



Insights into using plastic waste to produce activated carbons for wastewater treatment applications: A review

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ABSTRACT

This review explores the potential use of plastic waste for the preparation of activated carbons, which can be used as adsorbent materials to remove contaminants from water. Using discarded plastics to synthesize activated carbons has several benefits. Firstly, it helps to reduce the plastic waste burden that ends up in landfills and oceans or dumped on roadsides. Secondly, it creates a potential sector for using discarded plastics to treat pollutants further and approaches a closer circular economy scenario for plastics. Polyethylene terephthalate, tire, and plastic mixtures have been the plastic polymers most studied. The superficial area of activated carbons derived from plastic waste chars varies in a wide range, from 0.1 to 2152 m²/g. KOH seems to be the most widespread activated agent used, and the one that leads to the best textural properties. In general, the adsorption capacities of heavy metals were lower than 300 mg/g. On average, plastic waste chars have higher kinetic rates for adsorbing contaminants of emerging concern (CECs) compared to heavy metals. CECs uptake varies from 2 to 659 mg/g. Although the feasibility of developing porous materials is currently under research with promising results for a successful industrial application, some flaws regarding the granulometry, possible leaching, regeneration ability, and costs, among others, have not been addressed yet.

1. Introduction

Plastic waste pollution refers to the accumulation of discarded plastic materials in the environment, particularly in the oceans, rivers, and landfills. It has become a global concern due to its detrimental impact on ecosystems, wildlife, and human health [1]. The rise of plastic production and consumption over the past few decades has led to an alarming increase in plastic waste, posing significant challenges for waste management and environmental conservation efforts [2].

Marine animals often mistake plastic for food, leading to their injury or death. Additionally, plastic waste releases harmful chemicals into the environment, which can have long-term effects on wildlife and human health [3]. To safeguard ecosystems, protect wildlife, and preserve human health, immediate action to reduce, recycle, and properly dispose of plastic waste must be taken [4].

Industrial wastewater treatment is the process of removing contaminants from wastewater generated by industrial activities. It involves various physical, chemical, and biological methods to ensure that the water is safe before being discharged into the environment, or reused.

The importance of industrial wastewater treatment cannot be overstated, as untreated wastewater can have detrimental effects on both human health and the environment [5]. In recent years, European legislation related to the discharge of liquid effluents into the environment (Water Framework Directive) has become stricter, raising particular concerns regarding pollutants such as heavy metals and Contaminants of Emerging Concern (CECs). Heavy metals are bio-accumulative, non-biodegradable, and toxic, posing a hazard to human and animal health. The presence of heavy metals in water bodies may be due to natural causes or human activity such as waste disposal, industrial processes, or mining [6]. The CECs are a wide variety of chemicals that have recently been detected in the environment; they include pharmaceuticals, hormones and steroids, disinfection by-products, hygiene and personal care products, surfactants, flame retardants, household products, agrochemicals (pesticides and fertilizers), and microplastics, among others [7]. Chemical precipitation, coagulation-flocculation, membrane filtration, advanced oxidation, and ion exchange are examples of traditional methods for the remediation of heavy metals and CECs from wastewater [8–11]. However, these procedures

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have several limitations that prevent them from being used widely, including poor removal efficiency, significant energy consumption, and the production of harmful sludge [12,13].

Adsorption is a well-developed and cost-effective method to remove such pollutants from liquid effluents [13]. Typical adsorbent materials include alumina, activated carbon, clays, silica gel, composites, zeolites, and biomass of diverse origins, among others [14]. In recent years, novel low-cost activated carbons have also been produced from char obtained from the pyrolysis of plastic waste [15]. Pyrolysis is a thermal decomposition process that involves the transformation of organic materials into valuable products in the absence of oxygen at relatively high temperatures [16,17]. The pyrolysis process produces a liquid or oil that can be assimilated to a fuel or raw material for obtaining chemical products of interest, a gas with a low calorific value that is usually used to feed the energetic needs of the pyrolysis process, and a solid product, namely char, which presents proven adsorption capability even before activation [18]. The prime application as an adsorbent has gained attention due to the laudable textural properties these carbonaceous materials may reach after a convenient activation. However, other properties such as electrical conductivity and capacitance, optical properties, or extraordinary absorptivity enable these kind of materials for numerous applications, schematized in Fig. 1, such as a sensor for microbiological control [19] or photodetectors, construction of solar cells, energy storage [20] in batteries and supercapacitors [21], membrane separation [22] or as feedstock for electrochemical devices [23], as support for catalysts [24], etc.

The preparation of activated carbons from plastic polymers was first reported in the late 1970s and early 1980s [25–27]. Fig. 2 pictures the main milestones of activated carbon prepared from plastics as a precursor with potential applications in water treatment. These pioneer

studies developed the preparation of very porous materials from diverse polymers such as polyvinylidene chloride, polyvinyl chloride, polyacrylonitrile, polycarbonate, polyester, polyethylene, and polystyrene, by activation with CO_2 , H_2O or Cl_2 , leading to outstanding surface areas in the range of 700–2000 m^2/g [25]. However, since the outbreak of important concerns regarding the management of plastic waste, there has not been a remarkable evolution in this topic. It was in the early 21st century when the idea of plastic recycling took relevance, being polyethylene from plastic bottles massively researched. In 2004 was published the first work that explores the transformation of plastic bottles into porous carbonaceous materials, i.e. over 1000 m^2/g , being able to absorb phenol in water [28]. The first study reporting the adsorption of metals, Ni concretely, as an application of the valorization of plastic residues appeared in 2006 [29]. Since then, the adsorption of contaminants of emerging concern such as ibuprofen [30] and acetaminophen [31] has started to be intensively tested using carbon porous materials resulting from diverse plastic waste. The adsorption of metals has been continued since that with diverse metals such as Hg [32] or Co [33].

The research on porous carbon materials, although extensive in general terms, is scarce if the carbon precursor material is limited to plastic derivatives. Fig. 3 represents the evolution of the number of publications related to adsorption onto chars or activated carbons from 2000 to 2022. During this period, the adsorption into carbonaceous materials has been extensively studied, with 82,092 articles registered in the Web of Science (WOS) database, with 8205 articles solely for 2022. In contrast, the interest in researching carbonaceous adsorptive materials produced from plastic waste started around 2010, followed by an increasing trend, but with less research production compared to the total (including biomass origin). Looking in more detail into the year 2022, only 175 articles out of the total of 8205 were related to adsorption into

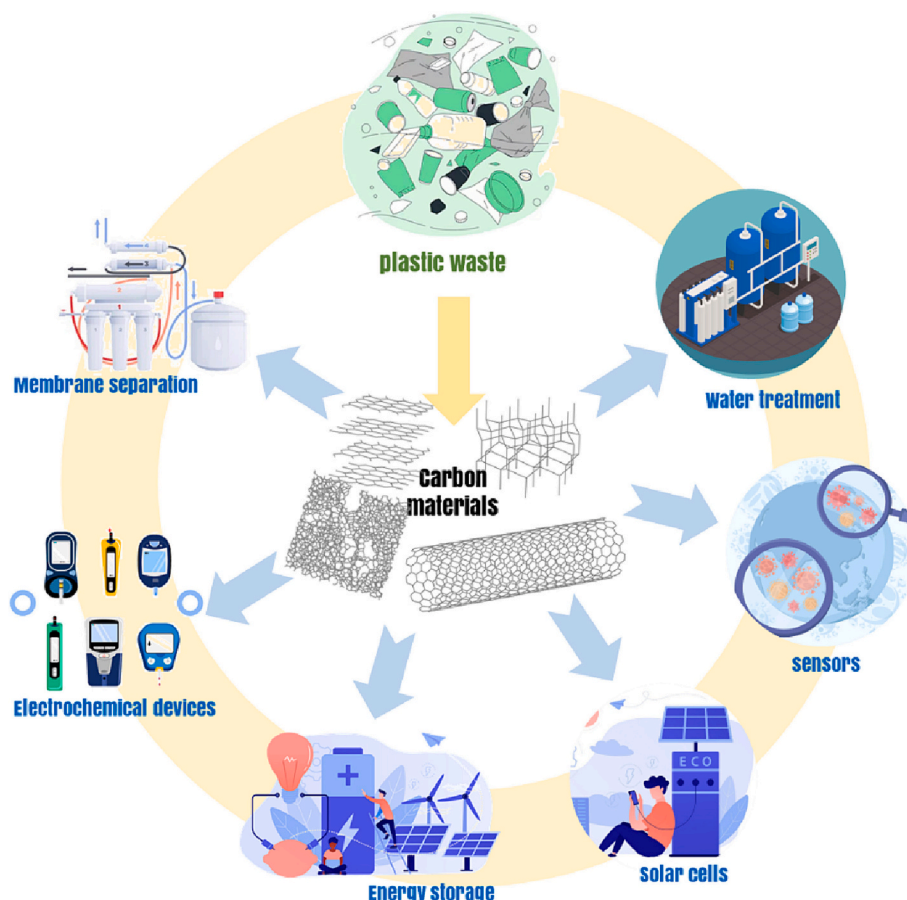


Fig. 1. Potential application of carbon-derived materials obtained from plastic waste as a feedstock.

