapper is necessary for producing good-qualityactivated carbon.

Drying of Wrapper Waste

The samples of waste wrappers were put into trays. These trays were first put to dry in the sunlight for 15 minutes.

Cutting of Wrapper Waste

The sample of the waste wrapper was cut into small pieces (Figure 6).



Fig. 6 Cutting of Wrapper Waste

Pyrolysis



Fig. 7 After Pyrolysis

Asmall-sized cutting wrapper was placed in the crucible,and the crucible was heated to 375ºC (ramp rate 10 °C /min.) in a muffle furnace for two hours in an environment of nitrogen gases. After two hours, the plastic trash sample had been turned to char. After cooling, the char was collected and kept in airtight PET bags to protect it from moisture and other contamination (Figure 7).

Sieving

To obtain a uniform particle size distribution and remove larger particles, activated carbon samples were sieved using 100 and 200 mesh sizes (Jaspreet Kaur et al. 2025). These mesh sizes were selected to obtain a fine and consistent particle fraction suitable for uniform dispersion and improved interaction with the matrix. Sieve analysis is a standard particle size characterization method used to evaluate particle distribution. The controlled particle size helps improve adsorption kinetics by reducing diffusion resistance while maintaining suitable handling and packing properties (Figure 8).

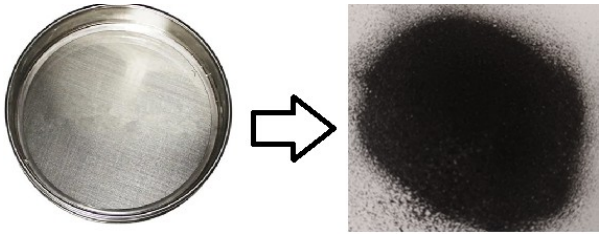


Fig. 8 Prepared Char

Impregnation

After gathering the char in a beaker, different impregnation ratios (3:1, 5:1, 7:1, and SAC 5:1) were applied to the char using KOH solution. The application of KOH in chemical activation significantly improves pore development and carbon yield; however, it also introduces considerable environmental and cost-related challenges. KOH poses significant risks due to its corrosive nature, necessitating meticulous handling and disposal practices to avert contamination of soil and water resources. The process of post-activation washing results in the production of alkaline wastewater that contains potassium salts, necessitating neutralization and treatment, thereby adding to the complexity of operations. The cost of KOH is notably high, and its limited recovery efficiency contributes to increased production expenses. The energy used in washing and drying contributes to total costs. Despite these limitations, the capacity to generate highly porous carbons frequently validates its application in valuable adsorption and energy storage sectors.

Magnetic Stirrer Process



Fig. 9 Stirring process

For activation, there is a need for a magnetic stirrer, and the contact time has been provided as 23 hours for the sample (Figure 9).

Washing

The obtained activated carbon was rinsed with 1N dilute HCL for one hour, as per the standard, to achieve the pH value 6-7 (Hosny et al. 2016a). Washing of the sample was carried out using distilled water multiple times (Figure 10a & b).

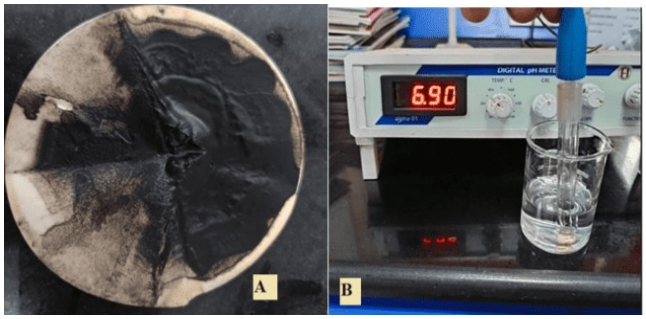


Fig. 10 (a) Activated Carbon after Water Wash (b) pH Range

Dry

The activated carbon samples were oven-dried to remove residual moisture after washing. The drying temperature and duration were selected to ensure effective moisture removal while preventing structural changes, oxidation, or degradation of the carbon framework. Moderate drying conditions are commonly applied for activated carbon to preserve its pore structure and surface functional groups (Cometa et al. 2022). where controlled drying conditions were used to maintain the physicochemical properties and adsorption performance of activated carbon



Fig. 11 Activated carbon in the Oven for drying

materials. In the oven, the temperature was set at 110 ºC for 4 hr. to remove the moisture from the obtained activated carbon (Figure 11).

