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IMPROVING THE QUALITY OF TYRE CHAR AS PART OF A CLOSED-LOOP ECONOMY

Abstract: The escalating accumulation of waste tyres necessitates the formulation of robust and economically sustainable waste management strategies. In response to this pressing concern, pyrolysis has emerged as a pivotal technology for tyre recycling, affording valuable by-products including charcoal, pyrolysis oil, and pyrolysis gas, contingent upon specific process parameters. Of particular significance is the valorisation of the solid fraction resulting from tyre pyrolysis, which holds promise for the reintroduction of this raw material into various production processes. This study explores three distinct processes aimed at enhancing the quality of carbonaceous materials: (1) heat treatment, which results in the remarkable reduction of volatile fractions by up to 94 %; (2) zinc leaching using a 20 % NaOH solution, achieving 59 % zinc extraction for potential electrochemical recovery; and (3) sulphur binding through $CaCO_3$ washing, effectively capturing 95 % of the sulphur content and mitigating SO_x emissions. The paper comprehensively outlines the advantages and limitations of these proposed solutions, while providing an in-depth evaluation of potential applications for charcoal based on the specific treatment methods used. The findings presented herein make a substantial contribution to the advancement of sustainable techniques for the valorisation of waste tyres, thereby bolstering environmental conservation efforts and fostering resource efficiency within industrial applications.

Keywords: waste tyres, pyrolysis, valorisation, waste management, the closed-loop economy

Introduction

The automotive industry stands at a critical juncture in its pursuit of a more ecologically sound and sustainable future. As global concerns escalate over climate change and environmental degradation, the urgency for innovative solutions to reduce carbon dioxide emissions has reached unprecedented levels. Improper disposal of waste tyres has emerged as a significant contributor to environmental pollution, releasing harmful pollutants into the atmosphere and posing substantial challenges in waste management [1, 2]. The worldwide production of used tyres is over 1 billion and constitutes approximately 2 % of all generated waste [3]. In the United States alone, the Federal Highway Administration's Office of Research, Development, and Technology reports an annual generation of around 280 million discarded tyres [3]. Amidst these concerning statistics, the demand for efficient and sustainable tyre disposal methods has become increasingly pronounced.

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Tyres are rubber products whose mechanical properties primarily depend on the type and quantity of polymer, filler, and plasticiser used. In rubber compounds, the application of activators is necessary to enhance the performance of accelerators, thereby expediting the process. One of the most effective activators is zinc oxide, which functions by forming complex compounds with accelerators (influenced by stearic acid, which acts as a plasticiser), facilitating the dispersion of these compounds in the rubber mixture [4, 5]. Furthermore, it is noteworthy to mention that sulphur stands as the prevailing vulcanising agent employed in tyre manufacturing. When subjected to heat in the presence of rubber, sulphur acts to create intermolecular bridges among individual polymer molecules. Other additives used in rubber production include carbon black.

Pyrolysis process of waste materials is one of the methods for recycling processed material [6, 7]. This approach exemplifies a closed-loop system, wherein the pyrolysis products serve the dual purpose of partially fulfilling electricity demand and contributing to the production of refinery products. The composition and availability of these pyrolysis products, however, vary depending on the parameters of the pyrolysis process, technological factors, and the degree of waste fragmentation, as comprehensively discussed in previous studies [8, 9]. For instance, the pyrolysis of a typical used tyre, weighing approximately 6 kg, can yield approximately 2.5 kg of char, 1 kg of steel, 2.2 dm^3 of pyrolysis oil, and 0.5 m^3 of gas [9]. Notably, the char derived from the pyrolysis of used tyres comprises up to 80 % resin by weight [10], resulting in distinctive morphological and chemical surface heterogeneity. Additionally, this charcoal contains various impurities, including application tools, iron filings, zinc, and sulphur, the latter of which can account for up to 6 % by mass [10]. The potential applications of this charcoal include its use as a primary fuel component in solidified fuels, such as in grate boilers [11]. Furthermore, the inherent characteristics of the char, including surface area, component content, and volatile components, render it a promising candidate for use as a pigment or filler in rubber applications. Nonetheless, it is imperative to exercise caution due to the significant sulphur content within the char, as this characteristic can lead to the emission of sulphur oxides, which may have detrimental environmental consequences. Therefore, addressing this sulphur content is a critical consideration in the utilisation of charcoal from tyre pyrolysis [12, 13].

