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None-emission carbon nanomaterial derived from polystyrene plastic waste for the adsorption of carbon dioxide

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Abstract

The hydrothermal treatment of polystyrene (P.S.) in the presence of potassium hydroxide resulted in a carbon-based nanomaterial used for an efficient carbon sorbent with a pores volume of 0.068cm^3/g. The material was characterized by different techniques that showed excellent physical and chemical properties. The sorbent's CO_2 capacity at 25 °C is 3.8 mmol/g at 1 bar and 3.0 mmol/g at 0.1 bar, and it regenerates when the temperature reaches 80 ± 5 °C. As a result, this PS-derived organic carbon-related compound exhibited the potential to absorb CO_2 from high-emissions sources. The conversion of plastic waste into carbon-based materials is a promising method for reducing plastic pollution and creating new value from waste. These methods have the potential to make a significant contribution when converted at a large scale as the best sustainable method for waste management.

Keywords: Upcycling; Polystyrene waste; Non-emission; hydrothermal; Carbon nanomaterials; Carbon dioxide; Adsorption

1.0. Introduction

Polystyrene (PS) is a synthetic polymer made from styrene monomers. It is a lightweight, durable, and inexpensive material used in various products, including food packaging, insulation, and disposable utensils. PS is non-biodegradable, meaning it can take hundreds or even thousands of years to decompose in landfills. Additionally, PS waste can leach styrene chemicals into the environment, contaminating soil and water that can harm wildlife and humans. Polystyrene waste is a primary environmental concern due to its non-biodegradable nature and high production

volume. PS waste can negatively impact the environment, including Landfill pollution. PS waste accounts for a significant portion of landfill waste because it does not decompose in landfills and can take up valuable space. PS waste can enter the ocean through rivers and streams and break down into tiny microplastics, which can be ingested by marine life and enter the food chain. The production and disposal of PS waste contribute to greenhouse gas emissions and climate change. PS waste can be controlled by Reducing consumption, or consumers can choose reusable products over disposable PS products whenever possible (Kigozi, 2024). PS can be recycled, but recycling rates are low due to the poor properties of the recycled particles (Zhang et al., 2013).

PS can be recycled using a variety of methods, including mechanical recycling, chemical recycling, and energy recovery (Kigozi, 2024). Mechanical recycling is the most common method for recycling, where it is shredded and melted into pellets. Chemical recycling involves breaking down PS waste into its constituent monomers. The monomers can then make new PS or other products, such as recycled fuels. PS can also be converted into carbon nanomaterials (CNMs) using various methods, including thermal pyrolysis, catalytic pyrolysis, and hydrothermal carbonization. Thermal pyrolysis involves heating PS waste in the absence of oxygen. This process breaks down the PS into CNMs and other products. Catalytic pyrolysis is similar to thermal pyrolysis but uses a catalyst to speed up the process. Hydrothermal carbonization involves heating PS waste in a pressurized water reactor. This process breaks down the P.S. into CNMs and other products (Liang et al., 2019; Yang et al., 2015).

Several challenges are associated with recycling PS and converting it into CNMs, including contamination from food and dirt. This contamination can make recycling PS or converting it into CNMs difficult. The process of CNMs can be expensive when using organic solvents and equipment. This is due to the need for specialized equipment and the cost of energy. There is also a limited market for recycled PS and CNMs. This is because these materials are not as well-known or well-established as virgin PS (Yang et al., 2015).

Despite these challenges, a growing interest is in recycling PS and converting it into CNMs. This is due to the environmental benefits of recycling PS and the potential of CNMs made from PS to be used in a variety of applications, such as CO_2 adsorption, energy storage, electronics, and catalysis (Cui et al., 2019; Jinsong et al., 2022; Shi et al., 2019, 2020). PS recycling and converting PS into CNMs are promising technologies for addressing the problem of PS waste. As the

technology develops, PS recycling and converting PS into CNMs will likely play an increasingly important role in reducing PS waste and producing valuable materials (Ali et al., 2021; Cui et al., 2021).

Carbon nanomaterials (CNMs) have several potential applications in carbon dioxide (CO_2) storage, including adsorbents to capture CO_2 from flue gas and other industrial emissions (Jinsong et al., 2022). CNMs have a high surface area and a strong affinity for CO_2, which makes them ideal for adsorption applications. Membranes that can separate CO_2 from other gases are solid and durable and can be tailored to have specific pore sizes that allow CO_2 to pass through while blocking other gases. Catalysts convert CO_2 into other useful products, such as fuels and chemicals. CNMs are efficient and durable catalysts that can be tailored to catalyze specific reactions (Kigozi, 2024).

CO_2 adsorption and storage (CAS) is a promising technology for reducing greenhouse gas emissions. CAS involves capturing CO_2 from industrial emissions and storing it in geological formations, such as depleted oil and gas reservoirs. CAS can help to reduce greenhouse gas emissions by preventing CO_2 from entering the atmosphere. CNMs play an important role in CAS. CNMs can be adsorbents to capture CO_2 from flue gas and other industrial emissions. This allows CO_2 to be captured and stored separately, which is important for safety and environmental reasons (Algozeeb et al., 2022).

Several challenges are associated with using CNMs for CO_2 storage, including the cost that makes CNMs currently expensive to produce. This makes it difficult for CNMs to compete with other materials, such as activated carbon, commonly used for CO_2 adsorption. The low selectivity of CNMs that adsorb other gases in addition to CO_2. This can reduce the efficiency of CO_2 capture and storage. The durability of CNMs makes them degrade over time, which can reduce their performance and lifespan. Research gaps are working to address these challenges and develop more versatile materials for CO_2 storage. For example, research is needed to develop new methods for producing CNMs at a lower cost and improved structures that are more selective for CO_2 and more durable (Liang et al., 2019). Activated carbon has a highly porous structure, which makes it an effective adsorbent material. The pores in activated carbon adsorb carbon dioxide molecules from the surrounding air, effectively removing it from the atmosphere.

The effectiveness of activated carbon in carbon dioxide capture has been demonstrated in several studies, with some researchers reporting a 90% capture rate (Algozeeb et al., 2022). This makes it a cost-effective solution for carbon dioxide capture, which is important given the high costs associated with traditional carbon capture and storage methods (Robertson et al., 2023). As the demand for activated carbon increases, the supply of activated carbon from polystyrene waste can meet this demand, providing a new source of revenue for waste management companies (Yuan, Li et al., 2020).

CO_2 capture using plastic waste-activated carbon can be achieved in some ways. One standard method is to use a process called pressure swing adsorption (PSA) (Yuan, Li et al., 2020). PSA is a cyclic process that involves alternating between high-pressure and low-pressure steps. In the high-pressure step, CO_2 is adsorbed onto the activated carbon. In the low-pressure step, the CO_2 is desorbed from the activated carbon and released into a storage or disposal system (El Essawy et al., 2017). Another method for CO_2 capture using plastic waste-activated carbon is to use a process called membrane separation. (Kaur et al., 2019a; Ribeiro et al., 2022). The cost of producing plastic waste-derived activated carbon is relatively low, and the technology can easily be scalable. CO_2 capture using plastic waste-derived activated carbon is a promising technology that has the potential to make a significant contribution to the fight against climate change (Bbumba, 2024; Bbumba et al., 2025).

Preparation of the plastic waste derived from activated carbon involves some main steps: The plastic waste is typically ground into small pieces and then mixed with a solvent. The solvent helps break down the plastic waste and remove any impurities. The plastic waste is then pyrolyzed. Pyrolysis is a process that heats plastic waste without oxygen. This process causes plastic waste to break into smaller molecules, including carbon. The final process is the activation of the pyrolyzed carbon. Activation is a process that increases the surface area of the carbon. The process is done by heating the carbon in the presence of a gas, such as steam or carbon dioxide and an activation agent (Hussin et al., 2021).