Prepared Activated Carbon from Plastic Waste

Activated carbon from char is shown in Figure 12.

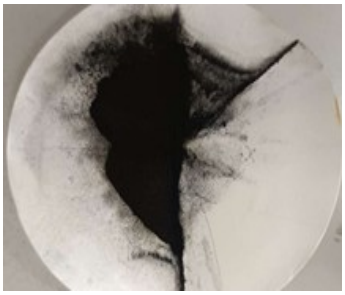


Fig. 12 Prepared Activated Carbon

(B) Preparationof Spent Activated Carbon

Preparation for Regenerated Spent Activated Carbon (SAC)

The raw material used for the preparation of activated carbon is spent activated carbon that has not been regenerated.

Raw Material Collection

Spent activated carbon as a raw material collected from the activated carbon cartridge of RO system. SAC was stored in bags (Figure 13).



Fig. 13 SAC Sample

Drying of SAC

The samples of SAC were put into trays. These trays were put first to dry in the oven for 15 minutes at 80 degrees centigrade.

Sieving

The SAC samples were sieved in 200 and 100-grade mesh to separate the larger particles and achieve a homogeneous particle size. Sieving is important for the development of a fine particle size of activated carbon, which is required for proper distribution in the matrix.

Impregnation

The char was collected in a beaker and treated with KOH Solution using various impregnation ratios of 5:1.

Magnetic stirrer process

The beaker was placed on a magnetic stirrer for 2 hours of activation.

Washing and drying

The obtained regenerated spent activated carbon was rinsed with 1N dilute HCL for one hour, and then thoroughly washed (Figure 14) with distilled water multiple times until the sample reached a pH of 6-7 (Hosny et al. 2016a). The obtained regenerated SAC has been dried in an oven at 110 ºC for 4 hours before being kept in desiccators (Cometa et al. 2022).

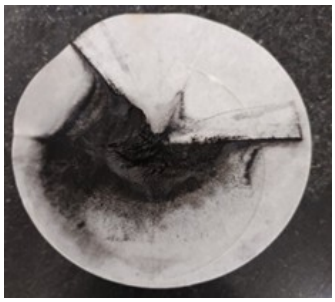


Fig. 14 After Washing SAC

Methods for Activated and Spent Activated Carbon

The activated carbon samples from plastic waste wrappers were studied for the percentage of the yield for spent activated carbon, CHNS elemental analysis, Iodine number, SEM (Scanning Electron Microscope), FT-IR (Fourier Transform Infrared Spectroscopy), and the presence of corresponding functional groups.

Yield of the Carbonization Process

The accurate weight of 1gm of the sample is taken and transferred into a pre-weighed crucible. The crucible is placed in the muffle furnace at 400ºC for 2 hours. After pyrolysis and cooling, the weight of the crucible is measured to calculate the char content using the following formula. Equation 1 (Pham 2023).

Yield of carbonization process (H)= 100 x $\frac{massofchar}{\text{mass of plastic}}$.....(1)

Percentage of the Yield

For the spent activated carbon, the percentage of yield is an important parameter. The amount that was produced from the dried precursor can be calculated by using the formula. Eqs.1(Pham 2023).

$$\text{Yield \%} = 100 \times \frac{\text{Weight of activated carbon produced (g)}}{\text{Weight of dried precursor used (g)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

CHNS Elemental Analyzer

The CHNS elemental analyzer is used to find and determine the percentages of carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) in a sample.Elemental analysis on developed samples was recorded by CHNSO Elemental Analyser, Elementar - Unicube (Fig. 15). Characteristics of char and developed activated carbon have been studied to analyze the Carbon (C), Hydrogen (H), Nitrogen (N), and Sulphur (S) % percentages in all our samples.



Fig. 15 CHNSO Elemental Analyser, Elementar (Unicube)

Iodine Number

The ASTM D 4607-94 test method establishes a defined process for determining the iodine number of activated carbon. The iodine number is the quantity of iodine in milligrams absorbed by one gram of activated carbon under certain test conditions. It is represented in the SI unit mg/g. The method employs an iodometric titration in which alkaline iodine (0.1N) is titrated against sodium thiosulfate (0.1N), with a 1% starch solution serving as an indicator. The procedure is taking a blank reading, followed by a reading with activated carbon (Babatunde, Garba, and Ali 2016; Tahir and Choudhry 2017).

