Research article

Household mixed plastic waste derived adsorbents for CO$_2$ capture: A feasibility study

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ABSTRACT

The feasibility of producing activated carbon (AC) from real Household Mixed Plastic Waste (HMPW) comprising of LDPE, HDPE, PP, PS, and PET for carbon capture via direct carbonisation followed by microwave-assisted or conventional thermally assisted chemical activation was investigated. A microwave-assisted activation procedure was adopted to assess the impact on the CO$_2$ capture capacity of the resulting AC using both a lower temperature (400 °C vs. 700 °C) and a shorter duration (5 vs. 120 mins) than that required for conventional activation. The results obtained showed that the AC yield was 71 and 78% for the conventional and microwave-assisted samples, respectively. Microwave activation consumed five-fold less energy (0.19 kWh) than the conventional activation (0.98 kWh). Thermal stability results indicated total weight loss of 10.0 and 8.3 wt%, respectively, for conventional and microwave-activated samples over the temperature range of 25–1000 °C, with ACs from both activation routes displaying a type 1 nitrogen isotherm. The dynamic CO$_2$ uptake capacity at 1 bar and 25 °C was 1.53 mmol/g, with maximum equilibrium uptake ranging between 1.32 and 2.39 mmol/g at temperatures (0–50 °C) and 1 bar for the conventionally activated AC. The analogous microwave-activated sample showed a higher dynamic CO$_2$ uptake of 1.62 mmol/g and equilibrium uptake in the range 1.58–2.88 mmol/g under equivalent conditions. The results therefore indicate that microwave activation results in enhanced carbon capture potential. To the best of our knowledge, this is the first-time microwave heating has been employed to convert household mixed plastic wastes directly into ACs for carbon capture applications. This report therefore demonstrates that the management of mixed plastics could lead to the development of a circular economy through the conversion of waste into value-added materials.

1. Introduction

Plastic waste is a cheap and common source of carbon and hydrogen, which could be used as a chemical feedstock or to produce energy. Conversion of plastic wastes to valuable products is generally achieved through pyrolysis, where the waste is subjected to a high-temperature treatment to obtain different fractions of gas, liquid (oil), and solid (char). These fractions are a reservoir of valuable resources, as value-added products such as hydrogen, high-value hydrocarbons, and different functional chemicals have reportedly been recovered from plastic waste (Ahmad et al., 2015; Yel et al., 2017). The carbon-rich nature of the solid char fraction obtained from the pyrolysis of plastic waste makes it useful as a precursor in the development of different activated carbons (ACs). These AC's can then be used as adsorbents for the removal of a wide array of environmental contaminants, such as trace metals (iron, nickel, lead, and cadmium), organic pollutants (polycyclic aromatic hydrocarbons, polychlorinated biphenyls), and gaseous pollutants (CF$_4$, SO$_2$) (Zhang et al., 2020).

Carbon capture using plastic waste derived ACs has also been reported (Yuan et al., 2020a), with most of the studies carried out using polyethylene terephthalate (PET) plastic as a precursor. PET waste is preferred over other plastic wastes in the development of ACs for carbon capture due to (i) its low level of impurities, which enhances the formation of micropores in the char and final AC; (ii) the ease of char formation through simple carbonisation; (iii) its availability in most metropolitan wastes; and (iv) its high oxygen content, which aids self-activation and the formation of oxygen-containing functional groups, which are helpful in the development of porosity when the char

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is treated with an activating agent such as KOH (Singh et al., 2020; Arenillas et al., 2005).

Polystyrene (PS) wastes have also been used to produce activated carbons for carbon capture applications (Sun et al., 2017). However, previous research shows that the synthetic routes were rather complicated. For instance, cross-linking agents such as carbon tetrachloride, formaldehyde, dimethyl acetal, or dichloro-p-xylene were used in combination with PS to produce PS-based ACs. This was done to aid the formation of char from PS and promote the generation of porosity in the formed char (Fu et al., 2019). Ren and his team reported a three-step route to form carbon sphere adsorbents from a PS-based macroreticular resin for CO_2 capture (Ren et al., 2022). The experiment involved pre-oxidation of the resin in air at 300 °C for 4 h before subjecting the oxidised resin sphere to further heating at 810 °C for 2 h. The resulting sample was then treated with gaseous ammonia and re-heated at 600 °C for 4 h in a vertical tube furnace to obtain the final AC. The difficulty in obtaining a significant amount of char for subsequent activation from the direct carbonisation of PS (de Paula et al., 2018) and the non-porous nature of the char may be the reasons PS-based wastes are used to a lesser extent in the production of ACs. Pure plastic wastes such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP) have not been used as precursors to produce activated carbons for carbon capture. The challenge with these plastic wastes is that, in general, only oils and gases are recovered during their direct carbonisation (Saebea et al., 2020; Dubdub and Al-yaari, 2020). This generally limits the use of these plastic wastes, which is problematic since they constitute a major component in real-world plastic waste (LDPE – 23%, HDPE – 19%, PP – 14%, PS – 9%, PET – 10%, polyvinyl chloride (PVC) – 6%, others – 19%) (Bodzay and Banhejyi, 2016).