Two fundamental approaches can be distinguished for improving the properties of carbon black and carbon char: mechanical and chemical methods. Mechanical methods primarily address issues related to transportation and storage. These methods include grinding, granulation, as well as the separation of steel cord residues using magnets [14, 15]. On the other hand, chemical methods rely on various chemical processes, such as heating, activation, demineralisation (acidic or alkaline), and surface modifications through oxidation or polymer grafting [16, 17]. Among the listed methods, heating deserves particular attention. It involves re-pyrolysing carbon material under different conditions than those in the original process, allowing for surface modification by unlocking active centres. Another highly promising method for chemically enhancing the quality of char is demineralisation. This process aims to reduce the content of the mineral fraction. Demineralisation can be carried out using acid or alkali solutions, depending on the composition of the mineral fraction. In some cases, it enables a significant reduction of ash content by up to 70 %, thus contributing to a substantial improvement in the quality of the carbon material [16]. However, effective solutions that can be scaled up and applied in industrial installations are still being sought.

The central objective of this investigation is to undertake a thorough characterisation of charcoal derived from waste tyres while concurrently evaluating the feasibility of its valorisation through the removal of steel cord remnants, heat treatment, zinc leaching, and sulphur binding processes. This research endeavour is multifaceted, encompassing not only the exploration of potential applications for the charcoal but also the identification of challenges associated with its commercial utilisation as a versatile resource in roles spanning from fuel to pigment, sorption material, and filler. These research pursuits are underpinned by a broader aim: to elucidate the intricacies of appropriately designing processes that facilitate the realisation of a circular economy. By examining the potential and pitfalls of charcoal valorisation and its role in promoting sustainability, this study contributes to the broader discourse on sustainable resource management and waste-to-value methodologies.

Methods and materials characterisation section

Materials

The study utilised char derived from a commercial tyre pyrolysis plant, where the process was conducted at a temperature of 350 °C in a rotating tubular reactor. This material underwent thorough analyses and was subsequently purified from the remaining steel cord residues using a magnet. Further valorisation methods, such as heating, zinc leaching, and sulphur bonding, were applied to the material. In Figure 1, a schematic diagram of selected methods for recycling waste tyres and improving the quality of the char is presented.

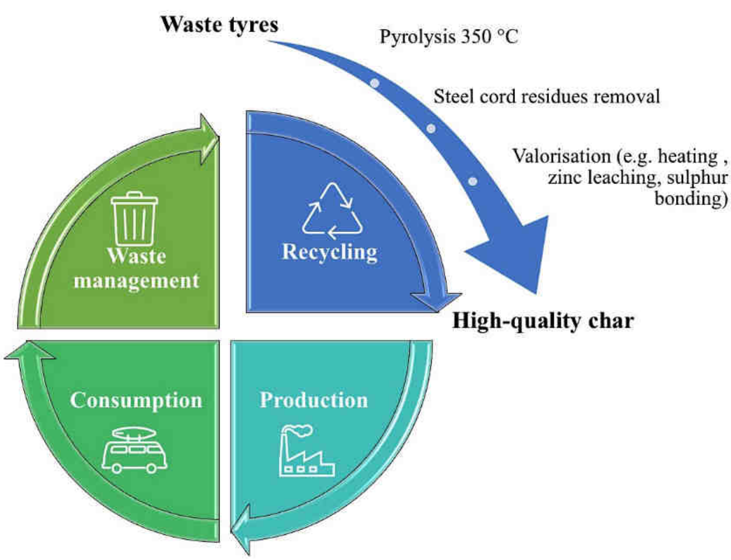

Fig. 1. Illustration of the chosen pathway for enhancing the quality of tyre-derived char within the context of the closed-loop economy

Methods of carbon materials analysis

The obtained carbon materials underwent proximate analyses, including moisture content (ASTM D-1509) [18], ash content (ISO 1171:2024) [19], volatile matter (PN-G-04516:1998) [20], and fixed carbon. The formulas used to determine the parameters described are shown below (equations (1)-(4)). The analyses were conducted in triplicate, and the results represent the arithmetic mean, with the reported uncertainty representing the standard deviation of the obtained analytical results.