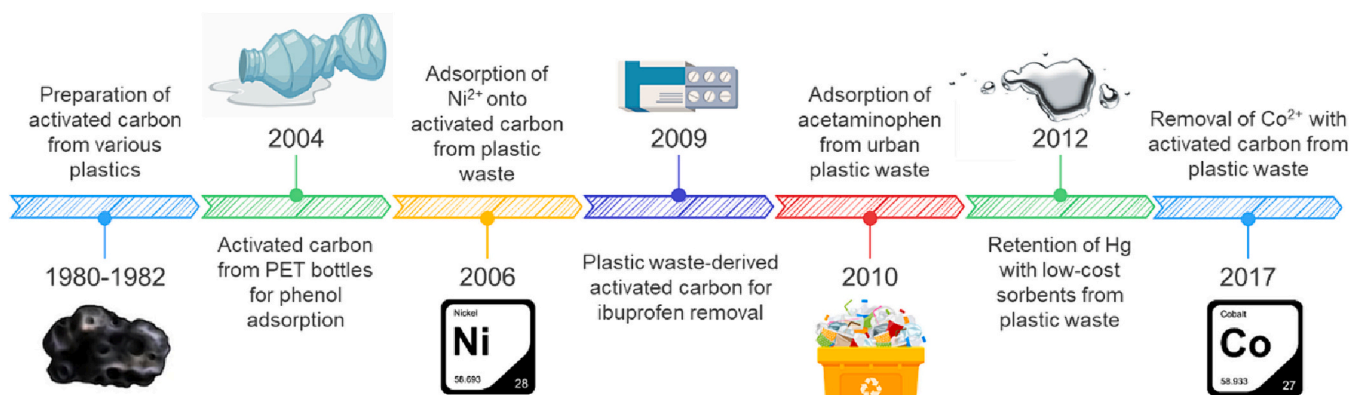


Fig. 2. Timeline milestones in the research of activated carbons produced from plastics and their application in water treatment. Data source: Scopus®.

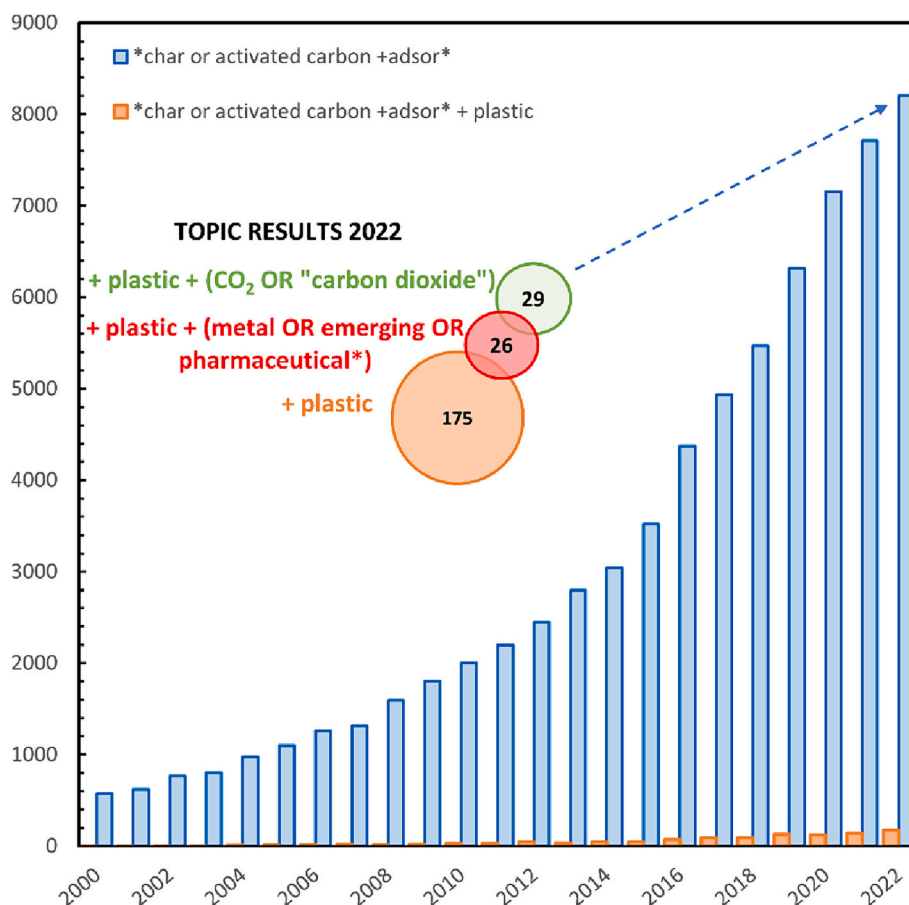


Fig. 3. Evolution of the number of publications related to adsorption into chars or activated carbons from 2000 to 2022. Results were extracted from Web of Science and the year 2022 has been studied in more detail (circles), dividing the results into four categories: adsorption into chars or activated carbons; those related to plastic char; plastic char for the adsorption of heavy metals and CECs and, plastic char for the adsorption of CO₂.

plastic waste-derived carbonaceous materials. Considering the final application, the adsorption of CO₂ seems to receive more attention compared to the adsorption of contaminants in liquid effluents (heavy metals and CECs). Although the number of articles published in 2022 on these two topics is similar (29 and 26, respectively), it has to be considered that, in the first case, just the contaminant CO₂ is studied, while the second case includes a wide variety of pollutants.

The plastic management problem and the potential application of chemical recovery through pyrolysis [34] lead to the production of carbon-enriched chars whose prime application has been addressed as

adsorbent [35–38], which has increased the attention of the research community in the last decades. Based on that, this review explores the potential of using plastic waste to create activated carbon, which can be used as adsorbent materials to remove contaminants from water. Although it is demonstrated that chars and activated carbon derived from plastic waste are reasonably effective in removing heavy metals and CECs, there are still some issues that need to be addressed before the commercial application of this process can be fully implemented. The review will help to understand future research needs and ensure the feasibility of product application at full scale. Using discarded plastics to

create activated carbon has several benefits. Firstly, it helps to reduce the plastic waste burden that ends up in landfills and oceans or is dumped on roadsides. Secondly, it creates a potential sector for using discarded plastic to further treat pollutants and approaches closer to a circular economy for plastics. Thirdly, activated carbon is one of the most recommended adsorbents for removing contaminants from water and adsorbing greenhouse gases, so using discarded plastics to create activated carbon can help address environmental pollution.

This review firstly examines the prime factors that affect the production of char from plastic waste and their further transformation into porous materials. Next, it addresses the characterization techniques that are commonly applied, especially those pertaining to the textural and superficial properties. Then, the performance of the prepared adsorbents on the removal of heavy metals and organic pollutants of emerging concern is reviewed, analyzing some variables affecting the process such as the pH, the initial concentration of the adsorbate, the temperature, and the contact time. Finally, some prospects, challenges related to the preparation methods, and future outlook are addressed.

2. Production of char and activated carbon

2.1. Production of char

There are various methods for producing char from plastic waste, including pyrolysis and hydrothermal carbonization. Pyrolysis involves heating the plastic waste in the absence of oxygen, resulting in the production of gas, liquid (oil), and solid (char) products [15]. Another method is hydrothermal carbonization, which involves subjecting the plastic waste to high temperatures and pressures in the presence of water, ultimately leading to the production of hydrochar [39]. Both methods have their advantages and limitations, but they offer promising solutions for transforming plastic waste into a valuable resource. However, further research and development are needed to optimize these recycling methods.