For effective utilisation of plastic waste, a mixed plastic comprising of LDPE, HDPE, PP, PS, PVC, and PET would need to be explored for a real application such as chemical recycling through thermal treatment to produce porous carbons for CO_2 capture since the separation or sorting of a complete mixture of plastics into constituent parts is not simple or economical. Understandably, reports have suggested that chemical recycling through pyrolysis leads to the generation of toxic waste like acidic gas, NOx (Jeswani et al., 2021), and volatile organic compounds, VOCs (Huang et al., 2013). In addition to these substances, CO_2 is also produced, which contributes to climate change. Interestingly, the impact of these toxic wastes can be managed or minimised. For example, acidic gas can be neutralised by dry adsorption on calcium hydroxide, while NOx can be converted to nitrogen and oxygen by catalytic reduction (Jeswani et al., 2021). Amine can be used to scrub CO_2 gas, while activated carbon can be used to adsorb VOCs (Ma et al., 2021). However, contrary reports have also suggested that chemical recycling of plastic through pyrolysis in the UK and Europe has a much smaller net impact on climate change (Gear et al., 2018; Somoza-Tornos et al., 2020). A recent study shows that chemical recycling of mixed plastics through pyrolysis has a 50% lower climate change impact compared to incineration or mechanical recycling (Jeswani et al., 2021).

Herein, we assess the feasibility of producing activated carbons from household mixed plastic waste comprising of LDPE, HDPE, PP, PS, and PET through simple direct carbonisation and activation using both a conventional furnace and a 2.45 GHz multimode microwave cavity to produce ACs for CO_2 capture. The use of microwaves in the activation stage during the production of ACs for CO_2 capture has been reported to improve the capture capacity of adsorbents (Shi and Liu, 2021). A great benefit of microwave activation in AC production is that it typically requires less electrical energy than conventional activation in a furnace. This is because char activation is fast and effective even at low temperatures, resulting in energy savings and reduced processing time (Alslaibi et al., 2013). The composition of the mixed plastic waste used in this study represents a typical household plastic waste composition in a municipal solid waste scenario in Europe (Bodzay and Banhejyi, 2016). Although typical "real-world" mixed plastic waste usually

contains PVC, it was excluded from this work due to health and safety concerns owing to the formation of chlorinated compounds at high temperatures. Other than this, our work has focused on working with household mixed plastic waste (HMPW). The limitation of this is that PVC would need to be sorted out from the other plastics before directly applying our method.

To the best of our knowledge, this is the first time that activated carbons from real household mixed plastic waste have been produced via direct carbonisation and chemical activation processes for carbon capture applications. Additionally, this study also analyses the electrical energy requirements for both microwave and conventional activation of HMPW-char, as well as the advantages of using microwave heating for the activation.

2. Experimental

Polyethylene bags (low-density LDPE), milk containers (high-density HDPE), food wrappings (PP), packaging foam (PS), and plastic liquid bottles (PET) were locally sourced from waste sites around Aberdeen in the United Kingdom. Apart from the polystyrene foam, the plastic waste was washed with distilled water, cut into pieces (<5 mm), and dried overnight in an oven at 105 °C. Polystyrene foam was dissolved in acetone to remove air bubbles before it was decanted and dried in an oven at 60 °C for 2 h (de Paula et al., 2018). The plastics were then mixed to give a composition representative of a municipal solid waste scenario in Europe (Barruetabena and Salas, 2007; Bodzay and Banhejyi, 2016). Specifically, LDPE (42 wt%, 4.2 g), HDPE (20 wt%, 2.0 g), PP (10 wt%, 1.0 g), PS (16 wt%, 1.6 g), and PET (12 wt%, 1.2 g) were physically mixed before being loaded into a quartz jacket and then placed in a vertical tubular furnace (Nabertherm, GmbH) for carbonisation. The mixed plastic sample was subjected to a heating ramp of 5 °C/min from room temperature to 600 °C and held at this temperature for 1 h. A constant nitrogen flow (100 ml/min) was fed to the reactor throughout. The obtained char was collected and labelled as '5 MP-char' and was then used for activation.

For chemical activation, the 5 MP-char (1 g) was added to a previously prepared 2.14 M potassium hydroxide (KOH) solution and stirred thoroughly for 4 h at 50 °C. The solution was subsequently filtered, and the solid dried at 105 °C for 12 h to remove all traces of water. The KOH-impregnated char was then heated in a vertical tubular furnace from room temperature to 700 °C at 5 °C/min and held at this temperature for 2 h under an N_2 flow rate of 200 ml/min. Alternatively, the KOH-impregnated char was mixed with 20 g Norit PK1-3, used as a microwave susceptor, and subjected to microwave heating at 400 °C for 5 min under nitrogen flow (200 ml/min) in a Flexiwave microwave instrument (MA186-001, from Milestone). The short microwave activation time was chosen based on previous reports that show shorter activation times favour better CO_2 uptake properties than moderate or long activation times (Durán-jiménez et al., 2020). Regardless of the activation method, the resultant activated carbons were washed with 25 ml of 1 M HCl to remove unreacted KOH and then rinsed with deionized water to neutrality before drying at 105 °C for 12 h. The final activated carbons were labelled 'CA-5MP' and 'MW-5MP' to denote conventional activation and microwave activation, respectively. The total electrical energy input required for the activation of 5 MP-char using conventional and microwave methods was evaluated using a self-assembled energy measurement setup comprising an oscilloscope (MSO-X-2024A), a current clamp (FLUKE i30s), a separation box, and a computer. In a typical measurement, the microwave or electrical furnace was plugged into a separation box previously connected to the mains. The current clamp was connected to the loop attached to the separation box and to an oscilloscope before being connected to a computer through the universal serial bus cable. For the duration of the heating, the oscilloscope continually monitored the voltage from the current clamp, which is proportional to the measured current with respect to time. The peak current was sampled at 4 Hz every cycle, and the power was estimated at

Table 1
Activated carbon yield, thermal stability, and physical properties of HMPW derived activated carbons.

