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Circularity and sustainability of recovered carbon black production from end-of-life tyre pyrolysis

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ABSTRACT

End-of-life tyres pose significant environmental and resource challenges. Mitigation strategies could be an exemplar of potential for circular economy through the recovery of materials that can be circulated back to tyre manufacturing. Recovered carbon black produced via pyrolysis of these end-of-life tyres, is an essential secondary raw material with the potential to partially substitute commercial carbon black in rubber formulation and enhancing material circularity in the tyre value chain. To date, the literature has predominantly focused on specific aspects of recovered carbon black, such as modification, its performance in rubber compounds, and environmental and economic assessments of production. However, a holistic perspective that combines these technical, environmental and economic aspects and evaluates the circularity potential of recovered carbon black remains scarce in current literature. Learnings from existing studies are fragmented, as they do not offer a comprehensive assessment on how recovered carbon black from end-of-life tyres can be effectively reintegrated into the tyre manufacturing value chain. This article addresses that gap by reviewing the state-of-the-art on recovered carbon black production and application together with sustainability assessment. This work develops an integrated perspective on the role of recovered carbon black in tyre manufacturing and outlines key pathways and challenges for scaling up its use to improve circularity in the tyre industry. It also proposes a functional unit definition according to the European Commission's product environmental footprint guide as "1 kg recovered carbon black in tyre manufacturing providing equivalent reinforcing performance of commercial carbon black over the average tyre lifetime".

1. Introduction

The global tyre industry, driven by increasing mobility demands, produces approximately three billion tyres annually for road and air transport, including passenger cars, trucks, buses, off-road vehicles, and aircrafts (Mayer et al., 2024). While this growth supports economic development, it poses significant challenges for achieving a decarbonised economy and meeting the United Nations Sustainable Development Goals (SDGs), particularly SDGs 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land). These challenges are primarily associated with the energy-intensive tyre manufacturing process, which is heavily reliant on fossil resources particularly oil and its derivatives such as synthetic rubber, additives, and fillers. The tyre industry has significant life cycle impacts, including for greenhouse gas emissions, waste generation and depletion of natural resources. For instance, each passenger car tyre requires around 10 kWh of energy expenditure, which is approximately the average daily electricity consumption of an Irish household (Wu et al., 2024b; my-power.ie, 2026); the corresponding greenhouse gas (GHG) emission is approximately 42 kg of CO_2 equivalent ($CO_{2\text{-eq}}$), about 70% of which comes from raw material extraction and processing (Sun et al., 2016).

The current linear model of tyre production is shown in Fig. 1(a), where raw materials are extracted, used and discarded, with limited reintegration of end-of-life tyres (ELTs) into the tyre value chain (Norris et al., 2023). As global mobility continues to increase, the demand for tyres is projected to grow annually at the rate of 3 to 5%, further intensifying these challenges (Chicu et al., 2020). Consequently, it is of paramount importance to explore strategies to incorporate circular economy principles across the tyre life cycle to mitigate the environmental and economic impacts of tyre production without compromising product quality. The European Commission's 2020 Circular Economy Action Plan emphasises the need to accelerate the shift towards a more regenerative, doubling circular material use by 2030 (COM, 2020).

The circular economy framework offers a promising pathway for transforming the tyre sector by promoting the recovery and reuse of

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materials from ELTs as shown in Fig. 1(b). This approach has dual benefits, namely, reducing the demand for virgin raw materials (such as natural rubber, synthetic rubber, commercial carbon black) and minimising the environmental impact associated with their extraction and processing (Purvis et al., 2023).