Pyrolysis has received great attention for recycling plastic waste [34,40,41]. Factors to consider in the pyrolysis process include the selection of an appropriate temperature, heating rate, and residence time [42]. In terms of operational factors, there are three types of pyrolysis: 1) conventional/slow pyrolysis; 2) fast pyrolysis; and 3) ultra-fast/flash pyrolysis [43]. Slow pyrolysis is characterized by slow heating rates, low pyrolysis temperatures, and long solid and gas residence times. It is used to modify the solid material, maximize the solid char product, and minimize the gas and oil produced [44]. Fast pyrolysis is the rapid thermal decomposition of carbon-containing materials in the absence of oxygen at high heating rates, intermediate pyrolysis temperatures, and short residence times. It is the most common method used to maximize liquid product yield [35]. Finally, flash pyrolysis is a very rapid thermal decomposition pyrolysis process with a very high heating rate, a high pyrolysis temperature, and a short residence time. The main products are gases and oils [45].

The temperature should be carefully controlled to ensure efficient conversion of plastic waste into products, while the heating rate and residence time should be optimized to achieve maximum product yields without compromising the quality of the products. Additionally, other factors such as pressure, feedstock composition, and water content should also be considered to achieve desired product properties and overall process efficiency. Chars pyrolyzed at 550 °C have demonstrated a higher adsorption capacity if compared to those pyrolyzed at 450 °C. This is attributed to the higher surface area presented by chars prepared at higher temperatures [6,46]. Other studies have found that the highest weight percentage (wt%) of char was achieved at a pyrolysis temperature of 460 °C from a plastic waste mixture. However, the tested temperature range, e.g., 460–600 °C, showed minimal influence on the char yield, which remained within a range of 0.9–1.1 wt% [47]. The obtained chars from the pyrolysis of high-density polyethylene (HDPE) plastic residue, carried out via fast pyrolysis within the temperature range of

400–450 °C, were characterized by a high content of fixed carbon (46 %) and volatiles (51 %) [35]. Also, the slow pyrolysis of HDPE plastic at 300 °C has been demonstrated to yield 33 % of char [48]. Generally, slow pyrolysis, carried out at low temperatures, i.e. below 450 °C, with a slow heating rate (0.1–1 °C/s), generates higher percentages of yield production (0.5–78 wt%). However, the percentages of yield production are notably influenced by various factors such as the plastic type, reactor design, particle size, and other operational parameters [49].

Also, the effect of different plastic polymers such as polyethylene (PE) either high density (HDPE) or low density (LDPE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), or polyvinyl chloride (PVC) on the yield and quality of pyrolysis products has been previously investigated [15,50–53]. For example, the goal of one specific study [41] was to investigate how plastic waste type affects the yield and quality of the liquid oil produced during the pyrolysis process. Compared to other plastics, polystyrene produced the most liquid oil (80.8 %) mainly composed of styrene (48.3 %), ethylbenzene (21.2 %), and toluene (25.6 %). Also, the composition of gaseous fractions when different biomass-plastic mixtures were pyrolyzed was investigated [52]. In general, HDPE, LDPE, and PP have positive synergetic effects on liquid yield in co-pyrolysis with solid biomass, whereas PET, PS, and PVC have positive synergetic effects on solid char or gas output.

Other alternative processes for the synthesis of solid carbonaceous materials have been reported, such as hydrothermal or catalytic-based pyrolysis processes that may impact the properties of the released char. For instance, hydrothermal carbonization is a thermochemical conversion method in which the plastic feedstocks are treated into aqueous solutions under pressure at mild temperatures, i.e. between 180 °C and 250 °C, to generate a hydrochar with diverse properties depending on the polymer nature and conditions [54], obtaining diverse allotropic forms of carbon, such as microporous sheets, graphene layers, or carbon dots [20,55]. The process, although interesting in tuning the char properties, may be lavish due to the costly equipment needed to develop the required high pressure (2–10 mPa). Pertaining to catalytic pyrolysis processes, the presence of solid enriches the nature of the char produced allowing the formation of carbon nanotubes, nanocages, and 2D nanosheets, among others [54,56].

2.2. Production of activated carbon

The adsorption capabilities of char from plastic waste can be enhanced through the incorporation of specific additives or treatments, such as chemical or physical activation or specific surface modification [15,57]. These methods can increase the surface area and porosity of the char, improving its ability to adsorb pollutants from various sources. Furthermore, ongoing research and development efforts should focus on optimizing the adsorption capacity of char from plastic waste as well as exploring new applications and markets for this valuable resource [15].

Activation methods are mainly divided into two categories: activation using chemical agents and activation using physical means. For chemical activation, the char is impregnated or mixed with chemical agents. Common chemical activation substances found in the literature include alkalis like NaOH and KOH. These alkalis react with the carbon and oxygen contained in the char. The gasification reaction produces CO and CO₂, which are responsible for the microporosity created in the char [58]. Also, chemicals like zinc chloride (ZnCl₂), potassium carbonate (K₂CO₃), phosphoric acid (H₃PO₄), and sulphuric acid (H₂SO₄), among others, have been used in the preparation of activated carbons [59]. Physical activation is a two-step procedure that involves carbonization (pyrolysis) in a neutral atmosphere, followed by activation using oxidizing gases like steam, carbon dioxide, and nitrogen, or air mixtures at elevated temperatures in the 800–1000 °C range. This technology is thought to be environmentally friendly because it uses no chemicals and does not need a washing step to eliminate the residual activating agent from the final solid at the end of the activation process [60]. However, the main drawbacks of physical activation are its high energy

consumption, extended activation period, and low adsorption capacity [61]. The composition and chemical structure of the raw plastic waste, the choice of an appropriate activating agent, and the time and temperature of pyrolysis and activation are the most crucial factors in the production of activated carbon for CO₂ capture.

3. Characterization of char and activated carbons obtained from plastic waste

Currently, several characterization techniques have been applied to characterize char and activated carbons produced from plastic waste, including point of zero charge, bulk density to provide details of the acidic and basic surface functional groups, elemental analysis, Scanning Electron Microscopy (SEM), N₂ adsorption-desorption isotherms to characterize the textural properties such as BET surface area, pore diameter, and pore volume; thermogravimetric analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR), etc. Table 1 shows a compilation of common characterization methods and references in the literature in which these techniques have been used.

The morphology of the activated carbon surface can be studied using SEM imaging. Fig. 4 shows activated chars produced from PET bottle waste using different activation methods. Physical activation with steam results in an agglomerate composed of small grains of material with void space in between, suggesting that the activating agent acts uniformly on the surface of the char. Chemical activation with KOH produces an activated char with pores of different sizes that suggest a progressive consumption of material [65].

In Table 2, elemental, proximate analysis, and textural properties obtained for char and activated carbons produced from diverse plastic waste are reported. The prime properties of an efficient adsorbent are the textural properties, the surface area, and the pore volume. According to the literature review, the char and activated carbons obtained from plastic waste have developed surface areas ranging from 0.1 to 2151 m²/g. Here, it is possible to notice that, in general, activation with KOH develops the highest surface area values: for example, 1002 m²/g for PET from bottle waste [65] and 2151 m²/g for polyacrylonitrile (PAN) [69] due to the severe reactivity with the carbon content of the char, leading to the formation of a great degree of microporosity as CO₂ is released in the process [80]. Physical activation treatment has also been reported to supply high surface areas. For instance, physical activation of PET waste using CO₂ provides a surface area of 1426 m²/g [30] and between 1110 and 1800 m²/g [64]. Similarly, the surface area reached 1235 m²/g when PET waste was physically activated with water steam [65].

The activation with chemical agents has been reported as more efficient than the physical; however, it strongly depends on the plastic precursor and the conditions of the activation process. The type of activating agent is a crucial variable that can be conveniently selected to improve the porous development of the prepared activated carbon. The textural properties of activated carbon prepared from PET with different chemical activation agents, i.e., phosphoric acid, sodium hydroxide, and potassium hydroxide, evidenced that H₃PO₄ and NaOH were not the most suitable activating agents for promoting high pore volume [81]. Nevertheless, the activated carbons produced with KOH displayed a very high porosity due to an enlargement of the small micropores. The activation of chars recovered from dirty plastic waste from municipal solid waste by physical activation (air and CO₂) and chemical activation (KOH and K₂CO₃) demonstrated that those activated under a chemical scheme presented improved textural properties [82]. The benefits of KOH versus NaOH or physical activation with CO₂ have been proven and confirmed during the activation of post-consumer plastic [58]. However, KOH leads to higher microporosity due to its higher corrosiveness compared to NaOH. Diverse examples support this aspect such as the activation of polyurethane foam [83] or PET [84]. In the case of mixed plastic waste, the activation of mixed plastic waste with NaOH has reported a much lesser surface area, i.e. 247 m²/g of NaOH vs. 487 m²/g of

Table 1
Usual methods to characterize plastic chars and activated carbons.