For the current study, the PS-ACT Plastic waste-derived carbon was produced to capture CO_2 from the point sources. The CO_2 capture process was typically carried out in a column. The column was filled with plastic waste-derived activated carbon. The CO_2-rich gas is then passed through the column. The CO_2 is adsorbed onto the porous activated carbon. The CO_2-free gas is then released

from the column. The adsorbed CO_2 onto the derived activated carbon can be stored or used in other applications. One standard storage method is to compress the CO_2 and store it in underground reservoirs. Another standard disposal method is injecting CO_2 into deep saline aquifers (Kaur et al., 2019b). CO_2 capture using plastic waste-activated carbon is a promising method with the potential to substantially contribute to protecting climate change. The technology is still under development, but it can potentially be a cost-effective and scalable solution to the problem of CO_2 emissions.

2.0. Materials And Methods

2.1. Synthesis of PS-ACT nanocomposite

Polystyrene (P.S.) plastic waste was picked around the Department of Chemistry, Makerere University. The P.S. was ground to small particles, cleaned to remove dirt, and dried at 45 ^oC overnight. The dried P.S. particles were heated in a white oil bath with a temperature of 100±5 ^oC for 45 minutes. The used temperature range is the P.S. glass transition temperature, which makes it brittle. The heated material was separated from the oil and then crushed to powder (PS-powder). The P.S. powder was then activated using potassium hydroxide (KOH) as the activation agent with a ratio of 1:3 (P.S.: KOH) in deionized water. The solution was mixed for 3 hours, transferred into a stainless-steel autoclave with a Teflon liner, and heated in an oven at 200 ^oC for 18 hours. After that time, the autoclave was cooled, and the sample was filtered and dried at 80 ^oC for three hours. The dried powder was labelled PS-ACT carbon nanomaterial (CNM) and taken for characterization.

2.2. Characterisation of the synthesized carbon nanomaterials

The materials were characterized by different methods for physical and chemical properties, as described below. The carbon nanomaterials that were produced were examined using various characterisation techniques for different physical-chemical properties. These include Transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray fluorescence spectroscopy, X-ray diffraction (XRD), Fourier transformation infrared spectroscopy (FTIR), and kinetic adsorption (Kigozi, Kali, et al., 2020);

a) Fourier Transformation Infrared (FTIR) spectroscopy

The surface functional groups of CNMs samples were analysed by Fourier Transformation InfraRed (FTIR) spectroscopy (Bruker Optik GmbH Vertex 70, Germany) and was scanned through a range of 600 – 4000 cm^{-1} (Turku et al., 2017)

b) Field emission scanning electron microscope (FESEM)

The morphological characterization was done with the Field Emission Scanning Electron Microscope (FESEM) 9GeminiSEM 500M/s Carl ZEISS-EDAX Z2 Analyser AMETEK). The magnification of the samples was done at different depth and power.

c) X-ray diffraction

The crystal structure of the CNMs powder samples was examined by the X-ray diffraction (Riguku Smartlab Auto sampler) using a Cu kα radiation with the International Centre for Diffraction Data (ICDD) database. The sample powders were scanned through a 2θ angel between 5 to 90 degrees (Singh et al., 2017).

d) Ultra-violent visible spectroscopy

The carbon samples were first dispersed in tetrahydrofuran solvent (0.5 mg/ml) and sonicated for 30 min. Each sample was individually scanned between 180 and 800 nm for the spectrum. (Shafeeyan et al., 2010)(Elmouwahidi et al., 2017).

e) Raman spectroscopy analysis

The Renishaw inVia Raman microscope from Renishaw plc Watton-under Edge Gloucestershire United Kingdom, with a fixed excitation wavelength of 514 nm, was used with an exposure time of 10s, laser power of 1%, accumulative scan of 10, and objective of X20 to examine the surface composition and structure of PS-ACT material (Kigozi, Kasozi, et al., 2023; Kigozi, Tebandeke, et al., 2023).

f) Thermogravimetric analysis (TGA)

(TGA) was executed on CNM samples using a TGA-DSC analyser (Jupitor STA449 F3 NTZSCH GmbH). The samples were heated in pure air at a flow rate of 10 cm^3/min from room temperature to 1000^oC with ramp temperature of 10 ^oC/min with a run time of 1 hour and 40 minutes using calcinated silica pan as reference material (Lim et al., 2010)(Van et al., 2014)(Lijuan et al., 2017).

g) Brunaver-Emmett-Teller (BET) analysis for specific surface area

The Nitrogen Adsorption/desorption isotherms were determined based on the 77K automated adsorption instrument (11-2370. Gemini Miceomeritics USA). The CNM samples were preheated at 90oC (ramp 10oC/min) and degassed at 300C in a vacuum with a holding time of 10 hours. The Nitrogen adsorption isothermal was measured over (P/Po) relative pressure, and the BET surface area (SBET) was calculated by the BET (Brunaver-Emmett-Teller) equation with adsorption data (Van et al., 2014). The micropore volume (V_{mic}), microporous surface area (S_{mic}) and external

surface area (S_{ext}) were obtained from the t-plot method (Van et al., 2014). The mesopore volume (V_{mes}) was acquired by the BJH (Barrett-Joyner-Halenda) method (Ghosh et al., 2019)(Van et al., 2014), and the total pore volume (V_{tot}) estimated from the sum of mesoporous volume (V_{mes}) and microporous volume (V_{mic}). With some assumption, the mean pore radius rmp was determined from the total pore volume and SBET.

2.3. Adsorption-desorption experiments of CO_2 with PS-ACT

The adsorption-desorption of CO_2 with PS-ACT was evaluated in a closed system. The apparatus contains a U-type glass column having a total stretch of 52 cm and a diameter of 1.2 cm. The inlet and outlet CO2 concentrations were measured by a Horiba infrared gas analyzer calibrated immediately before the test. The sample holder was loaded with 1 g of PS-ACT material, and a vacuum at 200 ^{o}C was created for two hours before supplying the flue gas in the system, which operated for 8 hours. The dynamic adsorption capability was measured using a gas mixture of 15% CO_2 and 85% N_2. The composition mixture is a standard model in industrial effluent power plants. The adsorption-desorption measurements were achieved at 25, 60, and 80 °C and with varying pressure from zero to 1.0 bar. The gas adsorption in millimole (mmol) was recorded at increasing pressure and fixed temperature. Similar conditions were also simulated (Kadi et al., 2020).

3.0. Results and discussion

3.1. PS-ACT material characterization

The PS-ACT material was characterized by different techniques to assess its physical and chemical properties. The FTIR analysis was carried out to determine the material's surface functional groups. As shown in Figure 1, different peaks for both the P.S. powder and PS-ACT samples can be observed. The fingerprint region of both materials exhibited rock vibration below 1000 cm^{-1} with C-C and C-O stretches between 1000 and 1500 cm^{-1}. The peaks are similar to those reported in the literature (Yaglikci et al., 2020). The diagnostic region of the spectra showed single bond stretches of C-H around 2900 cm^{-1} for the PS-ACT and P.S. powder samples. The P.S. powder also exhibited some stretch of the O.H. functional group at around 3890 cm^{-1} due to white oil interaction in the plastic pretreatment process.