Sample	Yield (%)	Mass loss (%)[a]	N_2 isotherm				CO_2 isotherm[g]	
			S_{BET} (m^2/g)[b]	V_t (cm^3/g)[c]	D (nm)	V_{micro} (cm^3/g)[d]	W_0 (cm^3/g)[e]	L_0 (nm)[f]
CA-5MP	71	10.01	311	0.10	1.50	0.10	0.17	0.55
MW-5MP	78	8.28	338	0.12	1.48	0.12	0.19	0.51

[c] total pore volume at P/P$_0$ = 0.99 from the Horvath-Kawazoe equation.
[d] total micropore volume at P/P$_0$ < 0.1 from Dubinin-Radushkevich equation.
[e] narrow micropore volume at P/P$_0$ < 0.01 (Dubinin-Radushkevich equation).
[a] Calculated from TGA data up to 1000 °C.
[b] Calculated using the BET equation.
[f] Average narrow micropore width (Stoeckli-Ballerini relation).
[g] CO$_2$ isotherms measured at 0 °C.

0.25-s intervals as a product of the peak current (or the root mean square equivalent) and the supply voltage (240 V). The total electrical energy input consumed was computed by calculating the area under the power-time curve employing trapezoidal integration using Equation (1).

$$E = \sum (t_i - t_{i-1}) \times \tfrac{1}{2} (P_i + P_{i+1}) \tag{1}$$

where E is the total energy consumed in kWh, P is the power in kW, and t, is time in hours.

The synthesised ACs were subjected to characterization using various methods to assess their properties, including their carbon capture potential, such as thermal stability, dynamic isothermal CO_2 capture, dynamic CO_2 adsorption-desorption cycles, N_2 adsorption isotherms, and CO_2 adsorption isotherms collected at various temperatures.

The thermal stability experiments were measured in a thermogravimetric analyser (TGA/DSC 3+ Star System, Mettler Toledo). Samples were subjected to a heating rate of 10 °C/min from 25 to 1000 °C under a 50 ml/min flow of N_2. Dynamic isothermal CO_2 uptakes were measured using the same instrument. In a typical run, 25.0 mg of the AC was first heated from room temperature to 100 °C with 50 ml/min N_2 gas flow and held at this temperature for 60 min to remove moisture and any pre-adsorbed CO_2. At the end of the 60-min period, the temperature was reduced to 25 °C under N_2 flow before the gas was switched to CO_2 (same flow rate). The adsorption stage was allowed to occur for approximately 20 min until a mass plateau was obtained, which indicated saturation. The mass gain during the adsorption step was used to calculate uptake as mmol of CO_2 adsorbed per gram of dry adsorbent. For cyclic adsorption-desorption experiments, the same procedure was applied, but after saturation was reached, the gas was switched to N_2 at 50 ml/min, and the temperature was increased to 100 °C for the desorption step. This adsorption-desorption cycle was repeated 10 times to assess the adsorbent's stability. On the other hand, the N_2 adsorption isotherms were measured at −196 °C using a volumetric sorption analyser (ASAP, 2020; Micromeritics). The same instrument was used for the CO_2 adsorption isotherms at different temperatures (0, 25, and 50 °C). Prior to the N_2 and CO_2 adsorption isotherm experiments, the

samples were first degassed at 300 °C for 6 h in N_2.

3. Results and discussion

3.1. Activated carbon yield, electrical energy input, and physical properties of HMPW-derived activated carbons

Table 1 shows the yield of AC prepared via conventional and microwave activation routes. The carbon yield is the weight of activated carbon produced relative to the initial weight of HMPW char used for activation. The carbon yield from microwave activation was higher (78%) than the yield from the conventional route (71%). Differences in carbon yield can be attributed to the different heating mechanisms used. The lower temperature and short activation time (5 min), combined with the uniform and targeted heating pattern of the microwave method, increased the yield in comparison to the conventional method by limiting the formation of gaseous products. Higher AC yields from microwave-activated samples have also been reported elsewhere (Parthasarathy and Narayanan, 2014; Sun et al., 2012). The total electrical energy input for the conventional and microwave activations was found to be 0.98 and 0.19 kWh, respectively (more details in the SI document). The results show that microwave activation consumed 5-fold less electrical energy than conventional activation, and this is because of both the shorter activation time (24-fold smaller) and lower activation temperature (300 °C lower) than conventional activation.