To achieve a circular economy in tyre manufacturing, recovered carbon black (rCB) produced from the pyrolysis of ELTs, is widely recognised as a promising secondary raw material for partially replacing commercial carbon black in tyre applications (Mohammad Zainol et al., 2024). There is a substantial number of reviews available on end-of-life tyre pyrolysis and rCB production. For example, Williams (2013) and Martínez et al. (2013b) presented comprehensive reviews of ELT pyrolysis focusing on the pyrolysis technologies and product composition. More recently Gao et al. (2022) critically reviewed ELT pyrolysis char analysing the influence of process condition and feedstock composition on char properties, as well as its use in high-value applications such as commercial carbon black replacement, activated carbon production and as a graphene precursor. Original research articles have individually assessed rCB upgrading and modification strategies, its incorporation into rubber formulations and different sustainability matrices such as separate environmental and economic assessments. However, despite the growing number of studies, a comprehensive perspective on the circularity potential of rCB that includes its sustainability assessment studies remains unavailable in current literature. Learnings from existing studies are often fragmented, with individual papers focusing on isolated aspects of ELT pyrolysis, rCB characterisation or application; the literature as a whole does not offer a perspective on how rCB can be effectively reintegrated into the tyre manufacturing value chain. This review evaluates the current state-of-the-art in ELT tyre pyrolysis and assesses the technical, economic, and environmental feasibility of using rCB in tyre manufacturing. The paper aims to address the gap in the research by providing a holistic understanding of the circularity potential of end-of-life tyres and rCB and in doing so, pave the way for more sustainable practices in the tyre industry.

2. Tyre composition and commercial carbon black

2.1. Tyre composition

A conventional tyre has a complex design (Fig. 2) comprising primarily natural and synthetic rubber, reinforcing fillers such as commercial carbon black and silica, mechanical strength-enhancing materials such as steel and textile fibres, vulcanising agents like sulphur, activators such as zinc oxide (ZnO), accelerators, and other additives including extended oil, antioxidants and antiozonants (Abbas-Abadi et al., 2022). The quantities of these raw materials vary across brand, tyre and vehicle type, operating conditions and country. It is a general practice for tyre manufacturing companies not to publish the exact composition of their products; however, a limited number of published studies report representative formulations. Table 1 provides a summary of the mass fraction and absolute mass of key components in a passenger-car tyre and a truck tyre.