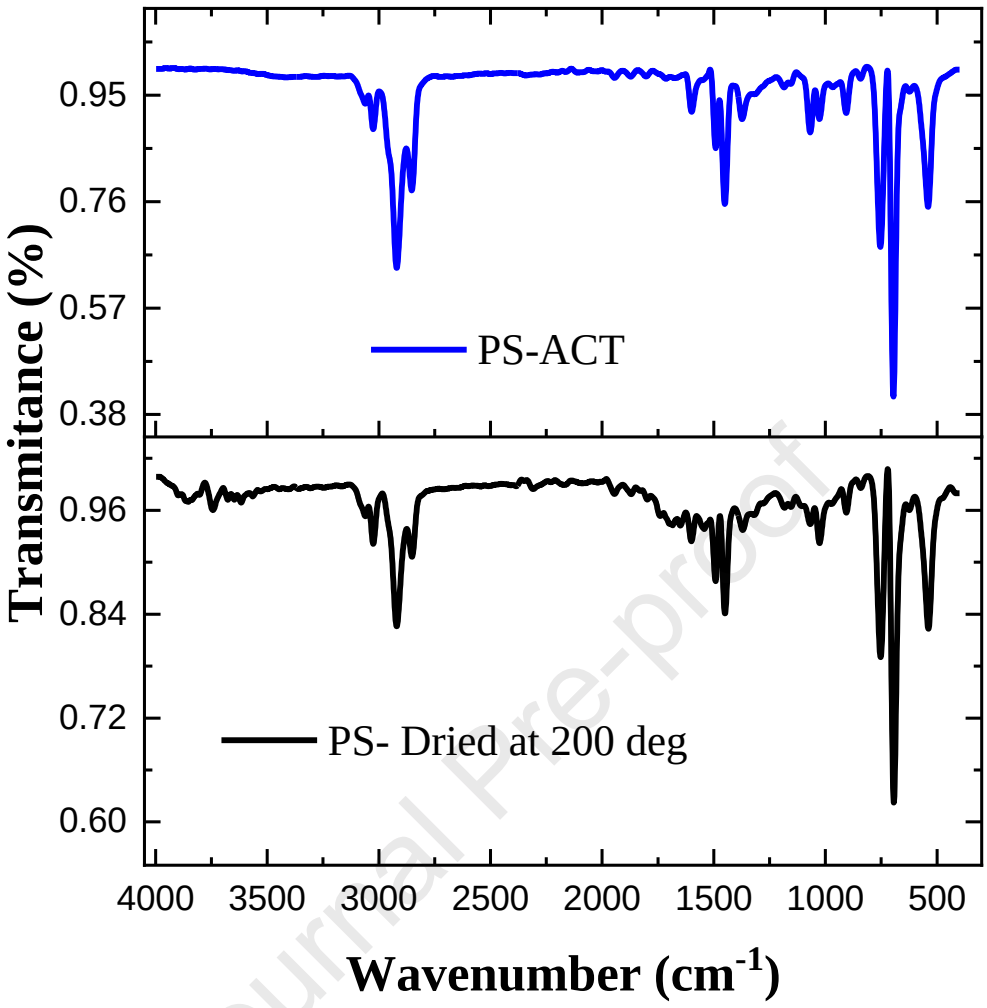


Figure 1: FTIR analysis of PS-ACT and P.S. powder materials

The UV-visible analysis of the PS-ACT material showed some transition of C-C and C-O bonds at lower wavelengths up to 300 nm. The transition with the C-C aromatic identifier corresponds to the π-π^* in the aromatic ring. The C-O transition corresponds to the n-π^* identification in the material structure, as shown in Figure 2. The Raman spectrum of the PS-ACT-activated material is shown in Figure 3. The analysis exhibited the D and G peaks at 1369.6 and 1563.3 $cm^{-1,}$ indicating disordered and graphitic carbon, respectively. The peaks contributed to the I_D/I_G band ratio of 0.84 and a 2D peak at 1848.8 cm^{-1}. The ratio of 0.84 indicates graphitized carbon with predominant crystalline carbon. This result is reported in the graphite carbon materials (Kigozi, Koech, et al., 2020).

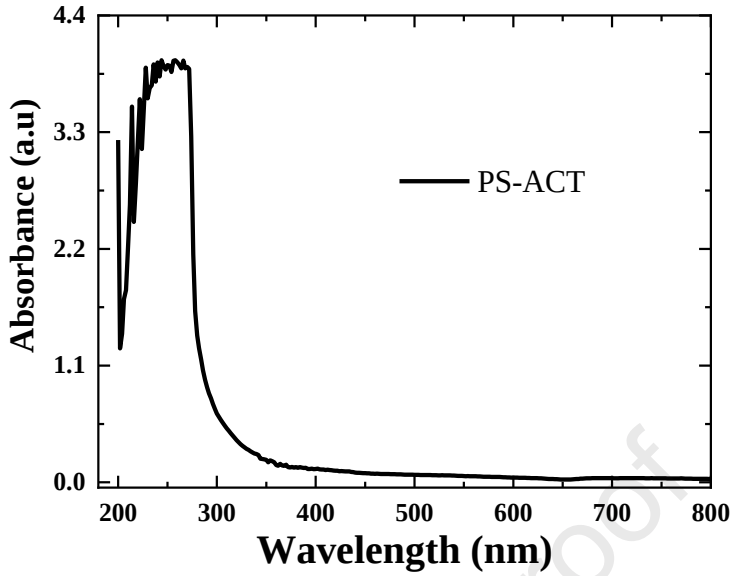


Figure 2: UV-visible spectrum of PS-ACT-activated material

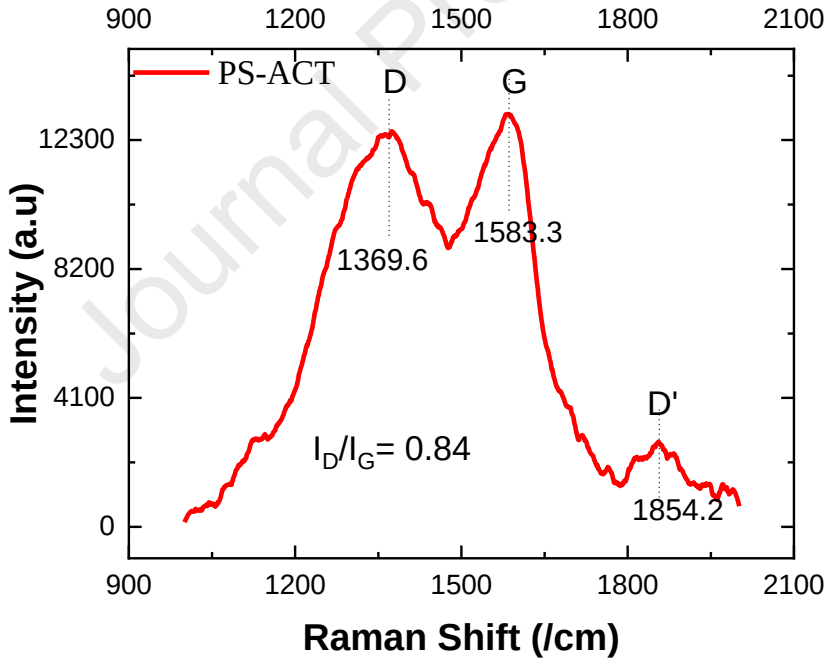


Figure 3: Raman Spectroscopy analysis of PS-ACT-activated material

The XRD analysis of PS-ACT material, as shown in Figure 4, exhibited vast, broad peaks at 2θ positions of 21.6 and 43.3°, corresponding to the (002) and (110) crystallographic planes of carbon-based material. These peaks indicate the amorphous nature of the material of PS-ACT. The peak

formation corresponds well with the one reported in the literature for amorphous and porous carbon (Kigozi, Kali et al., 2020).