Scanning electron microscope (SEM)

Scanning Electron Microscope (SEM) is used to find the surface properties and morphological structure. The morphological images on developed samples were recorded by Scanning Electron Microscope (SEM) Jeol (KM 6000 plus), Characteristics of char and developed activated carbon have been studied to analyze the morphological changes in all our samples.

Fourier transform infrared spectroscopy (FT-IR)

Fourier Transform Infrared Spectroscopy (FT-IR) is used to find the chemical bonds present in prepared samples. The functional group ability of developed samples was recorded by a Fourier Transform Infra-Red Spectrometer Thermo-Scientific (Nicolet 6700). Characteristics of char and developed activated carbon have been studied to analyze the variation of functional groups in all our samples (Balpreet Kaur, Gupta, and Bhunia 2019).

II. Results and Discussion

Yield of Carbonization Process

The three plastic trash samples were pyrolyzed at a temperature of 375ºC for 2 hours in the presence of inert nitrogen gas, a flow rate of 20ml per minute, to find out the char yield. The obtained char residue found by weight in all three test runs has been tabulated in Table 2.

Sr. No.	Empty crucible wt.(gm.)	Weight of plastic trash (gm.)	Weight with crucible with plastic trash (gm.)	After Pyrolysis wt. (gm)	Empty crucible wt. – after pyrolysis wt. (gm.)	% of Char
1	50.02	1.0	51.02	50.21	0.19	19 %
2	50.06	1.0	51.06	50.26	0.20	20 %
3	50.05	1.0	51.05	50.24	0.19	19 %
Avg.	50.04	1.0	51.04	50.71	0.19	19 %

TABLE2
Yield of the Carbonization Process

It is clear from the table that after pyrolysis, the char formed was 19% in yield on average (Ravi Verma and Choudhary 2025b). The KOH activation promotes dehydration, oxidation–reduction reactions, gasification, and pore development by forming intermediate potassium compounds (e.g., K_2CO_3, K_2O, and metallic K). At lower KOH-to-precursor ratios, activation is insufficient, resulting in limited pore formation and relatively higher solid yield. As the KOH ratio increases, pore development is enhanced due to more extensive carbon etching; however, excessive activation leads to increased carbon consumption, widening of pores, and a reduction in activated carbon yield. We have also incorporated a comparison with the findings defined by (Hussein et al. 2024) , which similarly demonstrated that increasing the KOH ratio improves porosity but decreases yield because of intensified gasification and carbon burn-off. These additions

provide a more comprehensive explanation of the relationship between KOH ratio, activation mechanism, pore development, and product yield.

Percentage of Yield of Activated Carbon

When char formed after pyrolysis was undergone for impregnation chemically, the activated carbon was developed. As per the impregnation with KOH Solution at different impregnation ratios 3:1, 5:1, 7:1, and SAC 5:1 have been performed to develop the activated carbon, the result of % yield for all different samples has been shown in Table 3A and 3B.

For the KOH/char ratio 3:1, the activated carbon yield was noted as 17.86 %. For different samples having KOH/char ratios of 5:1 and 7:1, the yield of activated carbon was calculated at 17.1 % and 18.05 % respectively. For the SAC sample having a KOH/char ratio of 5:1, the yield calculation is 18.24 %.

Sr. No.	Ratio of KOH/Char	Char wt.(gm.)	After activation with the KOH process, AC wt.(gm.)	After drying (gm.)	Yield % of AC
1	3:1	1.0	0.96	0.94	94 %
2	5:1	1.0	0.93	0.90	90 %
3	7:1	1.0	0.97	0.95	95 %

TABLE 3 (A)
Yield of Activated Carbon

Sr. No.	Ratio of KOH/Char	Char wt.(gm.)	After activation with the KOH process, AC wt.(gm.)	After drying (gm.)	Yield% of AC
1	5:1 SAC	1.0	0.98	0.96	96 %