$$M^a = \frac{m_{ad}}{m} \cdot 100\ \% \tag{1}$$

$$V^a = \frac{\Delta m}{m} \cdot 100\ \% - M^a \tag{2}$$

$$A^a = \frac{m_{aa}}{m} \cdot 100\ \% \tag{3}$$

$$C_{fix} = 100 - (M^a + V^a + A^a) \tag{4}$$

where: M^a - moisture content [%], V^a volatile matter content [%], A^a - ash content [%], C_{fix} - fixed carbon content [%], Δm - sample mass loss [g], m - sample mass [g], m_{ad} - mass of sample after drying [g], m_{aa} - mass of sample after ashing [g].

Furthermore, the char was characterised to assess its potential application as carbon black, and the following analyses were performed:

- Bulk density (ASTM D-1513) [21],
- pH of the aqueous extract (ASTM D-1512) [22],
- Toluene extract (ASTM D-1618) [23],
- Specific surface area by BET method (ASTM D-6556) using Micrometrics Gemini V [24].

Moreover, elemental analyses of the carbon materials were conducted using the EDX-7000/8100 Shimadzu, following the PN-EN 15309:2010 standard [25]. For this purpose, approximately 1 g of carbon material was weighed and placed in a cup. Measurements were taken three times for each sample and the results presented are the arithmetic mean. The surface morphology was also examined using the scanning electron microscope Phenom XL G2 Desktop SEM [25].

Methods of char valorisation

This section describes specific techniques for enhancing the quality of char from tyres. Additionally, we put forth potential applications for the resultant products generated from each distinct process, as illustrated schematically in Figure 2.

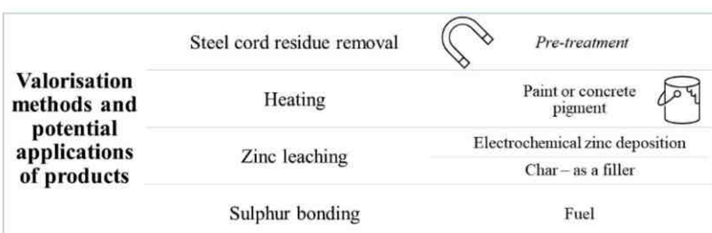

Fig. 2. Valorisation methods of tyres-char and potential applications of products

Steel cord residue removal

The remaining steel cord residues were removed using a laboratory magnet, which had a cylindrical shape with a diameter of 40 mm and a height of 10 mm. The pre-screened char, using a 1.0 mm sieve, was evenly spread on a filter paper, resulting in a bed thickness of 0.5 mm. Subsequently, using the magnet positioned 5 mm above the surface of the char, the remaining steel cord residues were separated. The efficiency of iron filings removal from the char was determined based on the mass difference of the char before and after the process, and the result was calculated as the arithmetic mean of five experiments.

Heating

The process known as "heating" aims to enhance the physicochemical properties of char by reducing the volatile content, thereby increasing the proportion of bound carbon, and expanding the specific surface area of the carbon material through desorption of impurities and gases adsorbed within its pores. A sample of 20 g of char was carefully weighed and placed inside a reactor with dimensions of 60 mm x 75 mm. The experiments were conducted under anaerobic conditions at temperatures ranging from 400 °C to 800 °C for 1 hour. The resulting carbon materials were subjected to proximate analysis, which included the determination of moisture content, volatile matter, mineral fraction, and fixed carbon (C_{fix}).