The thermogravimetric curves for the AC's are presented in Fig. 1a. It can be observed that both samples, CA-5MP and MW-5MP, show similar thermal decomposition profiles, although the total mass loss in the microwave-assisted activated carbon is smaller (8.28% wt.) compared to the weight loss displayed by CA-5MP (10.01%). Two distinct weight loss peaks are observed; the first is found in the temperature range 25–120 °C and the second in the range 600–1000 °C. These are attributed to the loss of water molecules and the decomposition of different functional groups such as –COOH, and –OH, respectively (Mumtaz et al., 2021). The N_2 adsorption isotherms for the two activated carbons are presented in Fig. 1b–and a summary of the textural parameters extracted from these
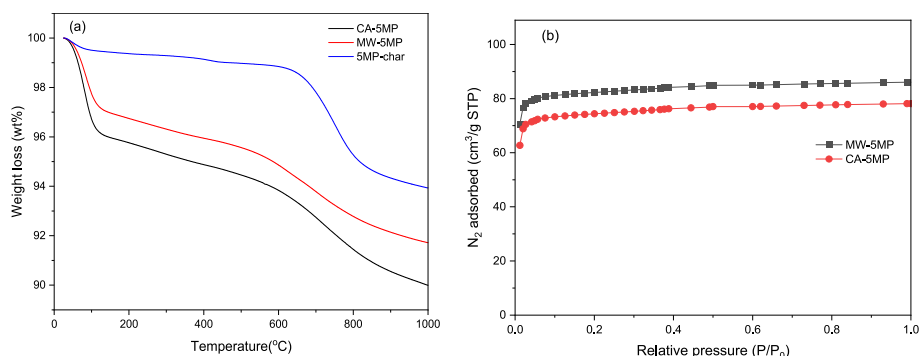
Fig. 1. (a) TG curves, (b) Nitrogen adsorption isotherms measured at −196 °C.
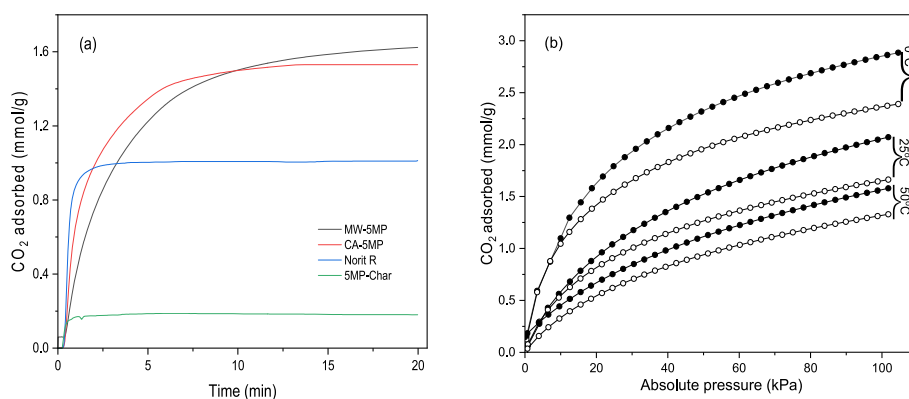
Fig. 2. (a) Dynamic CO_2 capture profiles at 25 °C and 1 bar (b) CO_2 isotherms of HMPW-derived ACs at different temperatures (filled circle for MW-5MP, empty circle for CA-5MP).

Table 2
Dynamic and maximum equilibrium CO_2 uptake of AC adsorbents prepared from mixed plastics.

Sample	Dynamic CO_2 uptake[a] (mmol/g)	Equilibrium CO_2 uptake[b] (mmol/g)		
		0 °C	25 °C	50 °C
CA-5MP-400	0.76	–	–	–
CA-5MP	1.53	2.39	1.67	1.32
MW-5MP	1.62	2.88	2.07	1.58

[a] Maximum dynamic CO_2 capture at 25 °C measured in the TGA.
[b] At 1 bar in the volumetric sorption analyser ASAP 2020, Micromeritics.

Table 3
Dynamic CO_2 uptake of some reported activated carbons at 25 °C and 1 bar, in 100% CO_2.

Carbon precursor	S_{BET} (m²/g)	CO_2 uptake (mmol/g)	Reference
Polyacrylonitrile	1884	2.50	(J. Singh et al., 2019)
Carpet waste	1910	1.90	Drage & Maroto-valer (2010)
Bagasse	923	1.74	Boonpoke et al. (2013)
HMPW (Microwave)	338	1.62	This study
HMPW (conventional)	311	1.53	This study
Grass cutting	841	1.45	Hao et al. (2013)
Polyacrylonitrile	2231	1.30	Shen et al. (2011)
Rice Husk	927	1.29	(Boonpoke et al., 2013)
PET/carbazole	418	1.09	Arenillas et al. (2005)
Chicken manure waste	618	1.09	Yıldız et al. (2019)
Beer waste	622	0.80	Hao et al. (2013)
MCM-48/APS	505	0.80	Kim et al. (2005)
Polyacrylonitrile fibre	1239	0.76	Bai et al. (2015)
Hexamethoxymethylmelamine	463	0.67	Goel et al. (2016)
PET/acridine	318	0.65	Arenillas et al. (2005)
Fly ash	161	0.60	Alhamed et al. (2015)
MCM-41	602	0.55	Boonpoke et al. (2013)
MCM-48/PEI	56	0.40	Kim et al. (2005)

experiments and from the CO_2 adsorption isotherms measured at 0 °C is presented in Table 1.