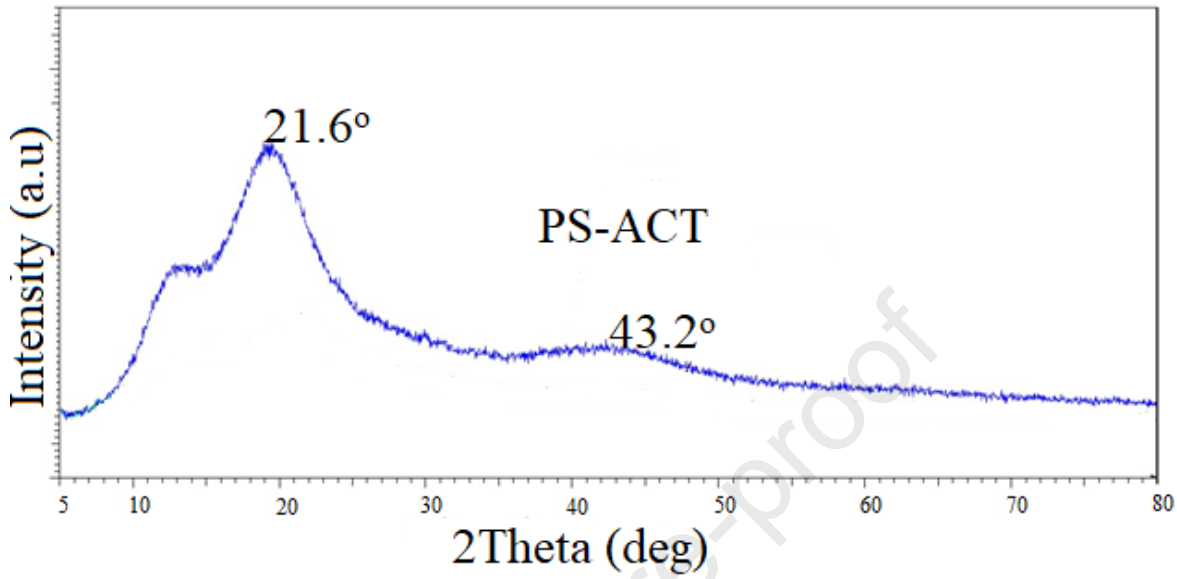


Figure 4: XRD analysis of PS-ACT-activated material

The SEM-EDX analysis was conducted to study the material's morphology and composition. The SEM monography of the PS-ACT-activated material, depicted in Figure 5, reveals the material structure's amorphous side with a degree of crystallinity. The material exhibited particles in some planes with pores and plain planes with more prominent pores, as shown in Figure 5(a & b) at 1µm magnification. The EDX analysis (Figure 6) revealed that the material composition mainly contains approximately 96% carbon, 3.4% oxygen, and traces of silica and sulphur as impurities. The impurities may have resulted from additives in the P.S. plastic material to impart some properties for the stability of the plastic. The high carbon percentage in the material matrix confirms a carbon-based material formation. The material is in close agreement with the composition of activated carbon material in the literature (Kigozi, Richard K et al., 2023).

TEM analysis was performed at different magnifications for the high in-depth material structure analysis, as shown in Figure 6. The use of 100 nm magnification, the PS-ACT material revealed that there were some networked fibres within the material. At 50 nm magnification, there is evidence of the nanofiber being surrounded with nanoparticles throughout the material, as shown in Figure 7 (a & b) show the material structure as also reported in the literature of carbonaceous materials from plastic-forming fibres and carbon nanotubes (Kumari et al., 2022).

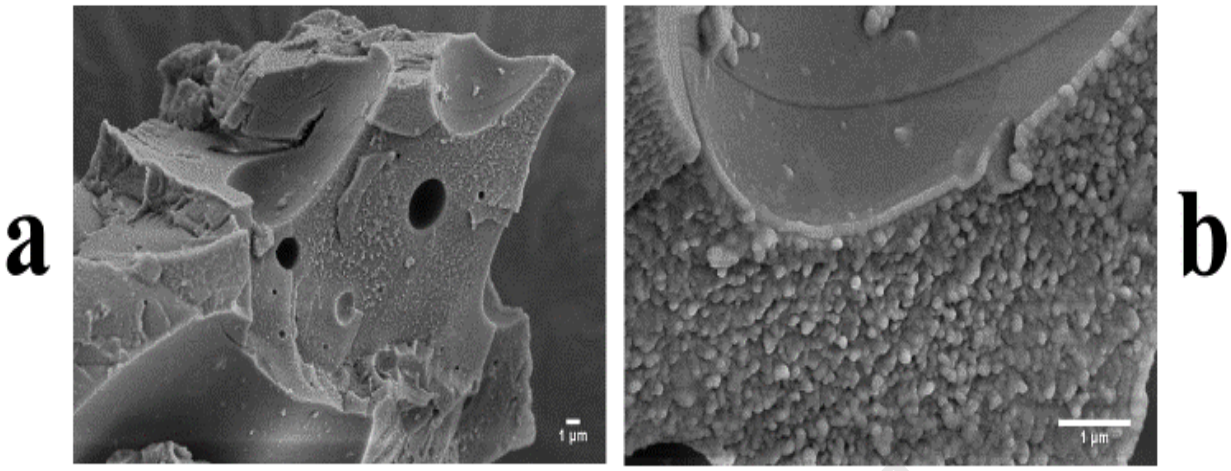
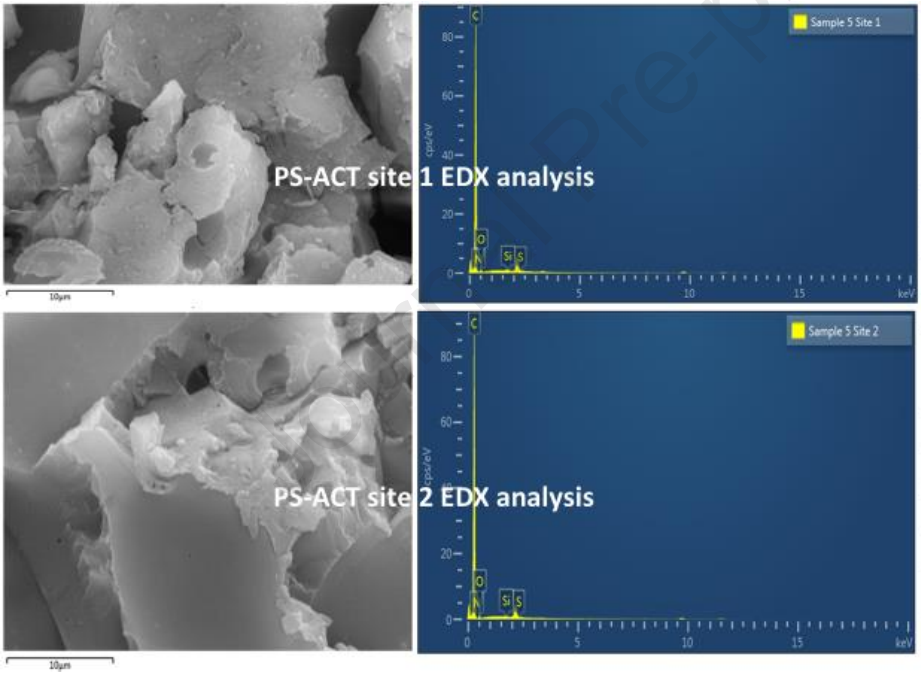


Figure 5: FESEM Analysis PS-ACT with 1um (a) 10.0KX, (b) 50.0KX magnification, respectively.



PS-ACT Site 1	Wt%	Wt% Sigma
C	95.95	0.25
N	0.00	1.85
O	3.99	0.24
Si	0.05	0.02
S	0.02	0.03
Total	100.00	

PS-ACT Site 2	Wt%	Wt% Sigma
C	96.64	0.22
N	0.00	1.75
O	3.35	0.22
Si	0.02	0.02
S	0.00	0.03
Total	100.00	