TABLE 3 (A)
Yield of Spent Activated Carbon

CHNS Analysis

The CHNS analyzer is employed to verify the subsistence of carbon, hydrogen, nitrogen, and sulphur in the samples. The outcomes of this analysis are outlined in Table 4 A & B. The carbon content of the original material, wasted plastic wrapper, was established at **76.60** percent. Meanwhile, the waste plastic wrapping comprised an unusually high ratio of carbon when matched to alternative stuff habitually reprocessed into activated carbon. Its high-carbon content and accessibility converted it into an exceptional prospect as a carbon foundation. On the other hand, the high carbon content simultaneously intended a lower proportion of additional important elements like hydrogen. Additional investigation would be necessary to decide whether any preprocessing may well be important to optimize the wrapper's composition for use inside carbon activation. The high carbon content confirms its suitability for activated carbon preparation. The precursor used in this study was collected waste plastic wrappers, which were cleaned, dried, and shredded prior to pyrolysis to ensure material consistency. The carbon contents of the char, 7:1 KOH-activated carbon, spent activated carbon, and 5:1 KOH-regenerated spent activated carbon were found to be 77.63%, 78.20%, 73.45%, and 79.80%, respectively. The increase in carbon content after activation, particularly for the 7:1 KOH-treated sample and the regenerated spent activated carbon, confirms the effectiveness of the activation process and demonstrates that the selected plastic waste contains a significant amount of fixed carbon, making it a suitable precursor for producing high-quality activated carbon (Ravi Verma and Choudhary 2025b, 2025a).

The influence of sulfur content on the adsorption performance of activated carbon. In detail, sulfur-containing functional groups enhance adsorption by introducing active sites that improve interactions with pollutant molecules through electrostatic attraction, hydrogen bonding, and surface complexation. Sulfur functionalities may also alter the electronic properties and surface polarity of activated carbon, improving its affinity toward specific contaminants, particularly heavy metals and certain organic compounds. However, excessive sulfur incorporation may partially block pore entrances or reduce the accessible surface area, potentially limiting adsorption performance. We refer to the report described by (Guo et al. 2024), which demonstrated that sulfur-containing surface groups play an important role in tailoring pore chemistry and improving adsorption efficiency by increasing the density of chemically active adsorption sites. This discussion has been added to better explain the relationship between sulfur content, pore chemistry, and adsorption behavior in our material.

TABLE4 (A)

CHNS Analysis for Activated Carbon

CHNS ELEMENTAL ANALYSIS					
Sr. No.	**Ratios**	**C %**	**H %**	**N %**	**S %**
1	Plastic Wrapper trash	76.60	11.38	0.15	0.94
2	Char	77.63	4.06	0.89	0.49
3	7:1	78.20	5.27	0.97	0.73

TABLE4 (B)
CHNS analysis for Spent Activated Carbon

CHNS ELEMENTAL ANALYSIS					
Sr. No.	**Ratios**	**C %**	**H %**	**N %**	**S %**
1	Without Regenerated SAC	73.45	3.12	0.59	0.56
2	5:1 SAC	79.80	2.20	0.40	0.73

Iodine Number ofActivatedCarbon

The iodine number value signifies the activation of carbon within the carbon-derived samples. Estimation of iodine number is in practice while converting the char into activated carbon. The iodine number value for the char derived from pyrolysis is observed highest value at 161.46mg/g, and without regenerated activated carbon, the highest value is at 350.18 mg/g. It has been observed that as the impregnation ratio rises, the iodine number of the AC increases. (Raut, Bedmohata, and Chaudhari 2023).

The value of iodine number for our samples having different impregnation has been shown in Table 5A & B. Increasing the impregnation ratio has resulted in an increase in iodine levels. The results imply that the optimum impregnation ratio is 7:1 while developing activated carbon by modifying the char with KOH. The iodine number increases with the ideal carbonization temperature. In the present experiment, it was found to be highest at 375ºC, with a highest value of 646.78mg/g, and for SAC 5:1, the highest value was 1152.36 mg/g. It has been found that below 350ºC, waste plastic was not fully pyrolyzed, as shown in Fig. 16 (a). Beyond 400ºC, the material was burnt completely, and ash in small quantities has been observed in Fig. 16 (b). Thus, 375ºC was considered the optimum carbonization temperature. The iodine value for SAC, with an impregnation ratio of 5:1, highest value at is 1152.36 mg/g (Ravi Verma and Choudhary 2025b).