Both samples displayed type I isotherms according to the IUPAC classification (Sing et al., 1985), indicating that the adsorbents are mainly microporous with a plateau observed at lower relative pressure (p/p0 < 0.1). The results displayed in Table 1 show that the surface area of the MW-5MP was slightly higher (338 m²/g) than that of the conventionally activated sample (311 m²/g). A similar trend was also found for the total pore and micropore volumes. The slight increase in surface area and total pore volume between microwave and conventionally activated samples is explained based on the differences between the two heating mechanisms. Microwave heating creates a temperature gradient due to heating from within, releasing light components and creating additional pores on the sample surface (Ji et al., 2007). CO_2 isotherms measured at 0 °C were used to assess the narrow microporosity (pore width <1 nm) in the samples. The smaller kinetic diameter of the CO_2 molecule compared to that of the N_2 molecule (3.65 vs. 3.30 Å) and the bigger quadrupole moment of CO_2 favour CO_2 diffusion into the narrower micropores at low relative pressures (Mahajan, 1991). The results obtained suggest that the average micropore width was slightly smaller in samples activated with microwaves. This is likely to be significant as CO_2 uptake at post-combustion capture conditions is known to be highly influenced by the size of micropores (Martín et al., 2010, 2011).

3.2. CO_2 capture capacity of HMPW-derived activated carbons under dynamic and equilibrium conditions

The dynamic CO_2 adsorption profiles of HMPW-derived activated carbons produced through conventional and microwave activation methods are presented in Fig. 2a and summarised in Table 2. Both AC's displayed higher dynamic CO_2 uptake than that of the parent char, which confirms the effectiveness of KOH as a chemical activator. Indeed, KOH is known to be an effective activating agent for generating micropores in carbon materials for CO_2 capture (Kaur et al., 2019). The

mechanism of KOH activation in the development and generation of micropores on carbon surfaces has already been reported elsewhere (Yuan et al., 2020b). When comparing the conventional and microwave-activated materials (Table 2), the MW-5MP sample presents a higher dynamic CO_2 uptake (1.62 mmol/g) than the CA-5MP sample (1.53 mmol/g). It was observed that the CO_2 uptake profile of sample CA-5MP displays faster CO_2 uptake kinetics in the first 10 min and thereafter reaches a plateau. But, in the case of sample MW-5MP, the absorption is slower in the first 10 min; beyond this period, it appears that it did not reach a plateau and continues to increase, resulting in a slightly larger uptake capacity than CA-5MP. The higher CO_2 uptake recorded by the MW-5MP sample is attributed to the small increase in micropore volume and the narrowing of the fine micropore diameter (Table 1). It is interesting to note that microwave activation at 400 °C and with only a 5-min activation time resulted in an AC with higher CO_2 uptake than the analogous AC prepared via conventional heating (700 °C, activation time = 120 min). For comparison, we also evaluated the CO_2 capture capacity of a HMPW-derived AC activated conventionally at 400 °C for 120 min (sample denoted as CA-5MP-400). The
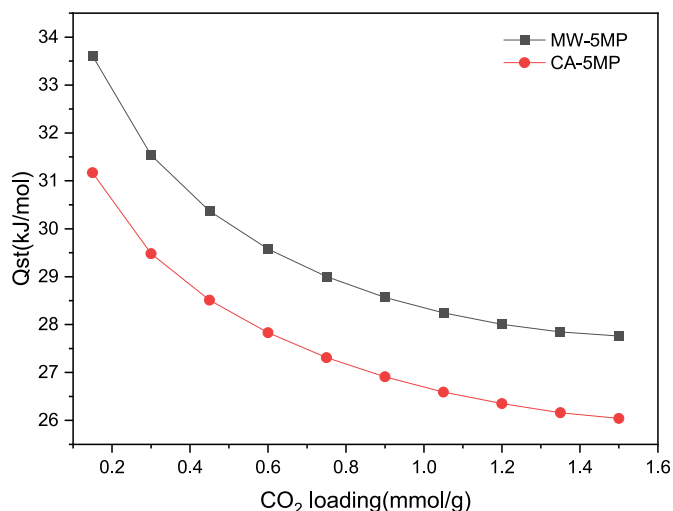
Fig. 3. Isosteric heat of CO_2 adsorption for CA-5MP and MW-5MP at different CO_2 loadings.

Table 4
Total and average single cycle adsorption – desorption capacity under dynamic conditions.

Sample	$Q_{T\ ads}$[a] (mmol/g)	$Q_{T\ des}$[b] (mmol/g)	Q_{SWC}[c] (mmol/g)	% Desorption[d]
CA-5MP	14.98	14.46	1.49	96.50
MW-5MP	15.60	15.18	1.56	97.31

[a] Q_{Tads} - total CO_2 adsorbed in 10 cycles.
[b] $Q_{T\ des}$ - total CO_2 desorbed in 10 cycles.
[c] SWC- stable working capacity.
[d] Percentage ratio of total CO_2 desorbed from 10 cycles.

dynamic CO_2 capture capacity for this sample was only 0.76 mmol/g at 25 °C. This confirms that the activation treatment using conventional heating at 400 °C does not yield an AC with especially good CO_2 uptake properties, thus confirming the unique effects of microwave activation.