Figure 6: EDX composition analysis of PS-ACT-activated material

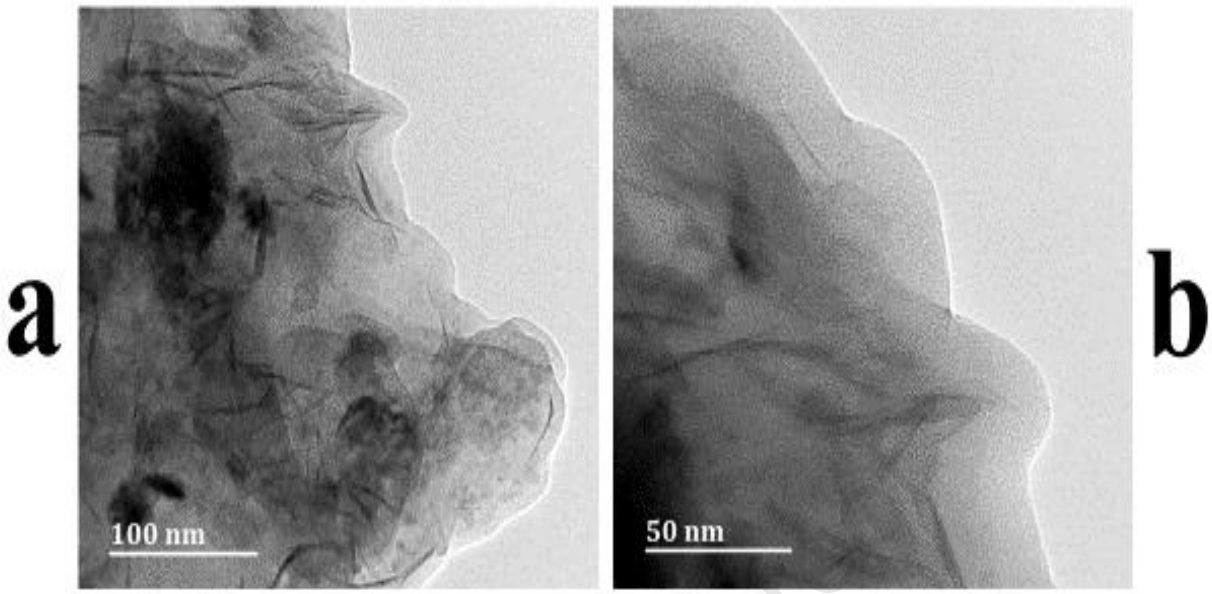


Figure 7: HRTEM Analysis PS-ACT with (a) 100nm, (b) 50nm scale, respectively

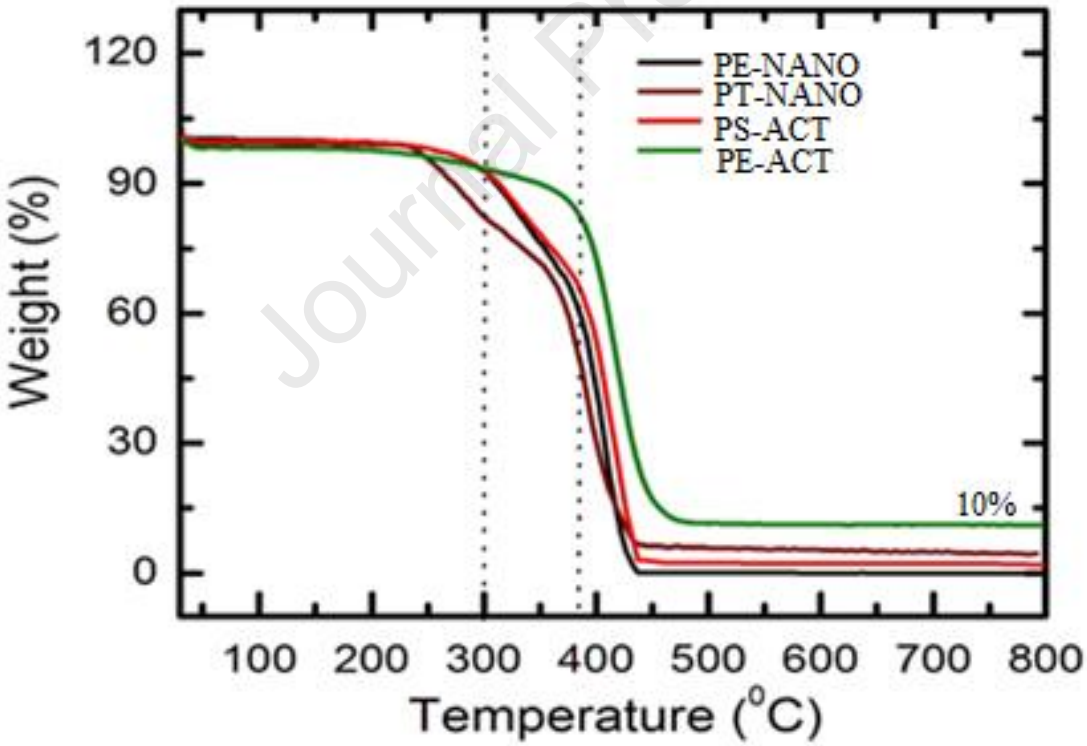


Figure 8: Thermal gravimetric analyzer (TGA) analysis for PE-ACT in comparison with other plastic-derived carbon nanomaterials

The converted plastic-activated CNM material (PS-ACT) was examined for thermal stability using thermogravimetric analysis (TGA) in comparison with other plastic-derived carbon materials. The current study sample showed up to 300 ^{o}C stability, as revealed in Figure 8. The material was compared with the previously handled plastic materials for stability (Kigozi, et al., 2023) This means that the materials can be used for applications where the temperature does not exceed 250 ^{o}C, including building and construction.

The synthesized sample of CNMs was also evaluated for the specific surface area (SSA) and pore volume from BET analysis, as shown in Figure 9 and Table 1. The PS-ACT sample exhibited an SSA of 323.57 m^2/g and pore volumes of 0.680 cm^3/g. The literature shows that narrow micropores enhance the adsorption energy of the material (Cui et al., 2021; Mu et al., 2021; Shi et al., 2019). The adsorption behaviours of the PS-ACT are exhibited in Figure 9, with high activity at higher relative pressure. The lower pore volume helps the material capture the CO_2 without escaping hence, high surface adsorption interaction.

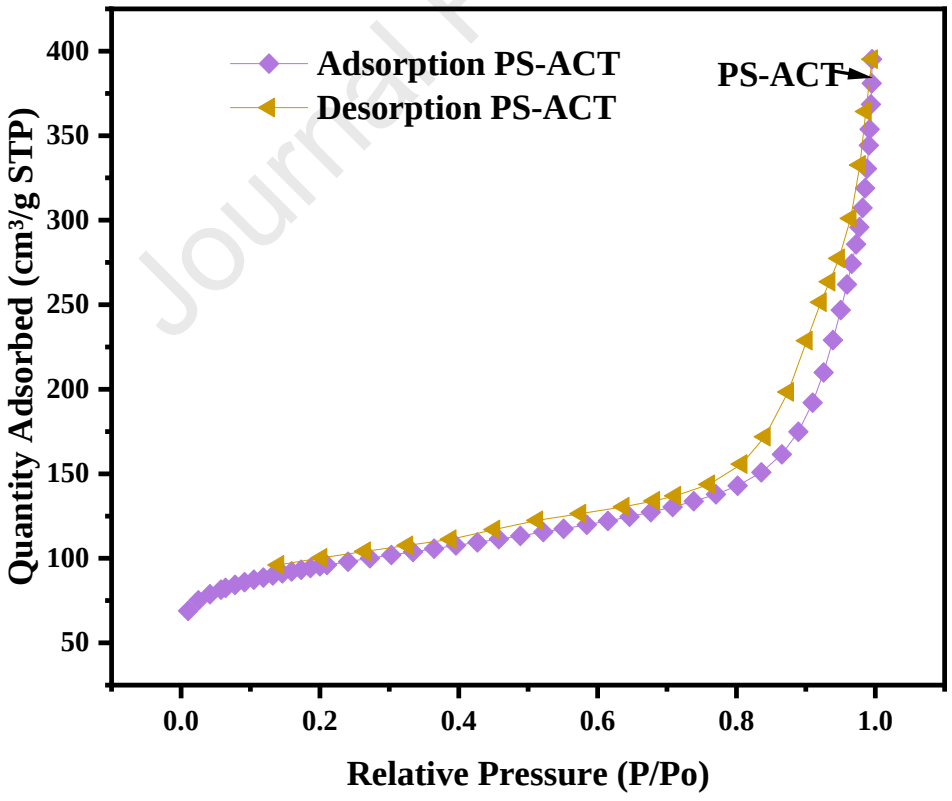


Figure 9: BET analysis of PS-ACT carbon material with sorption isothermal of N_2 at 77K

Table 1: The BET physical properties of the PS-ACT carbon nanomaterials

Sample	BET SSA (m^2/g)	Pore Volume (cm^3/g)	Pore diameter (nm)
PS-ACT	323.57	0.680	9.0

3.2. CO_2 adsorption evaluation with PS-ACT-activated material

Figure 10 exhibited the results of carbon dioxide dynamic adsorption experiments for the sample under the flue gas's 40 mL/min flow rate at 25°C, 60 ºC and 80 ºC. In general, the curves indicate the achievement of the mass transfer resistance phenomenon as the CO_2 being adsorbed (Kadi et al., 2020). The plots from the adsorption-desorption system exhibited good adsorption activity at 25ºC, even at a lower pressure, as shown in Table 2. When the temperature was increased, there was an exhibition of lower performance at lower pressures. The PS-ACT material revealed that the adsorption behaviour increased with the uptake of CO_2 at elevated pressure. The temperature change exhibited a change in the adsorption of CO_2. The increase in temperature at a fixed pressure showed a decrease in CO_2 adsorption, as indicated in Table 2, which may be due to gas expansion or a reduction in the material's pore volume. The kinetic simulation of the CO_2 uptake was done using the BJH Adsorption (Halsey: FAAS Correction) model that fitted the lines shown in Figure 10. The simulation fitted well with the experimental results. This indicates that the optimum condition for CO_2 adsorption was 25ºC with 0.1 bar of pressure (Robertson et al., 2023).