Zinc leaching

The proposed method for zinc recovery from char has been developed and modified based on patent application P.423325 [26] and consists of two main stages. The first stage, which is the focus of investigation in this study, involves the addition of zinc oxide to a solution in the form of sodium zincate, as described by equation (5). Subsequently, the second stage entails the electrochemical deposition of metallic zinc from the aqueous solution, as outlined by equations:

$$\mathrm{ZnO} + 2\mathrm{NaOH} + \mathrm{H_2O} = \mathrm{Na_2[Zn(OH)_4]} \tag{5}$$

$$\mathrm{A(+)}: 2\mathrm{OH^-} \rightarrow \frac{1}{2}\mathrm{O_2} + \mathrm{H_2O} + 2\mathrm{e} \tag{6}$$

$$\mathrm{K(-)}: \mathrm{Zn(OH)_4^{2-}} + 2\mathrm{e} \rightarrow \mathrm{Zn} + 2\mathrm{OH^-} + \mathrm{H_2O} \tag{7}$$

$$\mathrm{Na_2ZnO_2} + \mathrm{H_2O} \rightarrow \mathrm{Zn} + 2\mathrm{NaOH} + \frac{1}{2}\mathrm{O_2} \tag{8}$$

The experiments commenced with the preparation of a leaching solution comprising NaOH, H_2O_2, or a mixture of oxidising agents with concentrations ranging from 3 wt. % - 40 wt. %. Subsequently, 20 g of char was weighed and treated with the leaching solutions in quantities corresponding to 10 mL - 40 mL per gram of char. The mixture was then thermostated at temperatures ranging from 20 °C to 80 °C and stirred for 2 hours at 400 rpm. After cooling, the product was subjected to filtration, and the resulting carbon material was dried for 12 hours at 105 °C. An analysis of proximate and elemental composition using X-ray fluorescence was conducted on the obtained carbonaceous materials to determine the most effective parameters for zinc leaching. However, the filtrate was not subjected to analysis.

Sulphur bonding

The sulphur bonding method follows a similar approach as discussed above for zinc leaching. Different chemical agent was used for complete sulphur reaction. The calcium compounds bind sulphur into calcium sulphide/sulphate(VI). This step is of utmost significance due to the high sulphur content in the char and the potential release of sulphur oxides into the atmosphere during thermal processes [27]. The experiments were conducted within a concentration range of 5 % - 10 % $Ca(OH)_2$ and $CaCO_3$. The experiments were carried out at temperatures such as: 20 °C, 50 °C, and 70 °C, with solution-to-carbon mass ratios (*L/S*) ranging from 10 mL g^{-1} to 20 mL g^{-1}. The purified char was dried at 105 °C for 12 hours, and its sulphur content was analysed using an X-ray fluorescence spectroscope. Calcination process involves the endothermic decomposition of $CaCO_3$ (9) at 750 °C, with the simultaneous release of CO_2. Calcium hydroxide, $Ca(OH)_2$ (10), in the flue gases, decomposes through dehydration at temperatures above 400 °C, releasing water. The CaO that is formed exothermically reacts in the kiln with SO_2, producing a thermodynamically stable product - anhydrite $CaSO_4$ (mineral) (11).

$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2} \quad \Delta\mathrm{H}^{\circ}_{298^{\circ}\mathrm{C}} = -183\,\frac{\mathrm{kJ}}{\mathrm{mol}} \tag{9}$$

$$\mathrm{Ca(OH)_2} + \mathrm{Q} \rightarrow \mathrm{CaO} + \mathrm{H_2O} \tag{10}$$

$$\mathrm{CaO} + \mathrm{SO_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{CaSO_4} \quad \Delta\mathrm{H}^{\circ}_{298^{\circ}\mathrm{C}} = -486\,\frac{\mathrm{kJ}}{\mathrm{mol}} \tag{11}$$

Results and discussion

Characteristics of carbon materials

Tyres exhibits a complex structure that depends on the operating conditions and their intended use. The rubber compounds subjected to vulcanisation primarily consist of natural rubber and synthetic rubbers, constituting approximately 40 % of the compound's mass. Additionally, fillers, which can constitute up to half of the compound’s mass, sulphur (1.5 % - 4 %), resins, oils, and antioxidants (e.g., ZnO, Al_2O_3) are also utilised.