Fig. 16 (a) Fully not pyrolyzed (b) Ash form

Iodine number determination: The iodine number of the activated carbon was determined according to ASTM D4607. Each sample was analyzed in triplicate (n = 3) under identical experimental conditions. The results are expressed as mean ± standard deviation (SD). The relative standard deviation (RSD) was calculated to evaluate the repeatability of the analytical method.

TABLE5 (A)
IodineNumber value ofactivated carbon

Plastic waste wrappers	Ratio	Weight of AC (gm)	Iodine Number value(mg/g) Replicate 1	Replicate 2	Replicate 3	Mean ± SD (mg g^{-1})	Relative Standard Deviation (RSD %)
Char	Without Impregnation	0.5	159.36	157.42	161.46	159.41 ± 2.03	1.28%
AC	3:1	0.5	498.96	503.12	494.78	498.95 ± 4.17	0.84%
AC	5:1	0.5	605.88	611.42	600.31	605.87 ± 5.56	0.92%
AC	7:1	0.5	641.52	646.78	636.94	641.75 ± 4.92	0.77%

TABLE5 (B)
IodineNumber value of Spent activated carbon (Ravi Verma and Choudhary 2025a)

Plastic waste wrappers	Ratio	Weight of AC (gm.)	Iodine Number value(mg/g) Replicate 1	Replicate 2	Replicate 3	Mean ± SD (mg g^{-1})	Relative Standard Deviation (RSD %)
Without regenerated SAC	5:1	0.5	346.72	350.18	343.65	346.85 ± 3.27	0.94%

With regenerated SAC	5:1	0.5	1140.48	1152.36	1129.74	1140.86 ± 11.32	0.99%

The activated carbon's iodine number, which indicates its adsorption ability, typically ranges from 500 to 1200 mg/g, making it an excellent adsorbent (Grassi et al. 2012).

The iodine number test was performed in triplicate under identical experimental conditions, and the results are reported as the mean ± standard deviation (SD). The low standard deviation obtained confirms the good repeatability and precision of the experimental procedure. Furthermore, we have expanded the discussion by referring to (Soleimani and Rahmani 2025) regarding the importance of replicate measurements and statistical reporting for validating adsorption characterization methods.

Regeneration Process for Spent Activated Carbon

KOH treatment effectively enhances surface area and pore accessibility, the regeneration mechanism is highly temperature-dependent, with higher temperatures promoting greater pore development and structural reorganization. The enhanced regeneration performance can be attributed to the synergistic effect of KOH activation and thermal treatment, where impurity dissolution, adsorbate decomposition, carbon matrix etching, and micropore formation collectively restore the porous architecture, leading to improved surface accessibility and adsorption efficiency (J, M S, and V 2024).

Scanning Electron Microscope (SEM)

The surface morphology of the char and activated carbon samples was investigated using SEM analysis. The SEM images were recorded at different magnification levels, and the corresponding scale bars are provided in each image to ensure accurate interpretation of pore structures and morphological features. Specifically, the char sample is shown in Fig. 17A [27 × magnification], scale bar: [1 mm], while the unimpregnated spent activated carbon (SAC) sample is presented in Fig. 17B [27× magnification], scale bar: [1 mm]. The SEM images of KOH-activated char at a 7:1 impregnation ratio are shown in Fig. 18A and B [27× magnification], scale bar: [1mm], and the commercially developed SAC morphology is presented in Fig. 18C [100× magnification], scale bar: [200 µm], and D [27× magnification], scale bar: [1 mm].

The progressive development of pores during the conversion of char into activated carbon is evident from the SEM micrographs. Compared with the raw char, KOH-activated samples exhibit a more heterogeneous surface with enlarged cavities, interconnected pores, and surface cracks, indicating the formation of additional pore channels during chemical activation. The increased porosity can be attributed to the reaction between KOH and carbon, which promotes carbon etching and the generation of new microporous and mesoporous structures. Similar SEM reporting practices, including the specification of magnification and scale information, have been followed according to the recommended protocols in previous studies (Nassar et al. 2025).