The PS-ACT sample was evaluated for CO_2 adsorption due to its lower SSA of 323.57m2/g and narrow pore volume of 0.068 cm /g, as shown in Figure 9 and Table 1. These are the main properties of CO_2 adsorption. Most materials are not used for CO_2 adsorption due to their larger pore volume and high SSA, and the behaviours of the material with the adsorption-desorption isothermal are based on the side of CO_2 molecular size. The PS-ACT proved to have a Better isothermal character for adsorption at increasing relative pressure with distinct histolysis loops, as shown in Figure 9. The CO_2 adsorption was studied at different temperatures with variable pressure from 0.1 to 1.0 bars. The results from the study are close to different literature using different materials with higher SSA. Liang et al., 2021 reported the adsorption of CO2 with the activated carbon with SSA of 831 to 1158 m2/g, showing a range of 4.34 to 5.42 mmol/g. Yeh et al., 2001 reported desorption-adsorption in the range of 1.15 to 2.65 mmol/s through porous material of 300 m_2/g (Mu et al., 2021; Yeh et al., 2001). The current material exhibited a good adsorption capacity and selectivity for CO_2. Compared to the literature.

Table 2: **CO_2 adsorption at different temperatures and varying pressures**

Temp (°C)	Adsorption of CO_2 (mmol/g)		
	0.1 bar	**0.5 bar**	**1.0 bar**
25	3.0	3.4	3.8
60	0.05	3.2	3.6
80	0.05	0.15	3.4

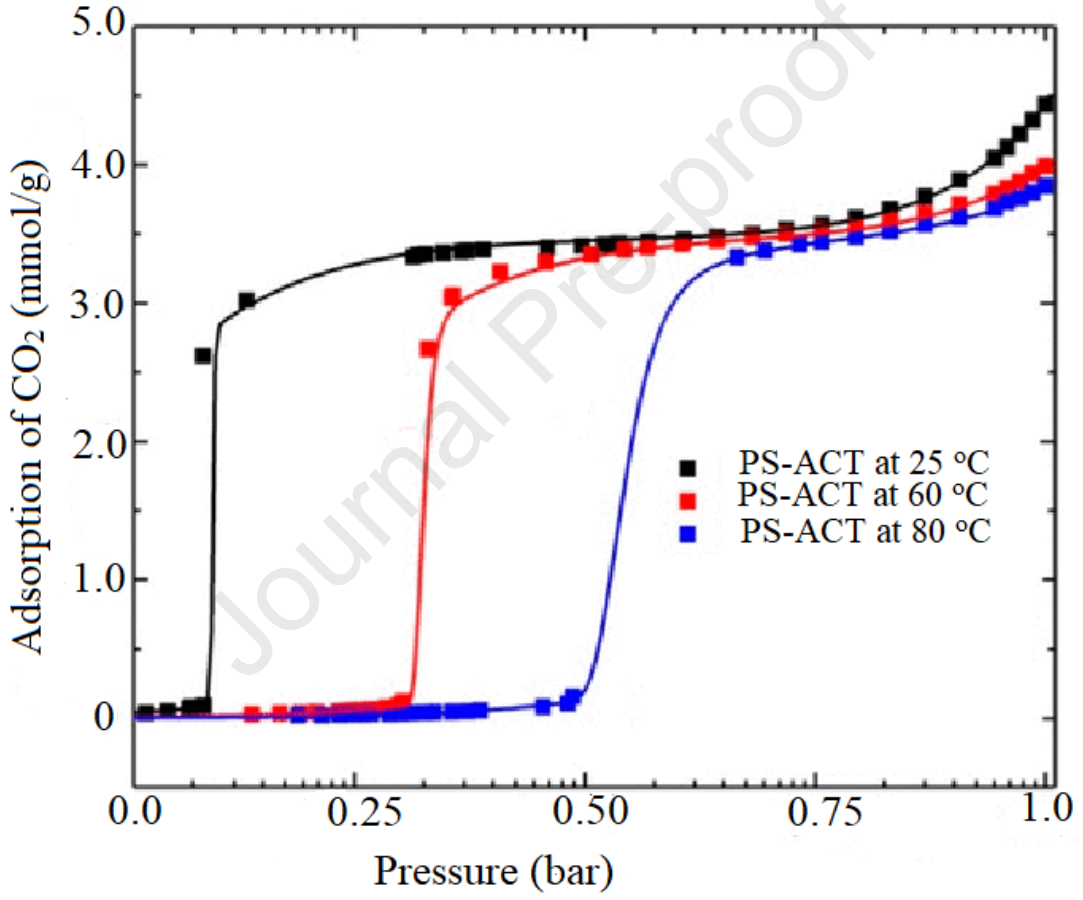


Figure 10: Carbon dioxide dynamic adsorption-desorption experiments

Adsorption selectivity of the materials with strong CO_2 affinity. Materials exhibited polar surfaces chemically interacting with CO_2, indicating higher selectivity at lower temperatures. The materials also exhibited very small pores (micropores) that can exhibit high selectivity due to size exclusion effects. CO2 molecules can fit into the pores, while larger molecules cannot. This means the material showed better selectivity at lower temperatures, as shown in the adsorption Table 2.

3.3. Alternative uses of impregnated carbon nanomaterials with CO_2

Captured CO_2-carbon-based loaded materials, also known as CO_2-CNM, offer exciting possibilities beyond just storing the captured greenhouse gas. This can be used in several applications, including;

The materials can act as a platform for converting captured CO_2 into valuable fuels or chemicals. This is done by introducing catalysts onto the surface of the loaded carbon to transform CO_2 into methanol, ethanol, or even synthetic natural gas. The materials can also be used to produce Carbon fibre precursors (Kumari et al., 2022). High-quality carbon fibres are essential for various applications, and CO_2-CNM can potentially be a precursor material for these fibres. The captured CO_2 can be chemically transformed to create strong, lightweight carbon fibres. CO_2-CNM can be incorporated into building materials like concrete or bricks for Reinforcement in building materials. The loaded carbon can enhance the strength and durability of these materials while also providing a method for CO_2 sequestration (Ahmadinia et al., 2012).

The impregnated activated carbon, CO_2-CNM, can be used in building air filters and is absorbent for indoor air quality. The loaded carbon can capture indoor air pollutants alongside CO_2, improving air quality. CO_2-CNM materials can enhance its capacitance of energy storage. By utilizing the captured CO_2 and the properties of carbon nanomaterial, these materials could potentially be used in supercapacitors for efficient energy storage applications (Lian et al., 2019). The loaded carbon in CO_2-CNM materials can support various catalysts used in chemical reactions. This could lead to the development of more efficient and sustainable catalysts, especially when combined with the captured CO_2 molecules for specific reactions. CO_2-CNM can potentially be used to separate valuable gases from mixtures as adsorbents for gas separation. The captured CO_2 within the material could influence its adsorption properties towards other gases, allowing for targeted separation processes (Robertson et al., 2022).

Different Studies suggest that CO_2-CNM can improve soil properties by increasing water retention and nutrient availability (Yuan et al., 2022). This could benefit agriculture by promoting plant growth and sustainably improving crop yields. It's important to note that these are emerging applications, and further research is needed to optimize the properties of CO_2-CNM for specific

uses. However, the potential for transforming captured CO_2 into a valuable resource for various applications holds significant promise for a more sustainable future.