Properties	Characterization method/equipment	Precursor of the carbonaceous material	Ref.
Textural properties (specific area, pores size, and volume)	N ₂ adsorption-desorption isotherms at 77 K	Post-consumer plastic wastes	[58]
		Plastic waste	[18]
		PVC and PE	[62]
		Plastic chars (PET, PE, PVC)	[46]
		PET	[6]
		PET	[30,63]
		PET	[64]
		PVC	[65,66]
		PE	[67]
		PAN	[68]
Morphology	Scanning Electron Microscopy (SEM)	PAN	[66]
		PS	[69]
		PS	[63]
		Tires	[70]
		Tires	[71–74]
		Post-consumer plastic wastes	[18,58]
		Plastic waste	[62]
		PVC and PE	[46]
		Plastic chars (PET, PE, PVC)	[6]
		PET	[75]
Surface functional groups	Fourier Transformed Infrared (FTIR) spectroscopy	PET	[63]
		PET	[65,66]
		PVC	[77]
		PAN	[66]
		PAN	[69]
		PS	[63]
		Tires	[72,74,78]
		PET	[64]
		Post-consumer plastic waste	[18]
		Waste tire	[79]
Composition	EDX analysis and elemental mapping	PVC and PE	[46]
		Plastic chars (PET, PE, PVC)	[6]
		PET	[75]
		PET	[65,66]
		PVC	[67]
		PAN	[66]
		Tires	[70,71,73,78]
		Plastic waste	[62]
		PET	[75]
		PET	[64]
Composition	X-ray fluorescence (XRF)	PVC	[67]
		Tires	[71,74]
		Post-consumer plastic wastes	[18]
		Waste tire	[79]
		Plastic chars (PET, PE, PVC)	[6]
		PET	[75]
		PE	[68]
		PAN	[66]
		PAN	[66]
		Tires	[74]
Composition	Elemental Analysis	PAN	[69]
		Tires	[70,74]
Composition	X-Ray photoelectron spectra (XPS)	PAN	[69]
		Tires	[70,74]

(continued on next page)

Table 1 (continued)

Properties	Characterization method/equipment	Precursor of the carbonaceous material	Ref.
Crystallinity	X-ray diffraction (XRD)	Plastic waste	[62]
		PVC and PE	[46]
		PET	[75]
		PET	[76]
		PET	[64]
Particle size	Zetasizer Nano ZS90	PVC	[67,77]
		Tires	[74,78]
		Plastic waste	[62]
Surface charge	Zeta potential	Plastic waste	[62]
		PET	[63]
		PAN	[66]
		PS	[66]
		Tires	[63]
Cation Exchange Capacity	pH at the point of zero charge (pHpzc) (Mass titration)	Tires	[70,74]
		PET	[30,65]
		PVC	[67]
Mineral content (metals)	Ammonium acetate extraction	Tires	[71,72]
		Tires	[74]
Mineral content (metals)	Acid extraction + Atomic Absorption Spectrometry (AAS)	Tires	[73]

*PE: polyethylene, PET: polyethylene terephthalate; PS: polystyrene; PVC: polyvinyl chloride; PAN: polyacrylonitrile.

KOH [58]. The activation with acids like H_2SO_4 and H_3PO_4 is another very popular strategy in which the acid is impregnated in the carbon precursor, leading to the formation of volatile species during the reaction and temperature rise. Consequently, the evaporation of this species triggers the appearance of pores. Some successful pyrolysis of PET-impregnated H_3PO_4 and treated at 800 °C reports areas of 1220 m²/g, comparable to those obtained after activation with KOH. The use of H_2SO_4 has described lower values, i.e. 583 m²/g [85].

The development of alternative greener chemical activation methodologies has been claimed as desirable due to environmental risks associated with KOH [80]. Nonetheless, the availability of studies dealing with alternative agents is limited in the field of plastic residues.

Numerous studies demonstrate the impact of activation temperature on the textural properties of activated carbons during the synthesis process. The activation temperature significantly impacts surface

properties like BET surface area, pore volume, etc., with an increase in temperature increasing these characteristic parameters. However, a rise in the activation temperature generally results in a solid yield reduction [59]. The combined activation from post-consumer PET, including heat treatment with sulphuric acid (chemical activation), followed by steam activation (physical activation) in the range of 500-800 °C, has demonstrated that the optimum activation temperature was 800 °C for increasing the BET surface area and pore volume [86].

Another crucial factor in the activation process is the impregnation ratio, defined as the relative proportion of the activating agent compared to the char or the char precursor. The impregnation ratio of activated carbons can greatly influence the surface area chemical properties and concentration of functional groups anchored on their surface [87]. In general terms, a higher impregnation ratio of a specific chemical can increase the number of oxygen-containing functional groups on the activated carbon surface. The tailoring of the surface with oxygenated groups has been reported to boost the adsorption performance as a result of specific interaction between the acidic centers of the carbon and the basic point of the adsorbate molecule [88], the latter enhancing the ability to retain pollutants such as organic molecules and, therefore, the overall performance of the material. However, in the case of heavy metals, the nature of the metal defines their preference for certain groups. For example, Pb^{2+} tends to be adsorbed on the π -electron cloud in the basal planes of the graphitic surface of carbon materials whereas other cations such as Ni^{2+} and Zn^{2+} are adsorbed on oxygen functional groups [89]. Additionally, a high impregnation ratio of activated carbon with a specific metal-chelating agent can enhance the selectivity of the carbon towards that metal. This allows for efficient removal of the targeted pollutant while minimizing interference from other contaminants present in the wastewater. However, there is a limit to the impregnation ratio beyond which the adsorption capacity starts to decrease. This is because an excessive impregnation ratio can lead to pore blockage and hinder the accessibility of the pollutants to the functional groups on the carbon surface [90]. Besides, the use of an excessive amount of the activating agent may result in a reduction of specific surface area because of a greater degree of chemical reaction that destroys pores [91]. Therefore, finding the optimal impregnation ratio is essential to maximize the adsorption capacity of activated carbons.

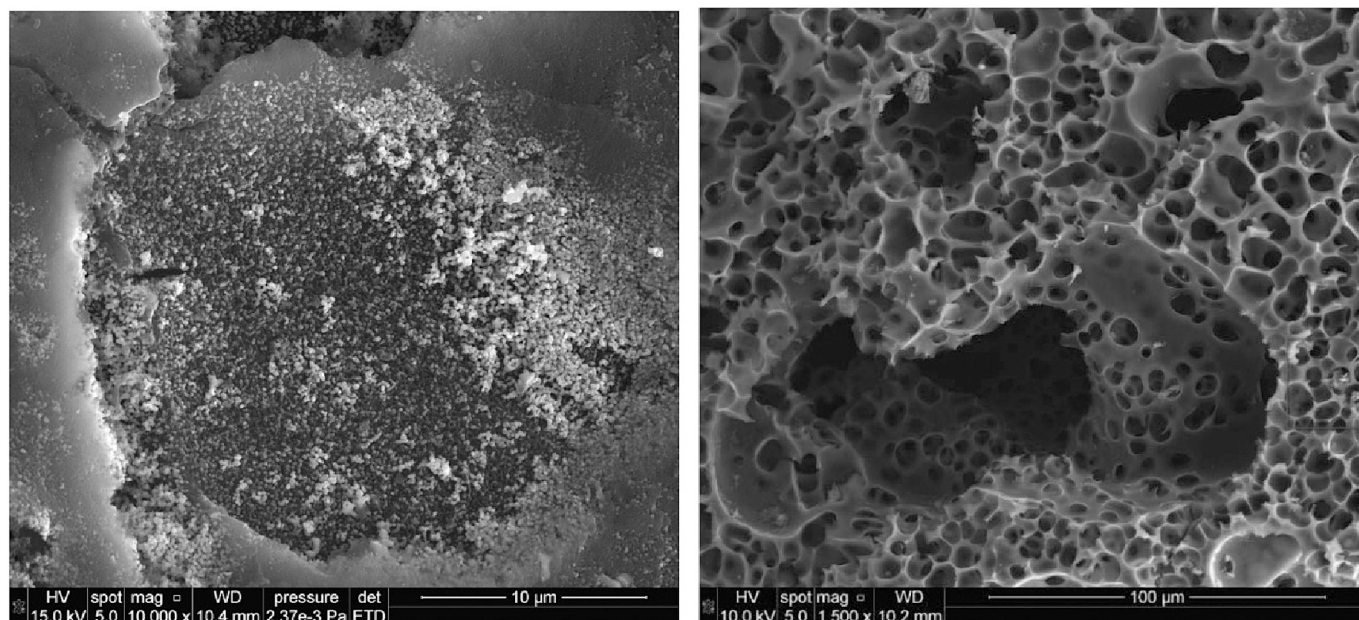


Fig. 4. SEM images of activated carbons produced from PET bottles waste using physical activation with steam (left) and chemical activation with KOH (right) [65].