The CO_2 isotherm at 0 °C reveals that the average width of the narrow micropores is slightly smaller than that obtained for the sample produced by the conventional activation method. Higher CO_2 uptake by activated carbons at low pressure (1 bar) and temperature (0–25 °C) has been shown to be significantly enhanced by the volume of ultra-micropores present in the adsorbents (Durán-jiménez et al., 2020). Furthermore, the CO_2 capture capacities shown by HMPW-derived activated carbons are higher (*ca.* 30%) than those of the commercial AC Norit R2030CO2 (a commercial AC developed for carbon capture; see Fig. 2a). Table 3 shows how the dynamic CO_2 uptake capacities of HMPW-derived ACs from this study compare with the literature. The ACs reported in this work generally compare favourably with the literature (Tiwari et al., 2017; Boonpoke et al., 2013; Mukherjee et al., 2019; Arenillas et al., 2005). Indeed, the only AC's that have higher CO_2 uptake are samples that possess a significantly higher surface area than the samples explored in this work. This gives a further hint that the textural properties of the HMPW derived samples are especially effective for CO_2 capture. The maximum equilibrium CO_2 uptake (0–50 °C; see Fig. 2b and Table 2) for the conventionally activated sample was in the range 1.32–2.39 mmol/g. The microwave-activated sample displayed higher

equilibrium uptakes in the range 1.57–2.88 mmol/g (see Table 2). The equilibrium uptake exhibited by the prepared ACs is comparable to or higher than some of the reported ACs from other carbonaceous materials (Zgrzebnicki et al., 2022; Czyz et al., 2013; Goel et al., 2016). As adsorption temperature increases, equilibrium uptake decreases, and this is consistent with an exothermic physisorption mechanism (Yuan et al., 2018) that has been reported previously for ACs from other carbon precursors (Yuan et al., 2020a; Zgrzebnicki et al., 2022).

3.3. Isosteric heats of adsorption

The isosteric heat of adsorption measures the intensity of interaction between CO_2 adsorbate molecules and the adsorbent material, and information from it could help in deducing both the mechanism of adsorption and the energy of regeneration (Abuelnoor et al., 2021). The isosteric heat of adsorption (Q_{st}) was determined from the CO_2 adsorption isotherms measured at different temperatures using the Clausius-Clapeyron equation (Tiwari et al., 2017). The results indicated that the Q_{st} value ranged from 27.8 to 33.6 kJ/mol for the MW-5MP sample and from 21.6 to 31.2 kJ/mol for CA-5MP. The magnitude of the values for heat of adsorption suggests a physisorption adsorption mechanism is likely. The results presented in Fig. 3 show that the heat of adsorption decreases with increasing CO_2 coverage for both samples, suggesting heterogeneity of the surface. Q_{st} values obtained for HMPW-derived ACs are smaller than those reported for microcrystalline cellulose-based ACs (i.e., 38.4 kJ/mol) (Biti et al., 2023), but higher than the values reported for PET-derived ACs (18.6–20.9 kJ/mol) (Yuan et al., 2020b). The relatively low Q_{st} values for HMPW-derived ACs obtained in this study imply that a relatively small amount of energy would be required for the regeneration of these adsorbents (Kaur et al., 2019b). This attribute is useful and of importance in terms of the practical utilisation of HMPW-derived activated carbons for cyclic CO_2 capture processes, where regeneration is present in each separation
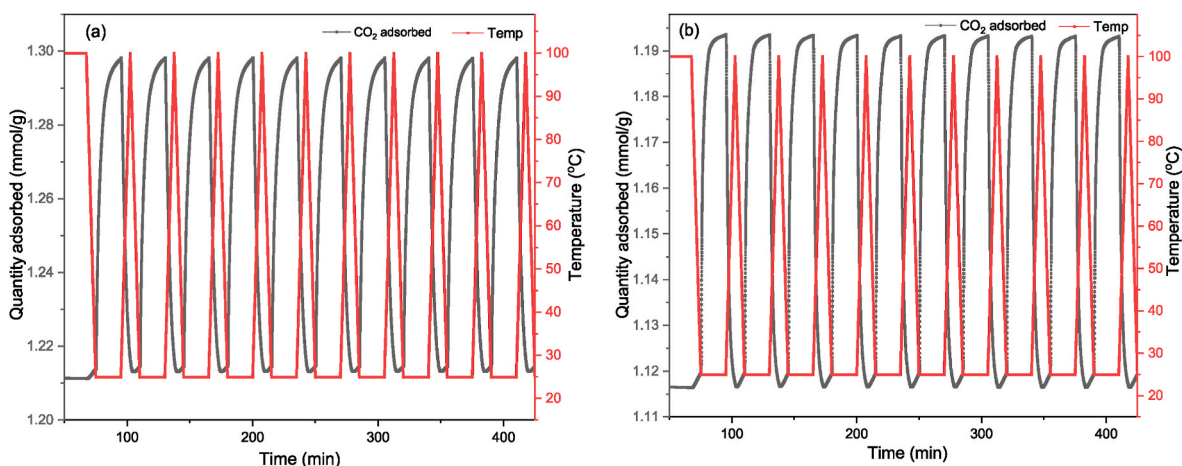

Fig. 4. Quantity of CO_2 adsorbed and temperature profiles in the adsorption-desorption cycles for (a) MW-5MP, and (b) CA-5MP.

Table 5

Cost analysis for the laboratory scale production of ACs from HMPW.