The carbonised material was sourced from a commercial tyre processing facility, where the process was conducted on an industrial scale at approximately 350 °C without the use of an inert gas flow. The process lasted several hours due to the reactor’s capacity. The reactor used was a rotary tubular reactor, and several dozen kilograms of tyres were fed into the process. The resulting carbonised material was then modified and heated in a laboratory setting at temperatures ranging from 400 °C to 800 °C, also without the use of an inert gas flow. The char derived from waste tyres through low-temperature pyrolysis was subjected to characterisation, as presented in Table 1. It can be observed that pyrolysis resulted in a significant reduction in the volatile fraction content from 67 % to 13 %, while increasing the proportion of bound carbon from 25 % to 66 %. Furthermore, the char exhibited a high mineral fraction content of 18.6 % by weight, consisting of, among others, 2.8 % Zn, 1.7 % S, 1.2 % Si, and 0.6 % Ca. In Table 1, the properties of the char and the parameters characterising carbon black were compared to assess potential application possibilities.

Based on the data presented in Table 1, which pertains to the characteristics of selected carbon black pigments from various manufacturers, the most pronounced resemblance is observed with pigment N880 and N772. The similarity may result from the fact that carbon fillers, specifically carbon black types such as N880 and N772, are commonly used in tyres. These fillers can constitute up to 30 % of the rubber composition. Nevertheless, in the case of the other pigments, there is a significant deviation in bulk density compared to that characterising the char derived from waste tyres. Hence, it becomes imperative to reduce the ash content and volatile fraction to minimise mass loss during the drying process at 125 °C.

Table 1

Comparison of the properties of char with selected carbon black pigments

Parameters		Waste tyres [28]	Char (350 °C) - this study	Carbon black			
				N330[b]	N550[b]	N772[b]	N880[c]
Heating loss at 125 °C	[%]	n.d.	1.3 ±0.2	n.d.	n.d.	n.d.	n.d.
Moisture	[%]	1.1	2.8 ±0.1	n.d.	n.d.	n.d.	n.d.
Volatile matter	[%]	67.2	12.7 ±0.3	n.d.	n.d.	n.d.	n.d.
Ash	[%]	6.6	18.6 ±0.2	max. 0.75	n.d.	n.d.	max. 0.5
Fixed carbon[a]	[%]	25.1	65.8 ±0.5	n.d.	n.d.	n.d.	n.d.
Sulphur content	[%]	1.8	1.7 ±0.1	max. 1.1	n.d.	n.d.	n.d.
pH	[-]	n.d.	8.6 ±0.1	7-10		n.d.	n.d.
Bulk density	[kg m^{-3}]	n.d.	585.4 ±0.6	370	360	520	530
Toluene discoloration	[%]	n.d.	96.4 ±0.5	min. 85	min. 80	min. 75	n.d.
Specific surface area	[m^2 g^{-1}]	n.d.	31.2 ±0.3	78	40	32	5-13

[a] calculated by difference, manufacturer's data ([b]Makrochem, [c]Mainchin Chemicals), n.d. - no data

The char was subjected to purification from the remaining steel cord residues using a magnet. A mass loss of 1.1 % was observed, which allowed reducing the iron content to 0.14 wt. %. The technology of removing steel cord residues using electromagnets is a commonly employed solution in industrial practice.

Table 2

Proximate analysis of char obtained from low-temperature (350 °C) pyrolysis and carbonaceous materials after heating processes

Heating temperature [°C]	Moisture [%]	Ash [%]	Volatile matter [%]	Fixed carbon[a] [%]
400	1.72	19.86	6.56	71.83
500	1.62	20.16	3.30	74.92
600	1.58	20.85	2.28	75.29
700	1.57	21.39	0.99	76.05
800	1.00	21.56	0.72	76.72

[a] calculated by difference

One of the effective methods to improve the quality of char by reducing the volatile fraction is through heating, during which volatile substances adsorbed in the pores of the carbonaceous material desorb from the carbon surface. Limiting the volatile fraction content is of utmost importance, as a high volatile fraction content significantly impacts the quality of off gases in combustion processes. Proximate analysis of the chars subjected to heating at temperatures ranging from 400 °C to 800 °C is provided in Table 2. It was observed that as the heating temperature increases, the mass proportion of volatile substances decreases from 12.7 % to 0.7 %, leading to an increase in the proportion of bound carbon (which is beneficial) and the mineral fraction (which is detrimental). Consequently, further processing of the char is necessary to effectively limit the ash content.