The activated carbon samples (Fig. 18A–D) showed a higher density of developed pores compared with the untreated char, confirming the effectiveness of KOH activation in improving surface accessibility. The SEM images reveal interconnected voids and irregular pore networks throughout the carbon matrix, which are favourable characteristics for adsorption applications. Among the tested samples, the 7:1 KOH-impregnated sample and SAC sample exhibited a highly porous structure, consistent with their higher iodine number values. The SAC sample prepared at a 5:1 KOH impregnation ratio showed a more developed and relatively uniform pore structure compared with the 7:1 sample, suggesting an optimum activation condition. Therefore, the enhanced pore formation and surface morphology obtained at the SAC 5:1 condition contributed to its improved adsorption performance(Ravi Verma and Choudhary 2025a).

To quantitatively support the SEM observations, pore size statistics were determined from the regenerated activated carbon. The pore size distribution confirmed the development and reopening of micropores and mesopores after KOH activation, corroborating the increase in accessible surface area and adsorption sites observed during regeneration. The regenerated carbon exhibits heterogeneous macropores with a broad size distribution, ranging from relatively small pores to much larger interconnected cavities, indicating successful pore reopening after KOH activation (Adaileh et al. 2025).

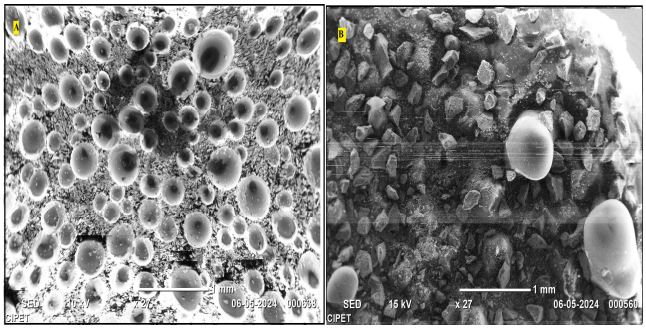


Fig. 17 SEM Analysis (A) Char (B) SAC without Impregnation

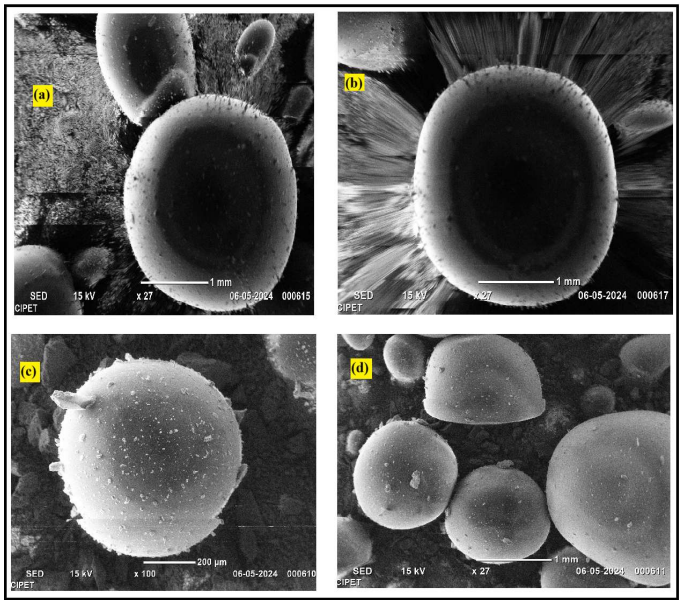


Fig. 18 SEM Analysis (A, B) 7:1 Impregnated with KOH (C, D) 5:1 SAC Impregnated with KOH

FourierTransformInfraredSpectroscopy(FT-IR)