Table 2
Characterization of different adsorbent materials obtained from plastic waste pyrolysis.

Material	Pyrolysis T (°C)	Activation/modification/treatment	Elemental analysis (%)					Immediate analysis (%)				Textural properties		Ref.	
			C	H	N	S	O	MC	VC	FC	AC	S _{BET} (m ² /g)	V _{MP} (cm ³ /g)		
Post-consumer plastic waste	500	CO ₂ (100 mL/min, 760 °C, 1 h)	–	–	–	–	–	–	–	–	–	–	68	0.008	
		NaOH (2:1, 300 °C, 1 h + 760 °C, 1 h)	–	–	–	–	–	–	–	–	–	–	247	0.084	[58]
		KOH (2:1, 300 °C, 1 h + 760 °C, 1 h)	–	–	–	–	–	–	–	–	–	–	487	0.180	
Post-consumer plastic waste	550	–	17.82	0.55	0.24	0	12.95	0.84	24.90	6.40	67.87	67	0.040 ^a	[18]	
Waste tire	–	KOH (1:2, 600 °C, 1 h)	–	–	–	–	–	3.40	0.8	83.60	12.00	–	–	[79]	
Plastic waste	>350	Magnetization (ratio 1:5 char: magnetite)	–	–	–	–	–	–	–	–	–	28.3	0.158 ^a	[62]	
PVC and PE	550	–	–	–	–	–	–	–	–	–	–	0.1-58.9	–	[46]	
Plastic chars (PET, PE, PVC)	550	–	36.80	0.18	0	0.14	–	8.11	7.89	73.20	10.80	0.3-5.3	–	[6]	
PET	600	Magnetization (10 g char in 1 L 0.1 M FeCl ₂)	–	–	–	–	–	–	–	–	–	33.6	3.120	[75]	
Tire	600	KOH (1:2, 600 °C, 1 h)	–	–	–	–	–	–	–	–	–	–	–	[78]	
Rubber from used tires	–	Solvent extraction (hexane; hexane:acetone; acetone)	79.2	6.2	1.1	0.08	12.03	3.94	39.0	55.0	2.02	1.2	0.002 ^a		
Mixture of plastic waste	420	–	82.00	5.70	0.50	1.35	1.77	1.03	38.50	52.70	7.77	23.7	0 (only meso)	[73]	
Tire	550	–	89.08	6.88	0.57	0.61	2.86	–	–	–	–	24	0.290 ^a	[117]	
Tire	550	Oxygenation (7 % oxygen, 550 °C)	–	–	–	–	–	0.39	5.81	82.9	10.9	74.5	0.253 ^a	[70]	
Tire	570	KOH (200 mL/min, 750 °C, 1 h)	80.45	1.04	–	0.91	11.28	–	–	–	–	82.0	0.302 ^a	[74]	
Tire	750	KOH (100 mL/min, 1:1, 750 °C)	69.00	–	–	–	27.1	–	–	–	–	265	0.090 ^a	[71]	
Tire	500	H ₂ O ₂ (60 °C, 24 h) + 900 °C, 2 h	78.76	1.06	0.29	1.96	7.04	–	–	–	10.89	562	0.280	[72]	
PET bottle waste	–	H ₂ O (8.33 mL/min, 900 °C, 1 h)	89.30	0.88	0.0	0.0	1.10	–	–	–	–	1235	0.590	[65]	
PET	–	KOH (1:2, 850 °C, 1 h)	75.53	1.91	0.0	0.0	1.27	–	–	–	–	1002	0.500		
PS	600	KOH (1:2, 850 °C)	–	–	–	–	–	–	–	–	–	65.4	0.009	[63]	
PVC	–	KOH 1 M (250 °C, 24 h + 700 °C, 2 h)	56.70	–	–	–	16.31	–	–	–	–	19.8	~0	[67]	
PVC	185	Hydrothermal treatment	14.95	–	–	–	33.17	–	–	–	–	–	–		
PVC	250	PCV + Fe ₃ O ₄ + Sodium carbonate	39.02	–	–	–	25.78	–	–	–	–	–	–	[77]	
PE-lined paper coffee cup	500	CO ₂ (500 mL/min, 900 °C, 3 h)	86.80	3.20	0.90	0.00	6.20	0.60	18.50	78.00	2.90	383	0.233 ^a	[68]	
PET	400 + 725	CO ₂ (925 °C, 1 h)	–	–	–	–	< 1	–	–	–	< 1	1426	0.473	[30]	
PET	–	–	75.20	–	–	–	–	–	–	–	–	1400	0.460 ^a		
PAN	300 + 800	CO ₂ (110 mL/min, 800 °C, 1 h)	61.70	–	5.60	–	–	–	–	–	–	1230	0.560 ^a	[66]	
PET/PAN	–	–	88.10	–	6.20	–	–	–	–	–	–	1117	0.500 ^a		
PAN	–	KOH (20 mL/min, 1:0.8, 800 °C, 1 h)	79.77	0.96	7.27	–	–	–	–	–	–	2151	0.868		
PAN	–	KOH (20 mL/min, 1:0.6, 600 °C, 1 h)	53.39	2.41	13.78	–	–	–	–	–	–	204	0.059	[69]	
PET	825	CO ₂ (10 L/h, 900 °C, 8 h)	–	–	–	–	1.80	–	–	–	–	1210	0.413		
PET	825	CO ₂ (10 L/h, 925 °C, 6 h)	–	–	–	–	2.20	–	–	–	–	1180	0.405		
PET	825	CO ₂ (10 L/h, 940 °C, 4 h)	–	–	–	–	2.10	–	–	–	–	1110	0.397	[64]	
PET	825	CO ₂ (10 L/h, 940 °C, 5 h)	–	–	–	–	2.30	–	–	–	–	1830	0.604		

^a Total pore volume. PE: polyethylene, PET: polyethylene terephthalate; PS: polystyrene; PVC: polyvinyl chloride; PAN: polyacrylonitrile.

4. Performance of plastic waste-derived activated carbons in the adsorption of aqueous heavy metals and contaminants of emerging concern

In practical applications, special attention should be paid to the influence of environmental factors on the removal of target pollutants. These factors will change the removal performance of plastic waste-derived activated carbons.

Additionally, depending on the activation agent used, the elemental and proximate analyses of the resulting activated carbon may showcase

varying characteristics. For instance, carbons activated with KOH often exhibit a higher carbon content due to the elimination of non-carbon elements and a decrease in oxygen due to the removal of oxygen-containing functional groups. Also, the ash content might be higher due to the introduction of inorganic content during the activation process. Fixed carbon content is also increased due to enhanced carbonization, resulting in a lower volatile matter content, as shown in Table 2. Activation with solvent extractions produced activated carbons with very high carbon contents. The combined effect of solvent activation involving the removal of volatile components, enhanced carbonization,

increased purity, and the promotion of carbon retention contributes to the generation of activated carbons with a higher carbon content from chars derived from plastic waste [73]. The ash content of the activated carbons obtained from plastic waste is a key factor in affecting their adsorption properties. Most studies report ash content relatively low, i. e., <12 %; however, ash content provided for char from a mixture of real plastic waste can reach important values [58].

4.1. Effect of initial pH

The pH is a very influential variable in the adsorption process. Bearing in mind that the charge of the surface is pH-dependent, the dissociation of functional groups on the active sites of the surface determines the type of attraction or repulsion with other molecules. The char, when added to the aqueous solution, may alter the acid-base properties of the solution, which may have an influence on the ionic state of the target component to be removed. This is of paramount importance when working with metals since the species distribution curves change with pH, obtaining precipitated metallic compounds at certain pH values [92].