The high content of the mineral fraction was also confirmed by microscopic analysis of the surface morphology of selected chars, as presented in Figure 3. Residues of steel cords were observed, but more prominently, the carbon materials exhibited a high degree of amorphousness and lacked a porous structure. Heating did not result in an increase in the ordered surface structure of the char or the development of a porous network. This could be attributed to the high brittleness of the analysed material and its low wear resistance. Low-temperature pyrolysis allowed for the production of a char with a specific surface area of 31 m^2 g^{-1}, while annealing the material at 800 °C increased the specific surface area to 59 m^2 g^{-1}. In the work by Gonzalez et al. [28], a char with a specific surface area of 109 m^2 g^{-1} was obtained, with the pyrolysis process conducted at 850 °C for one hour on a laboratory scale [28]. The results presented in the Table 1, specifically the temperature variations in the pyrolysis process, illustrate the impact on the properties of the obtained char. Additionally, examples from the literature show that process parameters, such as the type of feedstock, influence the specific surface area of the resulting char.

The development of the specific surface area of the char can be achieved through the use of physical activators (such as steam or carbon dioxide) or chemical activators (e.g., potassium hydroxide). However, when using car tyres as a precursor, the achieved values typically reach a maximum of around 300 m^2 g^{-1} [6, 28].

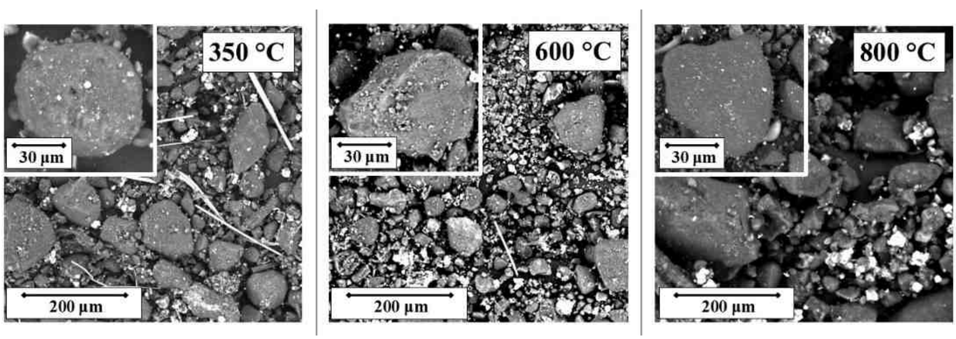

Fig. 3. Scanning electron microscope images of solid fraction from pyrolysis and heating processes

Zinc leaching process

One of the methods to reduce the mineral fraction in char derived from waste tyres is zinc leaching, which was carried out using two oxidising agents - sodium hydroxide and hydrogen peroxide, or their mixture in an aqueous solution. The most effective zinc removal (59 %) was observed when using a 20 % NaOH solution at a dosage of 20 mL g^{-1} at room temperature. The zinc leaching efficiency gradually decreased with an increase in the process temperature. In the work by Krzak et al. [26], it was observed that increasing the *L/S* ratio to 40 mL g^{-1} allows for a higher degree of zinc recovery. However, due to the high hydrophobicity of the analysed char, precise mixing of such a mixture was not feasible on a laboratory scale.

The use of hydrogen peroxide allowed for the recovery of approximately 40 % of zinc from the char, while the mixture of 20 % NaOH and 3 % H_2O_2 at 20 °C and *L/S* of 10 mL g^{-1} resulted in a 56 % zinc leaching efficiency. Economically, the most justified solution on a laboratory scale is the use of the NaOH and H_2O_2 mixture, given its twofold reduction in the volume of the consumed solution while achieving comparable efficiency in char purification as in the case of the 20 % NaOH trial at 20 mL g^{-1} and 20 °C. Dependencies of temperature, *L/S* ratio, and concentration on zinc leaching efficiency are presented in Figures 4a-c.