Conclusion

The polystyrene (P.S.) waste was converted was activated using KOH as the activating agent to produce the PS CNM material. The CNM from PS waste was used in carbon dioxide adsorption. The PS-ACT material was characterised by different techniques, including UV-Vis, Raman spectroscopy, FTIR, XRD, FESEM, and TEM. The FTIR revealed surface functional groups like C-C, C-O, and O-H. The Raman analysis resulted in a ratio of I_D/I_G of 0.95, indicating graphitized carbon materials structure. The XRD exhibited two broad peaks of amorphous carbon arrangement, and the EDX results showed a 96% carbon content in the material. The in-depth analysis using TEM indicated nanofiber grains surrounded by nanoparticles. The PS-ACT material was used for CO_2 adsorption with varying temperatures and pressures. The 25 ^oC with 0.1 bar adsorbed 3.0mmol/g, and there was an increase in adsorption with an increase in pressure. At 1.0bars, the adsorption was up to 3.8mmol/g at 25 ^oC. The increase in temperature at constant pressure showed a reduction in adsorption, and the increase in pressure at constant temperature exhibited a slight increase in adsorption. By converting polystyrene waste into activated carbon, we effectively used it to adsorb carbon dioxide from the point source or glue gases and provide a cost-effective carbon capture and storage solution. CNMs can be used as adsorbents, membranes, and catalysts for CO_2 capture and storage (CAS). CAS is a promising technology for reducing greenhouse gas emissions, and CNMs play an important role in CAS. As the technology continues to develop, CNMs are likely to play an increasingly important role in CO_2 capture and storage. This will help to reduce greenhouse gas emissions and mitigate the effects of climate change. With further research and development, this technology has the potential to become a vital tool in the fight against climate change.

Declaration of competing interests

- The authors state that no interests are at odds with the research work.

Availability of data and materials

- This article has all the data created or evaluated during this investigation.

Competing Interests

Authors disclose that there are no financial interests that are directly or indirectly related to the work submitted for publication

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Authors' contributions

The experiments were created, planned, and directed by GNK, ET, and. MK IK, SB PK conducted the research and created the first draught after conducting synthesis and Characterisation studies. The final draught of the book was reviewed by all the authors, who also approved it.

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References

Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Ahmadinia, E. (2012). Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. *Construction and Building Materials*, *36*, 984–989. https://doi.org/10.1016/J.CONBUILDMAT.2012.06.015

Algozeeb, W. A., Savas, P. E., Yuan, Z., Wang, Z., Kittrell, C., Hall, J. N., Chen, W., Bollini, P., & Tour, J. M. (2022). Plastic Waste Product Captures Carbon Dioxide in Nanometer Pores. *ACS Nano*, *16*, 7284–7290. https://doi.org/10.1021/acsnano.2c00955

Ali, S. S., Elsamahy, T., Koutra, E., Kornaros, M., El-Sheekh, M., Abdelkarim, E. A., Zhu, D., & Sun, J. (2021). Degradation of conventional plastic wastes in the environment: A review on current status of knowledge and future perspectives of disposal. *Science of The Total Environment*, *771*, 144719. https://doi.org/10.1016/J.SCITOTENV.2020.144719

Bbumba, S. (2024). An Insight into Isotherm Models in Physical Characterization of Adsorption Studies. *Advances in Image and Video Processing*, *12*(2). https://doi.org/10.14738/aivp.122.16738

Bbumba, S., Kigozi, M., Karume, I., Tochukwu, C., Murungi, M., Mary, P., & Kirabo, S. (2025). Prediction and Optimization of Process Parameters using Artificial Intelligence and Machine Learning Models. *Asian Journal of Applied Chemistry Research Volume*, *16*(1), 11–33. https://doi.org/10.9734/ajacr/2025/v16i1317

Cui, H., Xu, J., Shi, J., Yan, N., & Liu, Y. (2019). Facile fabrication of nitrogen doped carbon from filter paper for CO2 adsorption. *Energy*, *187*(115936), 1–6. https://doi.org/10.1016/j.energy.2019.115936

Cui, H., Xu, J., Shi, J., You, S., Zhang, C., Yan, N., Liu, Y., & Chen, G. (2021). Evaluation of different potassium salts as activators for hierarchically porous carbons and their applications in CO2 adsorption. *Journal of Colloid and Interface Science*, *583*, 40–49. https://doi.org/10.1016/j.jcis.2020.09.022

El Essawy, N. A., Konsowa, A. H., Elnouby, M., & Farag, H. A. (2017). A novel one-step synthesis for carbon-based nanomaterials from polyethylene terephthalate (PET) bottles waste. *Journal of the Air and Waste Management Association*, *67*(3), 358–370. https://doi.org/10.1080/10962247.2016.1242517

Elmouwahidi, A., Esther, B.-G., Agustin, F. P.-C., Francisco, J. M.-H., & Francisco, C.-M. (2017). Activated carbons from KOH and H3PO4-activation of olive residues and its application as supercapacitor electrodes. *Electrochimica Acta*, *229*, 219–228. https://doi.org/10.1016/j.electacta.2017.01.152

Hussin, F., Aroua, M. K., Kassim, M. A., Fazara, U., Ali, M., Hussin, C. :, Aroua, F. ;, Kassim, M. K. ;, & Ali, M. A. ; (2021). Transforming Plastic Waste into Porous Carbon for Capturing Carbon Dioxide: A Review. *Energies 2021, Vol. 14, Page 8421*, *14*(24), 8421. https://doi.org/10.3390/EN14248421

Jinsong, S., Cui, H., Xu, J., & Yan, N. (2022). Carbon spheres synthesized from KHCO3 activation of glucose derived hydrochar with excellent CO2 capture capabilities at both low and high pressures,. *Separation and Purification Technology*, *294*(121193). https://doi.org/10.1016/j.seppur.2022.121193

Kadi, M. W., Salam, H. M. A. El, Zaki, T., & Reda, M. (2020). Adsorption of carbon dioxide on Cu x Mg y (BTC) 2 MOFs : influence of Cu / Mg ratio. *J Nanopart Res*, *22*(143), 1–15. https://doi.org/10.1007/s11051-020-4855-1

Kaur, B., Gupta, R. K., & Bhunia, H. (2019a). Chemically activated nanoporous carbon adsorbents from waste plastic for CO2 capture: Breakthrough adsorption study. *Microporous and Mesoporous Materials*, *282*(February), 146–158. https://doi.org/10.1016/j.micromeso.2019.03.025

Kaur, B., Gupta, R. K., & Bhunia, H. (2019b). Chemically activated nanoporous carbon adsorbents from waste plastic for CO2 capture: Breakthrough adsorption study. *Microporous and Mesoporous Materials*, *282*, 146–158. https://doi.org/10.1016/J.MICROMESO.2019.03.025

Kigozi, M. (2024). CONVERSION OF SELECTED PLASTIC WASTE INTO CARBON NANOMATERIALS FOR APPLICATION IN THE ADSORPTION OF CARBON DIOXIDE AND ENERGY STORAGE [Makerere University]. In *Makerere University*

Library. http://makir.mak.ac.ug/handle/10570/13269

Kigozi, M., Kali, R., Bello, A., Padya, B., Kalu-uka, G. M., Wasswa, J., Jain, P. K., Onwualu, P. A., & Dzade, N. Y. (2020). Modified Activation Process for Supercapacitor Electrode Materials from African Maize Cob. *Materials*, *13*(5412), 1–21. https://doi.org/10.3390/ma13235412

Kigozi, M., Kasozi, G. N., Mohite, S. B., Zamisa, S., Karpoormath, R., Kirabira, J. B., Tebandeke, E., Baptist, J., & Emmanuel, K. &. (2023). Non-emission hydrothermal low-temperature synthesis of carbon nanomaterials from poly (ethylene terephthalate) plastic waste for excellent supercapacitor applications. *Green Chemistry Letters and Reviews*, *16*(1), 1–19. https://doi.org/10.1080/17518253.2023.2173025