The removal efficiency of biomass and plastic waste chars for Fe, Ni, Cu, Cr, Cd, and Pb has been reported to enhance with the increase of the initial pH from 4 to 6 [6]. However, over pH = 6, a significant decrease in the removal efficiency of the chars was observed. This phenomenon was attributed to the fact that, at higher pH, the metal ions become less soluble and more difficult to be adsorbed. If the pH is too high, the mechanism of metal removal changes from adsorption to precipitation. For example, during the adsorption of lead with char activated with KOH, the highly basic character displayed on the surface, promoted a pH rise that entailed the precipitation as $Pb(OH)_2$ [58]. Consequently, a weakly acidic solution environment was the most suitable pH for the remediation of lead in this case. A similar conclusion was drawn in the adsorption of lead with activated char from tire waste [79]. Similarly, the remediation of copper with activated carbon was obtained from PVC plastic waste, suggesting optimal pH values between 6 and 7 [67]. A similar direction was pointed to the removal of arsenic by chars produced by pyrolysis of PVC, PET, and PE, selecting a pH of 6 as the most appropriate for arsenic removal [46]. Extreme acidic conditions do not favor the adsorption of metals. At very low pH, the presence of a high number of protons competes with the positively charged metal ions for adsorption sites, whereas at high pH values, the surface charge of the adsorbent becomes positive and the electrostatic repulsive forces between the adsorbate and the adsorbent make the adsorption of metal ions difficult [92]. Different behavior was observed with Cr^{6+} adsorption during the application of a magnetically modified hybrid adsorbent composite, prepared from bio-sludge and plastic waste. The point of zero charge of the prepared material and the anionic nature of Cr^{6+} indicated the need for a highly acidic environment, i.e., pH of around 1.5, for efficient Cr^{6+} removal [62].

From the above analysis, it is concluded that pH has an enormous influence on the removal of heavy metals by char and plastic waste-derived activated carbons. Therefore, choosing the appropriate pH is essential, and generally, a weakly acidic solution environment is more favourable for char and plastic waste-derived activated carbons to eliminate most heavy metals.

4.2. Effect of initial contaminant concentration

The influence of initial adsorbate concentration is an important factor to be considered for effective adsorption [93]. Diverse authors have reported that an increase in adsorbate concentration leads to higher adsorption capacity [94–96]. The rate of adsorption initially increases with the higher initial adsorbate concentration, as the driving force for mass transfer is higher. At high concentrations, there are more adsorbate molecules available for binding to the adsorbent sites. However, if the concentration becomes excessive, the rate of adsorption may

start to reach a plateau. This may be due to the saturation of active sites on the adsorbent material or the formation of adsorbate clusters that hinder further adsorption [97,98].

4.3. Effect of temperature

The temperature at which adsorption takes place plays a crucial role in determining the efficiency and effectiveness of adsorption processes. Understanding the impact of temperature on adsorption is therefore of great significance in optimizing adsorption systems and improving their overall performance [99].

The isotherms of rubber tire char physically activated for Ni and Pb adsorption at 25, 35, and 45 °C were studied, obtaining an increase of 5 % in adsorption capacity with increasing temperature [72]. A positive value for the adsorption heat was obtained, suggesting endothermicity. In contrast, negative values of adsorption heat were recorded in the process of copper adsorption into PVC waste carbon activated with KOH, indicating that the process was exothermic [67].

4.4. Effect of contact time and kinetics models

In general, as contact time increases, the effectiveness of removing heavy metals and other pollutants rises progressively. The removal efficiency is improved in the early stages because of the strong driving force and many adsorption sites. The adsorption sites eventually attain saturation as the adsorption progresses, and the adsorption rate declines until equilibrium is reached. The pseudo-first order and pseudo-second-order kinetic models are the most widely used in adsorption kinetics research and are often used to reflect the adsorption rate and dynamic adsorption equilibrium [100]. The pseudo-first-order model assumes that physical adsorption influences the adsorption rate and that this impact is reversible while adsorption is taking place [101]. The pseudo-second-order model, in contrast, presupposes that chemical processes have an impact on the adsorption rate [102]. Other researchers have proposed new mechanistic models to elucidate the adsorption kinetics of the removal of copper by oxygenated and non-oxygenated tire chars by incorporating the effect of pH changes [103].

The study of the performance of activated carbon derived from pulverized waste tires in the removal of heavy metals revealed that the produced activated carbon had a faster adsorption rate than commercial formulas [74]. This adsorbent showed equilibrium within 6 h, while the equilibrium of the commercial sample was reached after 24 h. Furthermore, the pseudo-second-order model showed very good agreement with the experimental data. The investigation of the removal of ibuprofen by activated carbons obtained from cork and plastic waste found that the ibuprofen removal was fast, i.e., within 1 h, and that the experimental data were fitted by a pseudo-second-order kinetic model with good correlation [30]. However, other authors found that the lead removal process onto chars from the co-pyrolysis of pine, used tires, and plastic waste was a slower process, e.g. above 48 h to reach equilibrium, in which it seems that adsorption and desorption play competition as cations compete for the binding sites [73].

4.5. Isotherm models

Adsorption isotherm modeling is of fundamental importance while designing sorption-based systems. Some of the most applied and known isotherm adsorption models are the Langmuir adsorption model, which assumes that adsorption occurs through a monolayer of molecules on the surface, with each adsorbed molecule being independent of others [104], or the Freundlich adsorption model [105]. Other isotherm adsorption models are the Sips model [106] and the Brunauer, Emmett, and Teller (BET) model [107], among others.

4.5.1. Adsorption of heavy metals

Various studies have investigated the adsorption capabilities of

activated carbons derived from different plastic precursors for the removal of heavy metals from contaminated aqueous effluents. Table 3 summarizes the main parameters of the adsorption isotherms with metals. Most authors reported metal adsorption capacity values lower than 300 mg/g, although in some exceptional cases, researchers have reached values close to 700 mg/g with activated chars [58]. In contrast, investigations conducted with unmodified char from a plastic waste mixture aimed at a maximum adsorption capacity of approximately 60 mg/g at a pH of 5 [18]. Both adsorption phenomena were suitably modeled by the Sips isotherm.

Waste tire materials have similarly reported high lead saturation capacities. The optimum documented uptake for lead adsorption onto activated carbons derived from waste tires has been placed at pH = 7 and an adsorbent dosage of 2.5 g/L [79]. The maximum adsorption capacity has been reported as 93 mg/g for Pb at pH = 7 [78]. Other studies underscored the superior affinity of plastic-tire mixtures for lead ion removal [73]. Further investigations reported lead adsorption performances with tire waste, exhibiting capacities of 322 mg/g when using tire char activated with KOH (Fig. 5) [74], 49 mg/g activated also with KOH [71], and 312 mg/g using oxygen peroxide activation [72], all fitting well with the Langmuir model.

In the context of copper adsorption, waste tires were utilized as carbonaceous materials for the preparation of activated chars. The removal of copper through adsorption into surface pores and cracks of the material, without accounting for precipitation processes, reached 50 % adsorption with an initial concentration of 25 mg/L of copper and a char dose of 5 mg/L [70]. The Langmuir model has been fitted to model the adsorption capacities of metals onto activated char from tires, obtaining maximum values of 10.4 mg/g and 29.4 mg/g for Cd²⁺ and Cr³⁺, respectively [71]. Furthermore, tires as precursor materials have demonstrated adsorption capacities of 185.2 mg/g for Cu and 71.9 mg/g for Zn²⁺, respectively [74], while the highest saturation uptake for Cu²⁺ adsorption was 145 mg/g, using PVC materials and fitting in all the cases

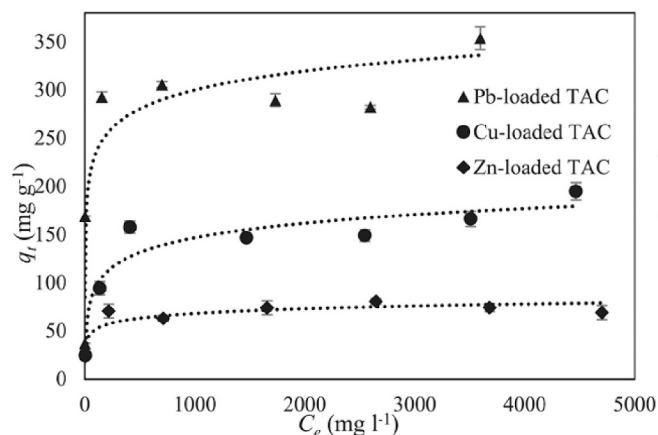


Fig. 5. Langmuir isotherms for the adsorption of Pb, Cu, and Zn into TAC (tire-activated carbon) [74].

to the Langmuir model [67].

PVC materials, in turn, were employed for arsenic removal, with a noticeable optimal removal efficiency of 99.4 % at a pH = 4 and a contact time of 15 min using a 20 mL solution with an initial concentration of 100 mg/L of As and a char dose of 0.5 mg, conforming to the Langmuir isotherm [46]. A magnetic char based on a magnetite composite from PVC has reported a maximum adsorption capacity of 0.6 mg/g for cobalt, lacking competitiveness if compared to activated materials [77].

For the removal of Cr⁶⁺ ions, plastic waste [62] and PAN [69] were effectively employed as precursors for the preparation of activated and functionalized materials, achieving adsorption capacities of up to 56.2 and 305.7 mg/g, respectively.