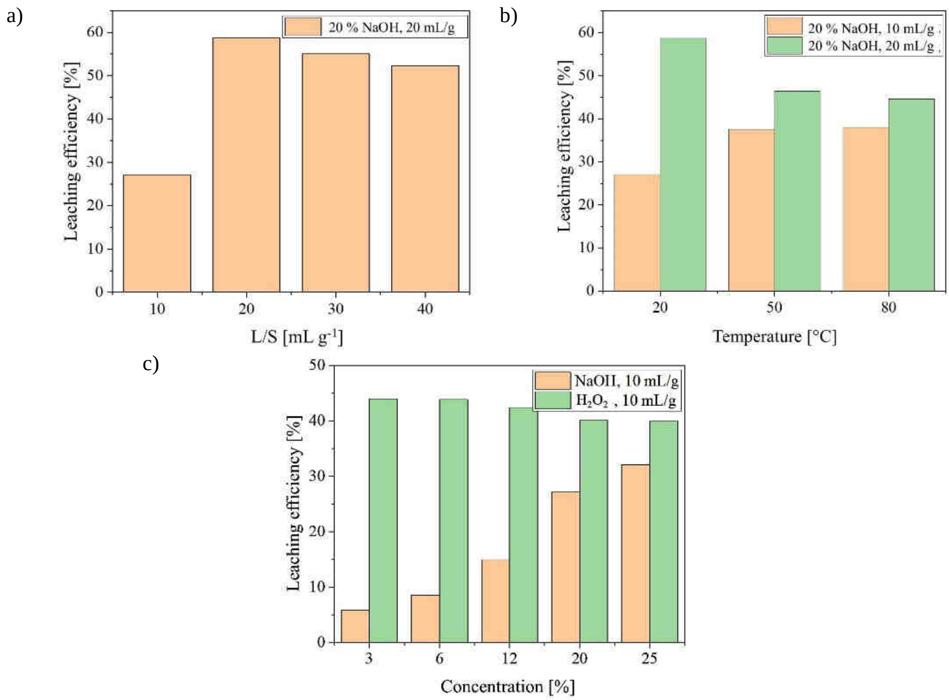

Fig. 4. Plots of the dependence of the amount of zinc leaching efficiency on: a) the amount of leaching solution relative to the carbonate, b) the mixing temperature, c) the oxidant concentration

The use of the leaching mixture also led to a reduction in the content of other elements such as Ca and Al by approximately 50 %. In the literature, there are reports of the possibility of recovering silicon from chars through demineralisation in a hydrochloric acid solution with concentrations of 2 M - 4 M [29]. In the work by Ilnicka et al. [30], an alternative method for zinc leaching from char was proposed. It involved subjecting the carbon material to a 0.1 M hydrochloric acid solution and resulted in a 39 % wt. reduction in the Zn content [30]. However, it was not determined whether zinc recovery from the leaching solution is feasible.

Sulphur bonding process

The sulphur content in char obtained from low-temperature pyrolysis of waste tyres was 1.69 wt. %. The sulphur content in the ash of untreated char was also determined and found to be 0.84 wt. %, indicating the necessity of sulphur bonding. The proposed method of chemically binding sulphur using aqueous solutions of calcium carbonate and calcium hydroxide results in an increase in the mineral fraction (primarily calcium) in the carbon product. However, this procedure is justified in cases where the char is intended for use in thermal processes to limit sulphur oxide (SO_x) emissions. The obtained carbonates were subjected to XRF analysis to determine the sulphur content, and then they were heated to 900 °C and the chemical composition of the solid fraction was reanalysed. Based on the conducted analyses, the D_{BS} parameter, which determines the degree of sulphur bonding, was calculated:

$$D_{BS} = \left(1 - \frac{S_b - S_a}{S_b}\right) \cdot 100\ \% \tag{12}$$

where: S_b - sulphur content before the process, S_a - sulphur content after bonding and heating.

The best result (D_{BS} = 95 %) was achieved when using a 10 % solution of calcium carbonate at room temperature. As the concentration of the solution increased, the efficiency of sulphur bonding decreased. A similar trend was observed with increasing mixing temperatures of the solutions (reduction by 4 % - 6 %). The application of $Ca(OH)_2$ resulted in twofold lower sulphur bonding efficiency compared to the calcium carbonate solution. Furthermore, the ash from trials *S5-S8* exhibited a 33 % higher calcium content than in trials *S1-S4*. The results of the most effective sulphur bonding trials are presented in Table 3.