Kigozi, M., Koech, R. K., Kingsley, O., Ojeaga, I., Tebandeke, E., Kasozi, G. N., & Onwualu, A. P. (2020). Synthesis and characterization of graphene oxide from locally mined graphite flakes and its supercapacitor applications. *Results in Materials*, *7*, 100113. https://doi.org/10.1016/J.RINMA.2020.100113

Kigozi, M., Richard K, K., Kingsley, O., Ravi, K., Omar LM, K., Balaji, P., Abdulhakeem, B., Gabriel N, K., Pawan Kumar, J., John Baptist, K., Azikiwe Peter, O., & Nelson Y, D. (2023). Porous carbon derived from Zea mays cobs as excellent electrodes for supercapacitor applications. *Open Journal of Analytical and Bioanalytical Chemistry*, *7*(1), 001–010. https://doi.org/10.17352/OJABC.000028

Kigozi, M., Tebandeke, E., Baptist Kirabira, J., & Kasozi, G. N. (2023). Solvo/hydrothermal upcycling of polyethylene plastic-waste into carbon-based nanocomposite for supercapacitor application. *Materials Science and Technology (United Kingdom), May*. https://doi.org/10.1080/02670836.2023.2215646

Kumari, M., Chaudhary, G. R., Chaudhary, S., & Umar, A. (2022). Transformation of solid plastic waste to activated carbon fibres for wastewater treatment. *Chemosphere*, *294*, 133692. https://doi.org/10.1016/J.CHEMOSPHERE.2022.133692

Lian, Y., Ni, M., Huang, Z., Chen, R., Zhou, L., Utetiwabo, W., & Yang, W. (2019). Polyethylene waste carbons with a mesoporous network towards highly efficient supercapacitors. *Chemical Engineering Journal*, *366*, 313–320. https://doi.org/10.1016/J.CEJ.2019.02.063

Liang, K., Liu, L., Wang, W., Yu, Y., Wang, Y., Zhang, L., Ma, C., & Chen, A. (2019). Conversion of waste plastic into ordered mesoporous carbon for electrochemical applications. *Journal of Materials Research*, *34*(6), 941–949. https://doi.org/10.1557/JMR.2018.493

Lijuan, H., Peng, Y., Feng, W., Peng, S., JinJun, L., & Zizheng, L. (2017). Tubular activated carbons made from cotton stalk for dynamic adsorption of airborne toluene. *Journal of The Taiwan Institute of Chemical Engineers*, *80*, 399–405. https://doi.org/10.1016/j.jtice.2017.07.029

Lim, W. C., Srinivasakannan, C., & Balasubramanian, N. (2010). Activation of palm shells by phosphoric acid impregnation for high yielding activated carbon. *Journal of Analytical and Applied Pyrolysis*, *88*, 181–186. https://doi.org/10.1016/j.jap.2010.04.004

Mu, L., Zhang, Q., & Cui, Q. (2021). Experimental Study on CO2Capture from Simulated Flue Gas with an Adsorption-Hydration Method. *Industrial and Engineering Chemistry Research*, *60*(8), 3411–3420. https://doi.org/10.1021/acs.iecr.1c00379

Ribeiro, R. S., Vieira, O., Fernandes, R., Roman, F. F., Diaz de Tuesta, J. L., Silva, A. M. T., & Gomes, H. T. (2022). Synthesis of low-density polyethylene derived carbon nanotubes for activation of persulfate and degradation of water organic micropollutants in continuous mode. *Journal of Environmental Management*, *308*, 114622. https://doi.org/10.1016/J.JENVMAN.2022.114622

Robertson, M., Obando, A. G., Nunez, B., Chen, H., & Qiang, Z. (2022). Upcycling Mask Waste to Carbon Capture Sorbents: A Combined Experimental and Computational Study. *ACS Applied Engineering Materials*, *1*(1), 165–174. https://doi.org/10.1021/ACSAENM.2C00030

Robertson, M., Obando, A. G., Nunez, B., Chen, H., & Qiang, Z. (2023). Upcycling Mask Waste to Carbon Capture Sorbents : A Combined Experimental and Computational Study. *Applied Engineering Materials*, *1*, 165–174. https://doi.org/10.1021/acsaenm.2c00030

Shafeeyan, M. S., Wan, M. W. A., Houshmand, A., & Shamiri, A. (2010). A review on surface modification of activated carbon for carbon dioxide adsorption. *Journal of Analytical and Applied Pyrolysis*, *89*(2), 143–151. https://doi.org/10.1016/j.jaap.2010.07.006

Shi, J., Cui, H., Xu, J., Yan, N., & Liu, Y. (2020). Design and fabrication of hierarchically porous carbon frameworks with Fe2O3 cubes as hard template for CO2 adsorption. *Chemical Engineering Journal*, *389*, 124459. https://doi.org/10.1016/j.cej.2020.124459

Shi, J., Yan, N., Cui, H., Xu, J., Liu, Y., & Zhang, S. (2019). Salt Template Synthesis of Nitrogen and Sulfur Co-Doped Porous Carbons as CO2 Adsorbents. *ACS Sustainable Chemistry and Engineering*, *7*(24), 19513–19521. https://doi.org/10.1021/acssuschemeng.9b04574

Singh, D., Malik, H. K., Gupta, C. K., & Singh, V. (2017). X-Ray Diffraction Studies for Identification of Polyethylene Terephthalate Fibres. *Indian Journal of Science and Technology*, *10*(17), 1–4. https://doi.org/10.17485/ijst/2017/v10i17/110232

Turku, I., Kärki, T., Rinne, K., & Puurtinen, A. (2017). Characterization of plastic blends made from mixed plastics waste of different sources. *Waste Management and Research*, *35*(2), 200–206. https://doi.org/10.1177/0734242X16678066

Van, K. Le, Thuy, T., & Thi, L. (2014). Activated carbon derived from rice husk by NaOH activation and its application in supercapacitor. *Progress in Natural Science: Materials International*, *24*(3), 191–198. https://doi.org/10.1016/j.pnsc.2014.05.012

Yaglikci, S., Gokce, Y., Yagmur, E., & Aktas, Z. (2020). The performance of sulphur doped activated carbon supercapacitors prepared from waste tea. *Environmental Technology (United Kingdom)*, *41*(1), 36–48. https://doi.org/10.1080/09593330.2019.1575480

Yang, X., Li, C., Zhang, G., & Yang, C. (2015). Polystyrene-derived carbon with hierarchical macro–meso–microporous structure for high-rate lithium-ion batteries application. *Journal of Materials Science*, *50*(20), 6649–6655. https://doi.org/10.1007/S10853-015-9214-

7/METRICS

Yeh, J. T., Pennline, H. W., & Resnik, K. P. (2001). Study of CO2 Absorption and Desorption in a Packed Column. *Energy and Fuels*, *15*(2), 274–278. https://doi.org/10.1021/EF0002389

Yuan, X., Li, S., Jeon, S., Deng, S., Zhao, L., & Lee, K. B. (2020). Valorization of waste polyethylene terephthalate plastic into N-doped microporous carbon for CO2 capture through a one-pot synthesis. *Journal of Hazardous Materials*, *399*, 123010. https://doi.org/10.1016/J.JHAZMAT.2020.123010

Yuan, X., Wang, J., Deng, S., Suvarna, M., Wang, X., Zhang, W., Hamilton, S. T., Alahmed, A., Jamal, A., Park, A. H. A., Bi, X., & Ok, Y. S. (2022). Recent advancements in sustainable upcycling of solid waste into porous carbons for carbon dioxide capture. *Renewable and Sustainable Energy Reviews*, *162*, 112413. https://doi.org/10.1016/J.RSER.2022.112413

Zhang, R., Liu, Y., Yu, L., Li, Z., & Sun, S. (2013). Preparation of high-quality biocompatible carbon dots by extraction, with new thoughts on the luminescence mechanisms. *Nanotechnology*, *24*(22), 225601. https://doi.org/10.1088/0957-4484/24/22/225601

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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