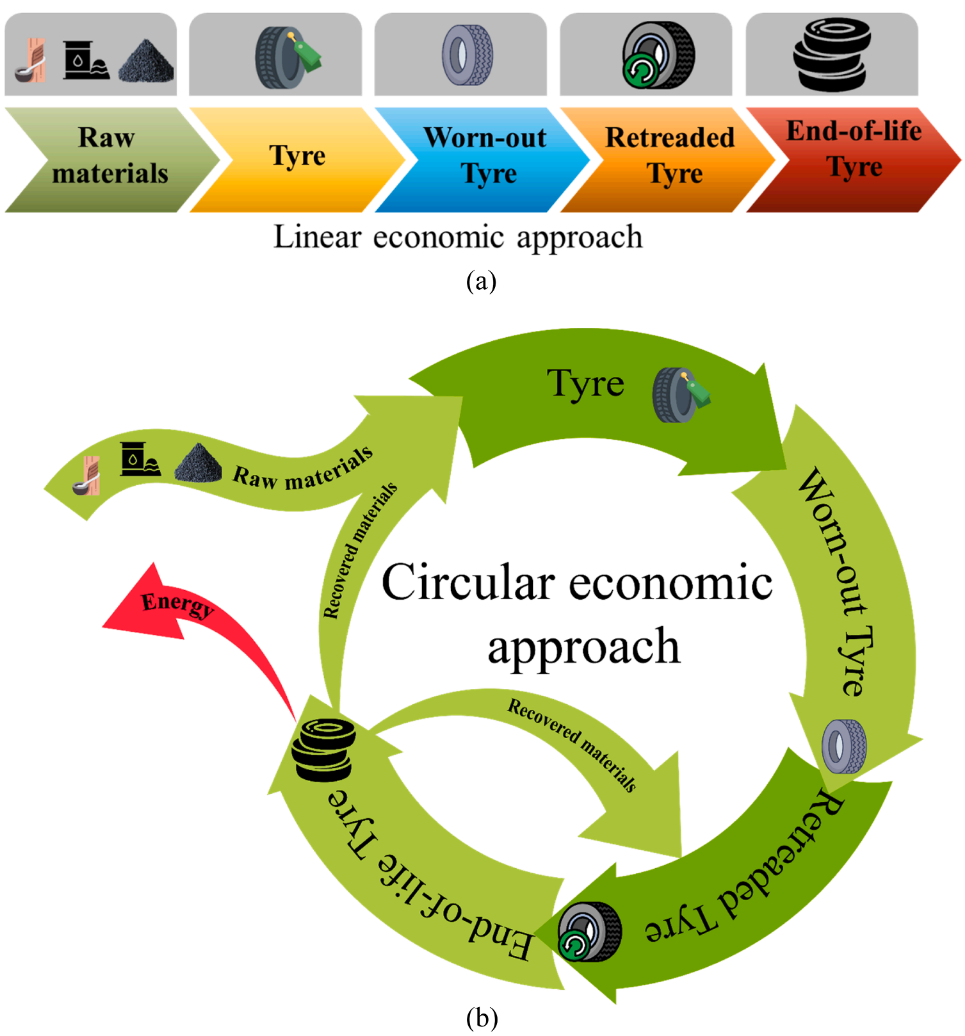

Fig. 1. Economic models of tyre production (a) Current linear economic model (b) Intended circular economic model.

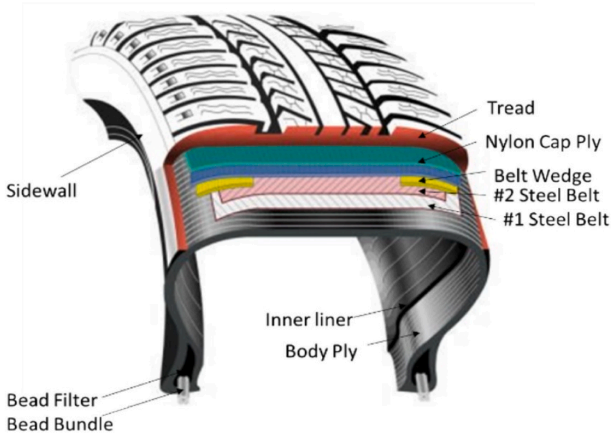

Fig. 2. Cross-section of a passenger car tyre reproduced with permission from Elsevier (Pei et al., 2024).

Table 1
Raw materials and their mass in a passenger car tyre (Chikri and Wetzels, 2019) and truck tyre (Shanbag and Manjare, 2020).

Components	Passenger car tyre		Truck tyre	
	Mass percentage (%)	Amount (kg)	Mass percentage (%)	Amount (kg)
Natural rubber	16	1.5	46.2	23.1
Synthetic rubber	26.6	2.5		
Carbon black	14.9	1.4	17	8.5
Steel	10.6	1	13.8	6.9
Textiles	5.3	0.5	4	2
Chemicals	14.9	1.4	14.4	7.2
Fillers	11.7	1.1	4.6	2.3

Natural rubber is derived from *Hevea brasiliensis* latex and is used in the treads, sidewalls, and inner liner of tyres. It consists predominately of cis-1,4 polyisoprene and is more prevalent in truck tyres (c. 27 to 37 wt.%) than passenger car tyres (c.16 to 21 wt%) (Kurian and Mathew, 2006; Valentini and Pegoretti, 2022). Synthetic rubber is produced by polymerisation monomers derived from petrochemical feedstocks. Natural rubber provides mass and elasticity to the tyre, while synthetic rubber enhances rolling life and heat resistance. Common types of synthetic rubber include butadiene rubber (BR), butyl rubber (IIR) and styrene-butadiene rubber (SBR).

Commercial carbon black (with a carbon content typically higher than 97 wt.% in ultimate analysis) and silica are used as reinforcing fillers to improve tensile strength and abrasion resistance. In conventional tyre manufacturing, carbon black is mixed with uncured natural and synthetic rubber polymer through a multistage mixing process using internal mixers or two roll mills (Robertson and Hardman, 2021). First the viscosity of the rubber polymer (natural and synthetic) is reduced by mastication, then commercial carbon black is gradually added alongside activators like zinc and stearic acid and finally it is vulcanised or cured using sulphur, plasticisers and antioxidants (Hess and Klamp, 1983). This results in the formation of uniform aggregates measuring 20–80 nm, which further develops interconnected percolating networks at loadings of 40–60 parts per hundred rubber (phr) (Robertson and Hardman, 2021). These networks produce high levels of bound rubber, approximately 20 wt.% of commercial carbon black, and deliver optimal reinforcement necessary for tyre application.