PET bottle wastes were employed in the preparation of activated

Table 3

Results of adsorption experiments in liquid effluents containing metals.

Material	Metal	pH	T (°C)	Adsorbent dosage (g/L)	q _{max} (mg/g)	Model	Reference	
Post-consumer plastic waste	Pb ²⁺	5-6	Room temperature	0.5	259	Sips	[58]	
					334			
					746			
Post-consumer plastic waste	Pb ²⁺	5	Room temperature	1	61.3	Sips	[18]	
Waste tire	Pb ²⁺	7	25	2.5	–	Freundlich	[79]	
Plastic waste	HCrO ₄	1.5	Room temperature	8	56.2	Langmuir	[62]	
PVC and PE	As	6	37	50	11.6	Langmuir	[46]	
								Cd
								Cr
Plastic chars (PET, PE, PVC)	Cu	6	Room temperature	–	–	Langmuir	[6]	
								Fe
								Ni
								Pb
								Pb
Tire	Pb	7	25	9.7	93.2	–	[78]	
Rubber from used tires	Pb	6	25	4	1.9	Data at initial metal concentration of 20 mg/L	[73]	
Mixture of plastic waste	Fe	3	30	0.5	25.2	Data at initial metal concentration of 22 mg/L	[117]	
Tire	Cu	5	24	5	0.2	Data at initial metal concentration of 25 mg/L	[70]	
								Pb
								Zn
Tire	Cu	–	20	4	185.2	Langmuir	[74]	
								Zn
								Pb
Tire	Cd	5	Room temperature	–	10.4	Langmuir	[71]	
								Cr ³⁺
								Pb
Tire	Ni	7.5	25	–	312.5	Langmuir	[72]	
								–
PET bottle waste	Fe ³⁺	4.4	25	4	14	Langmuir	[65]	
PVC	Cu ²⁺	6	25	1	145.7	Langmuir	[67]	
PVC	Co	–	25	2	0.6	Langmuir	[77]	
PAN	Cr ⁶⁺	2	25	1	305.7	Data at initial metal concentration of 448.7 mg/L	[69]	

*PE: polyethylene, PET: polyethylene terephthalate; PS: polystyrene; PVC: polyvinyl chloride; PAN: polyacrylonitrile.

carbons for the removal of Fe^{3+} ions, with saturation adsorption capacities of up to 14 mg/g [65]. This value was lower than the registered with a Darco® commercial formula, in which 74 mg/g of Fe^{3+} were adsorbed. The degree of microporosity was larger in the PET-derived activated carbon than in the commercial formula, and the increased adsorption of Fe^{3+} was attributed to the role played by the presence of more acidic groups in the latter which compete more favorably with protons for the adsorbent's surface active sites [65]. A comprehensive study on the adsorption of multiple metallic ions (Cd, Cr, Cu, Fe, Ni, and Pb) using chars derived from PET, PE, and PVC plastic materials, revealed a good fit for a Langmuir isotherm type [6]. From the different plastic mixtures, the highest sorption of Ni (43.32 %) and Cu (90.96 %) was shown by a mixture of PVC and PE pyrolyzed at 550 °C, while Cd (28.31 %), Fe (4.0 %), Pb (70.07 %) and Cr (99.01 %) by a mixture of PET and PE pyrolyzed at 550 °C. All experiments used 0.5 g of char and an initial concentration of 20 mg/L of the different metals.

4.5.2. Adsorption of contaminants of emerging concern

Regarding studies on the adsorption of CECs using char derived from plastic precursors, a summary can be found in Table 4. The adsorption of the pesticide 2-methyl-4-chlorophenoxyacetic acid (MCPA) using PET and PET/PAN blend-derived activated carbons (Fig. 6), achieved adsorption capacities of 341 mg/g and 200 mg/g, respectively [66]. A PET-derived activated carbon lab made under physical activation with CO_2 was also utilized for the removal of other CECs. The adsorptive removal of ibuprofen from this material reached a maximum adsorption capacity of 206 mg/g [30] whereas a commercial formula also activated with CO_2 from wood reported a similar uptake of 292 mg/g, and other activation of coal led to a higher capacity, i.e. 430 mg/g [30]. However, the plastic-derived adsorbent achieved a larger uptake over a wider pH range than some commercial adsorbents. This fact was attributed to the higher basicity of the PET-derived carbons, due to the delocalized π electron density of their graphene layers, which may act as Lewis base sites for adsorbing protons [108]. During the removal of cephalixin, an adsorption capacity of 21 mg/g was reached [109]. Other persistent organic pollutants, such as polyaromatic hydrocarbons (PAHs), have been investigated with PET-derived activated carbons. Sixteen different PAHs were tested [63], showing capacities of 4.0-7.6 mg/g, e.g., 6.6 mg/g for pyrene and 4.4 mg/g for acenaphthene. Comparatively, PET-derived activated carbons outperformed their PS plastic counterparts in capturing PAHs. PS-derived activated carbons have reported maximum uptakes of 3.8-6.3 mg/g for PAHs, e.g., 6.0 mg/g for pyrene and 3.8 mg/g for acenaphthene [63]. PS-derived carbon was also effective in the removal of the flame-retardant tetrabromobisphenol A from water, achieving an adsorption capacity of up to 117 mg/g [110]. Finally, the valorization of PET bottles on an activated carbonaceous material has demonstrated remarkable efficiency in removing p-nitrophenol from water, achieving an impressive adsorption capacity of 659

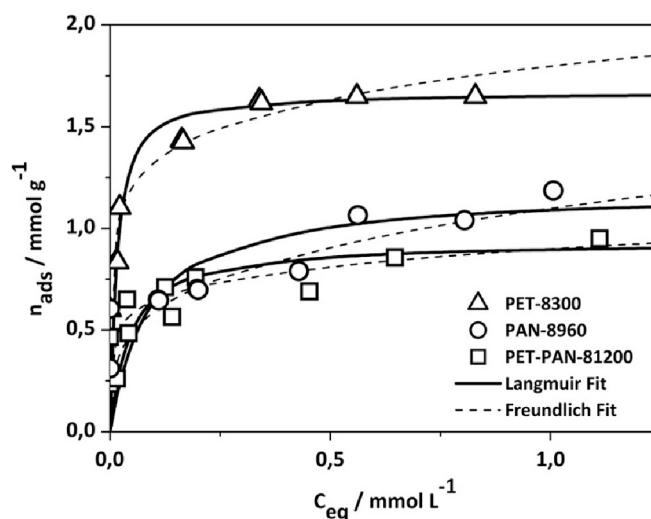


Fig. 6. Adsorption isotherms of MCPA obtained at 298 K, on the AC prepared from PET, PAN, and PET-PAN blend [66].

mg/g [65]. In this work, the performance of the prepared material was compared to a commercial formula. The PET-derived activated carbon exhibited higher adsorption uptake than the commercial Darco® formula, which retained only 182 mg/g of p-nitrophenol [65]. In other work, the use of PET led to activated carbons prepared via chemical activation with ZnCl_2 and K_2CO_3 . The activation with K_2CO_3 led to larger surface areas which positively impacted the uptake of 4-chlorophenol, i.e. 625 mg/g, which was even higher than the adsorbed amount with a commercial Darco® formula (303 mg/g) [111].

5. Prospects, challenges, and future outlook for industrial application

The valorization of plastic residues as precursors for activated carbon material is an interesting approach; nevertheless, there is a lack of thorough studies addressing the negative impact from a life cycle perspective. The activation of chars involves the consumption of chemicals, energy, and water that cannot be discharged. The chemical activation strategy provides enhanced control of the textural properties rather than the physical options, which enormously impacts the adsorption performance. However, the physical activation with H_2O or CO_2 is expected to be simpler, cheaper, and more feasible from an environmental point of view. Other alternative thermal processes of plastic such as hydrothermal degradation, although they lead to interesting carbonaceous materials with controlled morphology, require the use of expensive equipment due to the high required pressures which are

Table 4

Results of adsorption experiments in liquid effluents containing CECs.