Table 3

Results of sulphur bonding tests with $CaCO_3$ and $Ca(OH)_2$ calculated based on XRF elemental analysis

Sample symbol	Concentration		Temperature	*L/S*	Sulphur content	D_{BS}
	$CaCO_3$	$Ca(OH)_2$				
	[%]	[%]	[°C]	[mL g^{-1}]	[%]	[%]
S1	5	0	20	10	1.21	72
S2	5	0	70	10	1.13	67
S3	10	0	20	10	1.61	95
S4	10	0	70	10	1.51	89
S5	0	5	20	10	0.65	38
S6	0	5	70	10	0.56	33
S7	0	10	20	10	0.91	54
S8	0	10	70	10	0.84	50

In the literature, other methods of desulphurisation of char are described, including the use of aqueous KOH solution [31]. This process, in the case of charcoal, allowed for a maximum reduction of sulphur content by 37 % when using a 20 % solution and contacting it for one day [31]. The selection of the process and the chemical agent is conditioned by the intended use of the char.

Conclusion

In conclusion, this study has explored selected methods to enhance the quality of char derived from tyre pyrolysis, namely heating, zinc leaching, and sulphur bonding. The findings reveal the significant potential of these proposed techniques and their applicability in transforming the carbon material into technical carbon black. Initial char produced through low-temperature pyrolysis exhibited a high ash content, including zinc and sulphur, along with a considerable volatile fraction, which presented challenges for potential applications. However, by optimising heating parameters, volatile substances were substantially reduced, leading to nearly a twofold increase in the specific surface area.

The proposed leaching method demonstrated effective zinc extraction, resulting in a remarkable 59 % reduction in zinc content, and the possibility of electrochemically recovering this valuable metal from the filtrate. Zinc leaching using NaOH or H_2O_2 represents one of several viable methods to minimise the mineral fraction in the carbon material. Alternatively, demineralisation with hydrochloric acid, commonly employed to improve biochar quality, addresses predominantly alkali metal content, such as potassium, calcium, or sodium.

Furthermore, the presented sulphur bonding technique proves beneficial for cases where the char will serve in thermal processes or as fuel. By employing a 10 % calcium carbonate solution, approximately 95 % of the sulphur content in the char was permanently bound, thereby mitigating the formation of sulphur oxides (SO_x), which contribute to the greenhouse effect. Currently, in Poland, used tyres are utilised in cement kilns, where sulphur is incorporated into the clinker and is considered beneficial. However, while exploring alternative methods for managing char from used tyres, such as producing briquettes, it necessitates the reduction of sulphur content in the emitted flue gases. On the other hand, the ash, rich in sulphur, is suitable for agricultural use and is environmentally neutral.

Despite the valorisation of char derived from low-temperature pyrolysis of waste tyres through heating, zinc leaching, and sulphur bonding holds significant promise in addressing environmental challenges, it is essential to acknowledge certain limitations and potential challenges arising from the application of the proposed method. Selected limitations are presented below:

1) Scale-Up Challenges: Upscaling the optimised laboratory method to an industrial scale necessitates the design of suitable installations and reactors.
2) Environmental and Economic Considerations: The valorisation process should also take into account the environmental impact of using different reagents and chemicals. Proper waste management and consideration of potential by-products or secondary contaminants are essential to ensure a sustainable and environmentally friendly process. Additionally, these processes should be optimised in terms of reagent costs, waste disposal, and energy consumption.

Notwithstanding the identified constraints, the conducted research underscores the significant potential inherent in the proposed methodologies within the framework of the circular economy for car tyres. This investigation illuminates a spectrum of promising avenues for enhancing the quality of car tyre-derived charcoal, a pursuit of paramount significance in light of the escalating volume of tyre waste generation, limited alternatives for material recycling, and the burgeoning interest in semi-industrial and industrial pyrolysis facilities, which predominantly operate at lower temperatures.

The appropriate valorisation of charcoal presents a unique opportunity for zinc recovery and its subsequent utilisation as a pigment or filler in the polymer production industry, all while adhering to the tenets of sustainable waste management and resource utilisation. To fully realise this innovative approach to sustainable waste management, it is imperative that further research and development be undertaken to address and surmount the identified limitations, thereby unlocking the complete potential of these strategies.

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