Steel and textile reinforcements such as nylon fibres further provide structural strength and rigidity to the tyre. In addition, tyres contain sulphur, zinc oxide and a large number (often >200) of speciality additives used to control curing behaviour, processability and performance.

2.2. Commercial carbon black

As shown in Table 1 commercial carbon black is a significant raw material in tyre production with an annual demand of approximately 11 million tonnes per year for tyre production (Robertson and Hardman, 2021). Commercial carbon black is an extremely fine form of elemental carbon with an amorphous structure and very low ash content, typically below 0.5 wt.%. It is produced industrially via three main processes: furnace black, thermal black and channel black, of which the furnace black process dominates and accounts for about 95% of global production. In the furnace black process, heavy aromatic hydrocarbon fractions from petroleum refining or petrochemical streams are injected into a high-temperature reactor (around 1600 °C), where they undergo partial combustion and thermal decomposition in the presence of a fuel (usually natural gas) (Rosner et al., 2024). The resulting off gas contains fine carbon particles that are rapidly quenched, then separated, collected and pelletised to yield the desired carbon black grades. Accordingly, each tonne of commercial carbon black production in the furnace black process requires approximately 340 kWh of electricity and 6.2 tonnes of water, resulting in CO_2 emissions of 3.5 tonnes-equivalent (Rosner et al., 2024).

Carbon black is commonly characterised by primary particle size, aggregate size, specific surface area and structure (Fan et al., 2020). For tyre applications, primary particle sizes typically range from about 15 to 150 nm, with aggregate sizes following approximately a Gaussian distribution (Norris et al., 2023; Huang et al., 2005). The specific surface area, usually measured by nitrogen adsorption, is closely related to particle size and pore volume and generally lies between 40 and 150 m^2/g for tyre-grade materials (Rothon, 2017). The structure of carbon black, reflecting the extent of aggregation, branching and internal void volume is quantified by the Oil Absorption Number (OAN), expressed as the volume of dibutyl phthalate absorbed per 100 g of carbon black (Bansal et al., 1993). Tyre-grade products typically show OAN values of about 60–105 mL/100 g, with higher values indicating more highly structured aggregates and greater reinforcement potential (Norris et al., 2014). Tyre-relevant furnace blacks are often classified using American Society for Testing and Materials (ASTM) N-series grades (e.g., N110, N220, N330, N660), where "N" denotes normal curing behaviour and the subsequent digits refer to ranges of particle size, surface area and structure (Norris et al., 2023). Table 2 summaries key physiochemical properties of representative furnace grade commercial blacks and show the range of surface area and structures covered by standard ASTM N-series grades commonly used in tyre formulations.

3. End-of-life tyre mitigation and pyrolysis

3.1. Management and regulation of end-of-life tyres

Beyond the environmental challenges associated with tyre manufacturing, the management of tyres once they reach the end of their useful life has become a significant global concern. It is estimated that around 1.5 billion end-of-life tyres are generated annually worldwide, corresponding to approximately 26 million tonnes of solid waste (Commission E, 2024). Historically, landfilling was the dominant disposal method until the late 1990s and early 2000s. However, this practice poses serious risks to the environment, ecosystems, and human health, and has been banned in many regions including the European Union (EU) since 2003 (Kibria et al., 2024). In recent years, stricter regulations, growing scarcity of resources, and progress in polymer waste management have shifted the focus towards the recovery of valuable materials and energy from end-of-life tyres. This is driven in part by the high energy content in end of life tyres (>30 MJ/kg), which is more than that of bituminous coal (27 MJ/kg) (Dai et al., 2001). However, the implementation of mandatory ELT recycling remains

Table 2
Elemental composition and morphological properties of commercial carbon black compiled from references (Wang et al., 2000; Yuehong et al., 2006; Cardona-Uribe et al., 2021; Cardona et al., 2018; Roy et al., 1999).