Serial No.	Description	Remark	Conventional (£)	Microwave (£)
a)	Collection of HWMP waste	No cost as HMPW wastes is accessible and abundant	0.00	0.00
b)	Pretreatment (washing and shredding)	Distilled water used was obtained from in-house laboratory. Shredding was done manually with laboratory scissors.	0.00	0.00
c)	Drying of pre-washed samples	No. of hours × Power rating × Unit electricity cost 12 h × 1.0 (kWh) × 27p	3.24	3.24
d)	Vertical tubular furnace Cost of operation (Measured with oscilloscope)	Carbonisation of HMPW Operation cost: 0.86 kWh × 27p	0.23	0.23
		Activation of HMPW Furnace: 0.98 kWh × 27p, 0.19 kWh × 27p (microwave)	0.26	0.05
e)	Collection of pyrolysis fraction	Condensable fraction collected using ice-bath, non-condensable with gas bags, and char collected after cooling. No cost incurred	0.00	0.00
f)	Chemical cost	25 ml portion of acetone for PS processing: No cost	0.00	0.00
		KOH pellet @ 3:1 KOH/char ratio used for activation, and 25 ml portion of HCl for acid washing.	0.08	0.08
		Norit PK1-3 (20 g)	0.00	0.04
g)	N_2 gas (99.99%)	Carbonisation and activation	0.60	0.20
h)	Sieve paper	150 mm filter from in-house laboratory	0.00	0.00
i)	Packaging and storage	No cost incurred	0.00	0.00
j)	Overall cost	Addition of costs of (a) – (j)	4.41	3.84
k)	Overhead cost	10% overall cost	0.44	0.38
l)	**Total cost**		**£4.85**	**£4.22**

For costing on a small laboratory scale, the costs of collection, transportation, and pretreatment of HMPW, collection of pyrolysis fractions (condensable and non-condensable fractions during carbonisation), 25 ml of acetone, sieve paper, and packing and storage of prepared ACs have not been considered, but these should be factored in if costs were to be extrapolated at a larger scale.

cycle.

3.4. Cyclic CO₂ adsorption-desorption

The cyclic stability was assessed by performing 10 adsorption–desorption cycles using TGA and is presented in Fig. 4. As it can be seen, both HMPW-derived ACs showed stable performance during 10 consecutive cycles. The working capacities measured were 1.49 ± 0.00 and 1.56 ± 0.00 mmol CO_2/g for CA-5MP and MW-5MP, respectively. As seen in Table 4, CA-5MP adsorbed a total of 14.98 mmol CO_2/g across 10 cycles and desorbed a total of 14.46 mmol CO_2/g, representing the 96.50% desorption. For MW-5MP, the equivalent values were 15.60 mmol CO_2/g adsorbed, 15.18 mmol CO_2/g desorbed, and 97.31%

regeneration.

3.5. Cost analysis

An estimate of the cost for the laboratory-scale production of ACs from conventional and microwave activation routes was performed. Being a laboratory scale estimation, it may not represent the true benchmark cost for a direct scaling up; however, it would be useful in providing insights into the economics of AC production from HMPW through the approaches described in this study and their comparisons. The relationship between the energy consumption during AC production (i.e., carbonisation, activation, and drying steps) and the overall cost of the process, which is one of the key elements of cost analysis in scaling up (Jaria et al., 2022) could be deduced from it based on the extensive energy consumption determination experiments performed for both activation methods. The cost of collecting mixed plastic wastes, pre-treatment steps (cleaning, shredding, and drying), chemicals, energy consumption during carbonisation and activation, and equipment running, and operation costs constitute the cost elements for this analysis. The current unit cost of electricity in the UK was taken as £0.27 per kWh.

Table 5 shows the laboratory-scale cost analysis to produce ACs from HMPW via conventional and microwave activations, as elucidated in the flow chart presented in Fig. 5. The results indicate that the estimated cost to produce an equivalent amount of AC from HMPW via conventional and microwave activations was £4.85 and £4.22, respectively. The results indicate that for the conventional route, the cost elements that impacted largely on the overall cost were those accruing from drying, carbonisation, and activation steps, while for the microwave route, the contribution from the activation step was less than 1% of the overall cost. This result shows that it is 15% cheaper to produce AC from HMPW through microwave activation compared to conventional activation, which again demonstrates that microwave activation saves money compared to conventional activation due to the lower energy input during activation. However, the cost reported in this study is higher (2-fold) than £2.25 (Chauhan et al., 2023) for the laboratory-scale production of ACs from crop residues. This is related to the higher cost of electricity in the UK than in India (0.27 vs. 0.0043 kWh), although the cost of production is expected to reduce when production is carried out on a commercial scale.