Material	CEC	pH	T (°C)	Adsorbent dose (g/L)	q_{\max} (mg/g)	Model	Reference
PET	MCPA	3	–	–	341	Langmuir	
PET/PAN	MCPA	3	–	–	200	Langmuir	[66]
PET	Ibuprofen	4	30	0.67	206	Langmuir	[30]
PET	PAHs	5	24	8	4.4-7.6	Langmuir	[63]
PS	PAHs	5	24	8	3.2-6.3	Langmuir	[63]
PET	bisphenol A	6	25	0.4	2.3	Langmuir	[118]
PET	Cephalixin	NA	30	0.4	21.3	Langmuir	[109]
PS	tetrabromobisphenol A	8	25	0.03	117	Langmuir	[110]
PET bottle waste	p-nitrophenol	NA	25	4	659	Langmuir	[65]
PET bottle	4-chlorophenol	NA	Room Temperature	1	625	Langmuir	[111]
PE-lined paper coffee cup	Ibuprofen	–	–	3.33	36	Data at initial concentration of 120 mg/L	
	acetaminophen	–	–	3.33	36	Data at initial concentration of 120 mg/L	[68]

*PAHs, polycyclic aromatic hydrocarbons; MCPA, 2-methyl-4-chlorophenoxyacetic acid (pesticide).

hardly scalable for a large-scale industrial application. In addition to the challenges of the process, PET has been vastly researched as the raw material for the preparation of adsorbents, whose pyrolysis leads to a low yield. More studies on evaluating the potential of other polymers or even their mixtures are encouraged from a practical point of view.

Several factors affect the feasibility of industrial applications of the activated carbons produced from plastic precursors. The granulometry greatly affects the hydrodynamics expected in a real industrial installation. A small particle size is usually observed in chars. A fine powder from 1 to 600 μm is normally obtained [112], which leads to impressive pressure losses, blockages, or difficulties in separating the activated char from the liquid phase [113]. Different techniques have been suggested to overcome these drawbacks. Granulation of the activated char is a common technique that prevents the aforementioned issues; however, it entails other drawbacks such as loss of porosity and high production costs due to the need to use binders to form the granules [113]. Moreover, there is a lack of knowledge regarding the granulation of activated char produced from plastic precursors.

Magnetization of char particles is another method to overcome the separation of the activated char from the liquid phase. The magnetization of a char can easily promote the separation from the liquid phase using an external magnetic field. The preparation of magnetic plastic char has been recently described, aided by the co-precipitation of iron salts [62]. The magnetic char reported a Cr^{6+} adsorption capacity of 56.2 mg/L and an increase in the surface area compared to the bare plastic char. In contrast, offering a much more anticipated result, other studies have reported a decrease in surface area after Fe loading using an impregnation method through co-precipitation of iron salts, due to pore occlusion [75]. Dynamic adsorption experiments in a fixed-bed column set-up showed an adsorption capacity of 1.9 mg/g for As^{3+} with an inlet concentration of 0.3 mg/L and a flow rate of 3 mL/min [75].

It is also important to determine the leaching properties of the char to establish the potentially harmful components that can be released in the real application. In this sense, it has been established that plastic chars after chemical activation are more stable compared to their native chars [58]. The Total Organic Carbon (TOC) released by the activated and stabilized chars was minimal if compared to the non-activated precursors.

Furthermore, it is expected that the solid char may contain metals that are typical of plastic production. TiO_2 is used as a white pigment and has UV-absorbing and stabilizing properties [114]. ZnO and Sb_2O_3 are used as multifunctional additives, e.g., pigmentation properties, flame retardants, or fungicides [114]. Barium sulfate is added as an inert filler to increase the stiffness and hardness of plastics [114]. However, Ti and Zn were not found in the leachate of plastic char after activation, nor other hazardous metals such as Hg, Cd, and Pb [58].

The ability of the chars to be regenerated is a key factor for industrial applications and it directly affects the operation costs of the facility. Rubber tire-activated char by physical activation was tested for the reusability of Ni^{2+} adsorption in a column set-up [72]. The desorption process was carried out by washing the saturated material (50 mg) with 100 mL of 0.1 M HNO_3 for 2 h. Approximately 98 % of the Ni^{2+} was desorbed in this process. Five consecutive adsorption-desorption cycles were performed and only an ~ 11 % decrease in adsorption capacity was recorded, as illustrated in Fig. 7. The regeneration using magnetized PET char employing 0.1 M H_3PO_4 after 3 regeneration cycles in a fixed-bed column reported only a 13 % loss of As^{3+} adsorption [75].

The cost of the final product is one of the critical factors in understanding the economic feasibility of the process; however, there is a lack of research studying this aspect [115]. The factors responsible for the final cost of the activated char include the cost and availability of the precursor (natural, agro-industrial by-products, or synthesized products), the production conditions (chemicals and energy consumption), and finally, the regeneration capability [116]. The location where the materials are made also influences the cost. The cost of the char has been estimated as approximately US\$ 25 per ton considering the cost of the

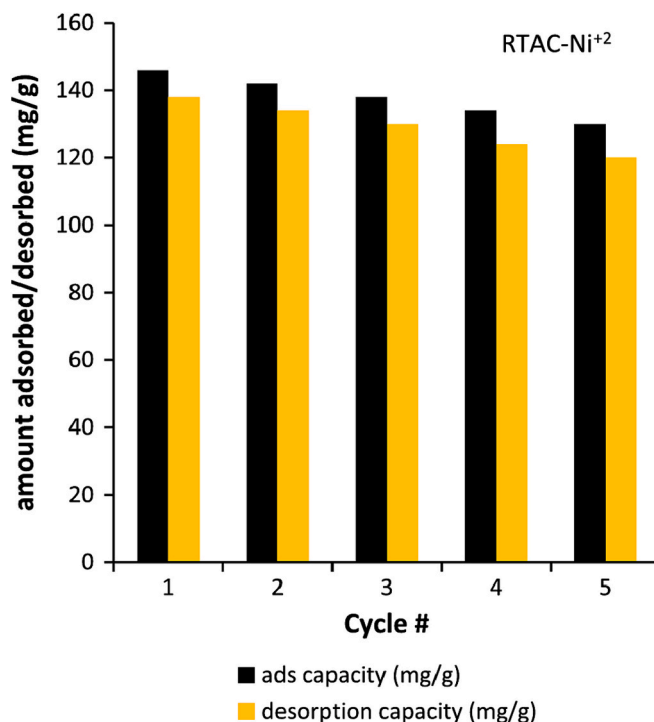


Fig. 7. Recycling of rubber tire activated carbon (RTAC) in the removal of Ni^{2+} (Ni^{2+} concentration, 200 mg/L; washing time, 120 min; washing temperature, 45 °C; adsorbent dose, 50 mg; and pH, 7.5) [72].

precursor (waste rubber tire granules), transport, chemicals, electrical energy used in the process, and labor. In contrast, the commercial activated carbon market price was US \$285 per ton [72]. Differences in the cost of commercial and plastic formulas may overcome the limitations in the targeting performance, seizing the possibility of revalorizing this kind of waste.

6. Conclusions

There is limited research on the production of activated char using plastic precursors, aggravated when only the treatment of liquid effluents with plastic char is considered. According to the database Web of Science, only 26 out of the total of 8205 articles published in 2022 related to adsorption into activated chars studied carbon materials derived from plastic waste applied for heavy metals or CECs adsorption. PET, tire, and plastic mixtures are the plastic materials most studied.

The superficial area varies in a wide range from very low 0.1 to a stunning 2152 m^2/g . Although there is not a clear trend, KOH is the most widespread activated agent used, and the one with the highest superficial area released. An increase in activation temperature improves the textural properties; however, it decreases the yield of activated char.

In terms of final application, the following conclusions can be withdrawn:

- In the case of wastewater treatment containing heavy metals, a high impregnation ratio of activated carbon with a specific metal-chelating agent can enhance the selectivity of the carbon towards that metal, increasing the presence of functional groups.
- A weakly acidic solution is the optimal pH for heavy metal adsorption.
- The adsorption of heavy metals using plastic waste chars varies between 0.2 and 746 mg/g.
- The adsorption of CECs using plastic waste chars varies between ~ 2 to over 600 mg/g.

- On average, the ability of plastic waste char to adsorb CECs is higher than the reported for heavy metals. The kinetics have also been labelled as faster than those observed for metals.
- Maximum CECs adsorption was found to be p-nitrophenol into PET bottle waste char activated with KOH.

For a successful industrial application, it is necessary to address the topics of granulometry, possible leaching, regeneration ability, and costs. The costs of producing activated carbons from plastic waste could be ten times less, which combined with the fact that waste is converted into a valuable product, makes activated carbons produced from plastic waste precursors a great alternative to conventional activated carbons, aligning with the concept of circular economy.

CRedit authorship contribution statement

Ledicia Pereira: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Ventura Castillo:** Writing – original draft, Investigation, Formal analysis, Data curation. **Mónica Calero:** Writing – review & editing, Project administration, Funding acquisition. **Gabriel Blázquez:** Writing – review & editing, Investigation. **Rafael R. Solís:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **M. Ángeles Martín-Lara:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

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

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