FT-IR analysis was carried out for two different carbon samples: 7:1 KOH-impregnated activated carbon and 5:1 KOH-regenerated spent activated carbon (SAC). The SAC sample was treated with KOH at a 5:1 impregnation ratio to investigate the modification of surface functional groups and compare the chemical characteristics with the prepared activated carbon. The FT-IR spectra revealed several characteristic bands associated with oxygen-, nitrogen-, and carbon-containing surface functionalities. The vibrational assignments were verified by comparison with reported standard FT-IR spectra and previous studies on activated carbon materials (Balpreet Kaur, Gupta, and Bhunia 2019). The absorption bands observed in the range of 1100–1300 cm^{-1} were assigned to C–O stretching vibrations associated with ether, ester, and phenolic groups. The bands appearing at approximately 1434 and 1585 cm^{-1} correspond to aromatic skeletal C=C stretching vibrations, indicating the presence of condensed aromatic carbon structures. The peaks observed at 2846 and 2883 cm^{-1} were attributed to C–H stretching vibrations of aliphatic structures and overlapping O–H stretching vibrations associated with carboxylic groups. A broad band near 3400 cm^{-1} was assigned to O–H stretching vibrations of hydroxyl groups, confirming the hydrophilic nature of both carbon samples due to the presence of oxygen-containing functional groups(Nandiyanto, Oktiani, and Ragadhita 2019). A weak band around 3787 cm^{-1} observed only in the SAC sample was attributed to N–H stretching vibrations of amine/amide functionalities, suggesting the retention of nitrogen-containing surface groups after regeneration. The 7:1 KOH-activated carbon exhibited additional changes in FT-IR peak intensity compared with regenerated SAC, indicating the modification of surface chemistry during chemical activation. The peak near 1238 cm^{-1} was assigned to C–N stretching vibrations, indicating the presence of nitrogen-containing groups, while the band around 1369 cm^{-1} was associated with C–F stretching vibrations. The absorption band near 1700 cm^{-1} was attributed to C=O stretching vibrations of carbonyl/carboxyl groups and conjugated aldehyde structures.

Overall, the FT-IR spectra demonstrate that KOH activation modifies the surface functional groups by promoting the development of oxygen-containing active sites and altering the carbon framework. The regenerated SAC sample retained similar inherited functional groups compared with the prepared activated carbon, indicating that KOH treatment effectively restored surface functionality. The identified functional groups are consistent with previously reported activated carbon materials and the assignments described in the literature. These surface functionalities may contribute to enhanced adsorption through surface interactions with target molecules (Ragab, Mettwally, et al. 2024). Figure 19 presents the FT-IR spectra of the investigated samples.

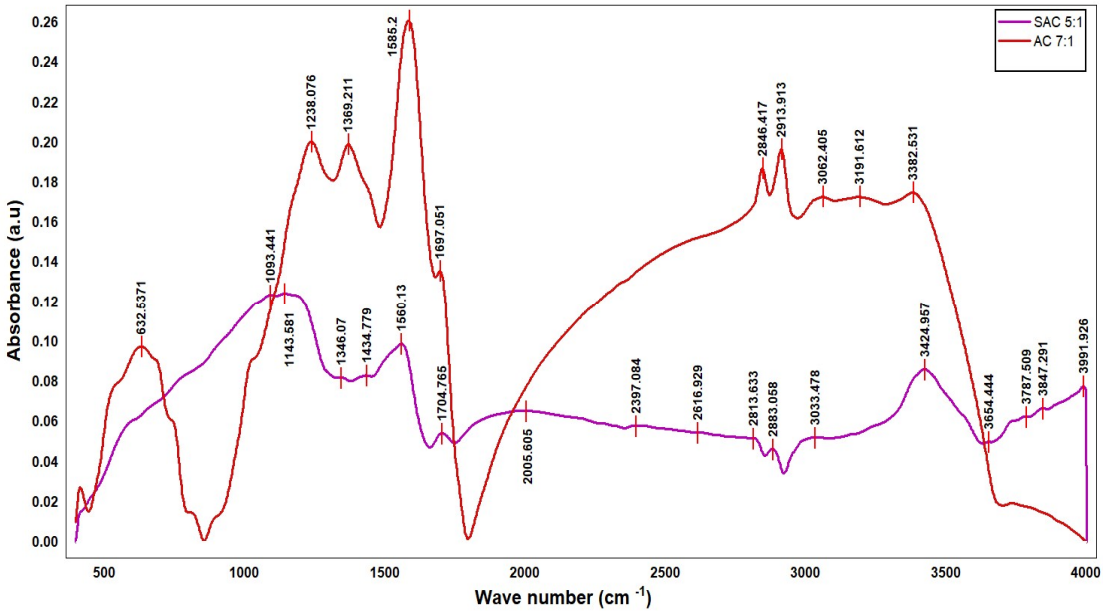


Fig. 19 FT-IR spectra of sample 7:1 Ratio (KOH/CHAR) activated carbon & 5:1 Ratio (SAC)