From the experimental results and the estimated laboratory scale cost analysis presented in Table 5, 10 g of mixed plastic feedstock produced 0.71 g of AC at a cost of £4.85 using conventional activation and 0.78 g of AC at a cost of £4.22 for the microwave. The quantities of CO_2 adsorbed under dynamic condition by 0.025 g samples of these ACs were 1.53 and 1.62 mmol/g, respectively. This means that a total of 43.45 mmol/g CO_2 would be adsorbed by 0.71 g AC prepared via conventional activation, and 50.54 mmol/g CO_2 by 0.78 g AC from microwave activation. Consequently, 1 kg of AC produced via conventional and microwave activations proposed in this study would adsorb over 61 and 64 mol of CO_2/kg of the prepared adsorbent, respectively, under similar experimental conditions described in this study based on a simple linear relationship assuming ideal system conditions with no heat or mass transfer limitation within the systems. In terms of cost, a total of £4850 and £4220 would be required to produce 1 kg of AC from HMPW through conventional and microwave activation, respectively. In the UK for example, the cost for landfilling of plastic waste is £92.15/t (Schyns and Shaver, 2021), and the cost for mechanical recycling of 1 kg of plastic waste is £185 (Nikiema and Asiedu, 2022). These waste management costs, when compared to the treatment technique proposed in this study, may be considered cheaper if viewed from the initial cost of adoption only. However, this cost proposal is based on laboratory scale production estimations, which would significantly vary when the production is carried out on an industrial scale. Again, it could be reasoned that the recovery of valuable chemical feedstocks such as aromatics (Siddiqui and Redhwi, 2009), aliphatic hydrocarbons (Siddiqui and
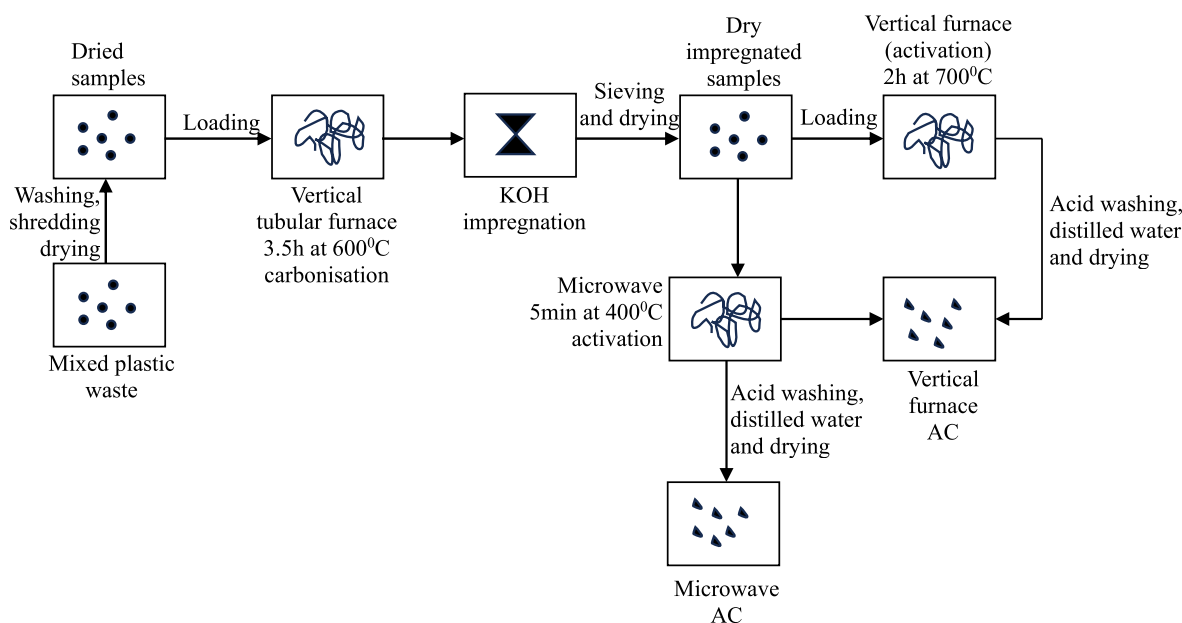
Fig. 5. Process flow chart for the laboratory production of AC from HMPW.

Redhwi, 2009) from the condensable fraction, and hydrogen (López et al., 2011) from the non-condensable fraction during the carbonisation of HMPW could help offset some of the cost of HMPW processing to ACs for CO_2 capture.

4. Conclusion

The feasibility of producing activated carbons from household mixed plastic waste comprised of LDPE, HDPE, PP, PS, and PET via chemical activation was investigated. The experiment involved the carbonisation of mixed plastics using a vertical furnace to obtain the char before subsequent activation of the char using a conventional furnace (700 °C, 120 min) and a microwave (400 °C, 5 min). Preliminary findings show that the derived AC's exhibited potential for CO_2 capture. The textural properties of the ACs from both activation routes indicated that the surfaces were entirely microporous based on the obtained type I N_2-adsorption isotherm. The dynamic isothermal CO_2 capture at 25 °C and 1 bar for the conventional and microwave-activated ACs were 1.53 and 1.62 mmol/g, respectively, with the microwave-activated sample displaying a higher CO_2 capture than the sample activated via conventional furnace. The maximum CO_2 uptake at adsorption temperatures of 0, 25, and 50 °C under equilibrium conditions for the microwave-activated AC ranged from 1.58 to 2.88 mmol/g, while a range of 1.32–2.39 mmol/g was obtained for the conventional activated sample. More interestingly, the ACs showed stable performance for 10 adsorption-desorption cycles with total CO_2 adsorption above 14.00 mmol/g and this was attributed to the material's textural properties. In addition, the ACs displayed an excellent CO_2 regeneration capacity with over 96% desorption efficiencies over 10 adsorption-desorption cycles. The total electrical energy input for the microwave activation (0.19 kWh) was 5-fold lower than that for the conventional activation (0.98 kWh). However, the estimated costs to produce ACs through conventional and microwave routes on a laboratory scale were £4.85 and £4.22, respectively. The scale-up process estimation shows that over 60 mol of CO_2/kg of prepared ACs could be adsorbed based on a simple linear relationship assuming an ideal system conditions with no heat or mass transfer limitation within the systems, which makes the utilisation of HMPW to produce CO_2 adsorbents a viable technique with great potential.

Concluding, the findings of this work indicate that real-world mixed plastic waste, which currently poses a challenge in terms of its management, could be used to prepare adsorbents for CO_2 capture. This innovative plastic waste management alternative, not only would help address the issues of plastic pollution, but will also contribute to CO_2 emissions mitigation, to help in stabilising the currently fast-growing climate change issue. However, it is important to note that PVC was excluded from the plastic mixture used in this study and as such, this would pose some practical challenge since PVC would need to be separated from the mixed plastics.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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