Application of Activated Carbon

The prepared activated carbon exhibits promising potential for wastewater treatment applications due to its developed porous structure, high iodine number, and abundant surface functional groups. Activated carbon materials have been widely investigated for the removal of various contaminants, including heavy metals and organic dyes. For example, reported activated carbon adsorbents have demonstrated high adsorption capacities toward heavy metal ions such as Pb^{2+}, Cd^{2+}, and Cr (VI), where adsorption is mainly governed by surface complexation, electrostatic attraction, and ion exchange mechanisms. Similarly, carbon-based adsorbents have shown effective removal of dyes such as methylene blue due to their high surface area and developed microporous/mesoporous networks (Elfiky et al. 2023). highlight the importance of pore structure and surface functional groups in improving adsorption efficiency for emerging water pollutants. In the present study, the enhanced pore development after KOH activation, together with oxygen-containing functional groups identified by FT-IR analysis, suggests that the prepared activated carbon can provide abundant adsorption sites and favorable interactions for pollutant removal. Therefore, the developed activated carbon has potential for application in wastewater purification and environmental remediation(Hussin et al. 2021).

- Simple process to capture carbon dioxide (CO_2) from the environment. Activated carbon is used with a filter for gas purification to remove odour, dust, and other hydrocarbons who present in the air (Jiang et al. 2019).
- The medical sector also uses activated carbon to treat poisonings. In many countries, activated carbonintheformofcapsulesortabletsisusedforMedicinal purposes.Heavy metals like Fe, Cu, Pb, and Zn are absorbed by the activated carbon and Pb was dominantly absorbed (Puspitasari et al. 2020).
- Foodand alcoholic beverage areasalso use activated carbonfilters to filter organic impuritiesfromwhiskeyandvodkatoremoveundesiredcompo nentslikeodor,colour,taste,and manymore (Chaemsanit, Matan, and Matan 2018).
- Activated carbon is a highly ecologically friendly adsorbent frequently used in wastewater treatment. In recent years, pyrolyzed plastic-based char and activated carbon have emerged as the dominant options as adsorbents for purifying wastewater. Activated carbon's capacity to remove colour is well acknowledged (Gupta, Bhardwaj, and Rawal 2022).
- Activated carbon is commonly used to filter chlorine water before it is deemed safe to drink (Mazhar et al. 2020).
- Air purification, water purification, and air emission in industry all use activated carbon to reduce contamination due to its excellent adsorption capacity (Ravi Verma and Choudhary 2025c).

III. Conclusion

In the present work, activated carbon from plastic waste wrappers was successfully produced by the pyrolysis process methodology, and the char yield obtained was 19% on average and the KOH/ char sample ratios 3:1, 5:1, 7:1, and 5:1. SAC - 17.86 %,17.1 %,18.05 %, and 18.24 % yield of activated carbon were observed. CHNS values validate the Carbon % present in plastic waste wrapper and char, 7:1 KOH/Char activated carbon (SAC), and spent activated carbon 5:1 KOH regenerated. It is found 76.60,77.63,78.20,73.45, 79.80 % respectively. The activated carbon was produced from char and underwent activation with a 1 N KOH solution for an

optimal period of 23 hours and at impregnation ratios of 3:1, 5:1, 7:1, and 5:1 (SAC). The highest iodine value of the 7:1 ratio is 646.78 mg/g, and for (SAC) spent activated carbon, the highest iodine value is 1152.36 mg/g. This indicates the adsorption potential and validates the formation of activated carbon. We utilized SEM analysis to determine the morphological structure of the activated carbon and to see the network of interconnected voids and pores throughout the samples. FT-IR analysis confirms the presence of stable functional group bonds. The results unambiguously reveal that activated carbon is highly effective in absorbing contaminants in water, particularly those originating from industrial effluents. The adsorption nature of activated carbon has been utilized for many important applications. These types of activated carbon may be utilized in air purification and the purification of wastewater to make it easy to remove dyes and colorants from wastewater and make water hazardless.

Spent activated carbon is better than Activated carbon produced through char by the pyrolysis process. The findings of this study demonstrate the practical potential of waste-derived activated carbons as sustainable and low-cost adsorbents for wastewater treatment, industrial effluent purification, dye removal, and air purification. In particular, the regenerated spent activated carbon, owing to its higher iodine value and carbon content, exhibited superior adsorption characteristics, indicating its greater suitability for large-scale environmental remediation applications. These results support the valorization of plastic waste and spent RO filter media within a circular economy framework and provide a promising route for developing cost-effective adsorbent materials for future water and environmental treatment technologies.

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Conflict of interest:

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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