Commercial carbon black		Elemental composition					Surface and pore properties		Average primary particle size (nm)	oil absorption number (OAN) (ml/100 g)*
Grade	Production process	Ultimate analysis (wt.% dry and ash free basis)				ash	Specific surface area (m^2/g)	Pore volume (cm^3/g)		
		C	H	N	S					
N110	Furnace	-	-	-	0.7	0.5	124–130	-	15–18	113
N220	Furnace	-	-	-	-	-	112–115	0.465	20–25	114
N330	Furnace	99	0.4	-	0.6	0.4	76–80	0.114	28–36	102
N550	Furnace	98.80	0.30	0.3	0.6	<1.5	39–41	-	39–55	121
N660	Furnace	-	-	-	-	<0.05	34–36	-	56–70	90
N770	Furnace	-	-	-	-	<0.05	31–32	-	71–96	74

* the oil absorption number (OAN) value is calculated based on how much (in millilitres) dibutyl phthalate 100 g carbon black can absorb (Bansal et al., 1993).

challenging due to the high annual production volume, and the material's inherent resistance to degradation (Bing et al., 2021).

3.2. Valorisation of end-of-life tyres

Conventionally, ELTs are either reused as whole tyres or processed into smaller fractions for material or energy recovery. Fig. 3 shows the end-of-life tyre valorisation routes currently available globally. Whole tyres are often repurposed in civil engineering projects, such as the construction of dams, walls, barriers, artificial reefs, and for erosion control (Oikonomou and Mavridou, 2009). The major concern in these applications is the weathering of the ELTs, which leads to polyaromatic hydrocarbon (PAH) leaching and microplastic pollution (Banasiak et al., 2019; Zoroufchi Benis et al., 2023). Alternatively, ELTs are shredded or ground to produce feedstocks for various materials and energy recovery pathways. The extent of shredding and grinding depends on the intended valorisation pathway. The energy recovery pathways include incineration and gasification, while the material recovery pathways include production of crumb rubber (Sunthonpagasit and Duffey, 2004), rubberised asphalt (Lo Presti, 2013), rubberised concrete (Fazli and Rodrigue, 2020) and devulcanisation (the process of breaking sulphur cross-links in processed rubber to partially restore its plasticity and reprocessability) (Bockstal et al., 2019).

3.3. Pyrolysis of end-of-life tyres

Pyrolysis of end-of-life tyres provides an attractive route for simultaneous material and energy recovery, resulting in the production of solid (pyrochar/ raw recovered carbon black), liquid (pyro-oil) and gaseous (pyrogas or syngas) fractions. In this thermochemical conversion process, ELTs are first shredded or grounded and then heated to 300–900 °C in an oxygen free atmosphere, typically using gases such as nitrogen (Chen and Yeh, 1996), argon (Sharma and Ghoshal, 2010) and carbon dioxide (Kwon et al., 2019). The primary degradation of natural rubber occurs at approximately 320 to 400 °C, while synthetic rubbers degrade mainly at temperatures between of 400 and 520 °C. The additives such as oils, plasticisers and organics, start to degrade at 320 °C or higher (Han et al., 2018; Campuzano et al., 2023); secondary volatile degradation starts at temperatures above 500 °C (Rahman et al., 2022). Long-chain aromatics are cracked into smaller hydrocarbons, increasing the fraction of non-condensable volatiles. Fig. 4 shows the ELT pyrolysis process and the main reactor configurations (Lewandowski et al., 2019).

Pyrochar, the focus for rCB production, consists primarily of elemental carbon (50–90 wt.%) derived from both the original tyre carbon black and carbonised rubber residues, accompanied by metal traces and ash whose levels vary with process conditions and tyre composition (Czajczyńska et al., 2017). Pyro-oil forms as a dark brown, aromatic liquid with a high heating value of 40–45 MJ/kg, containing

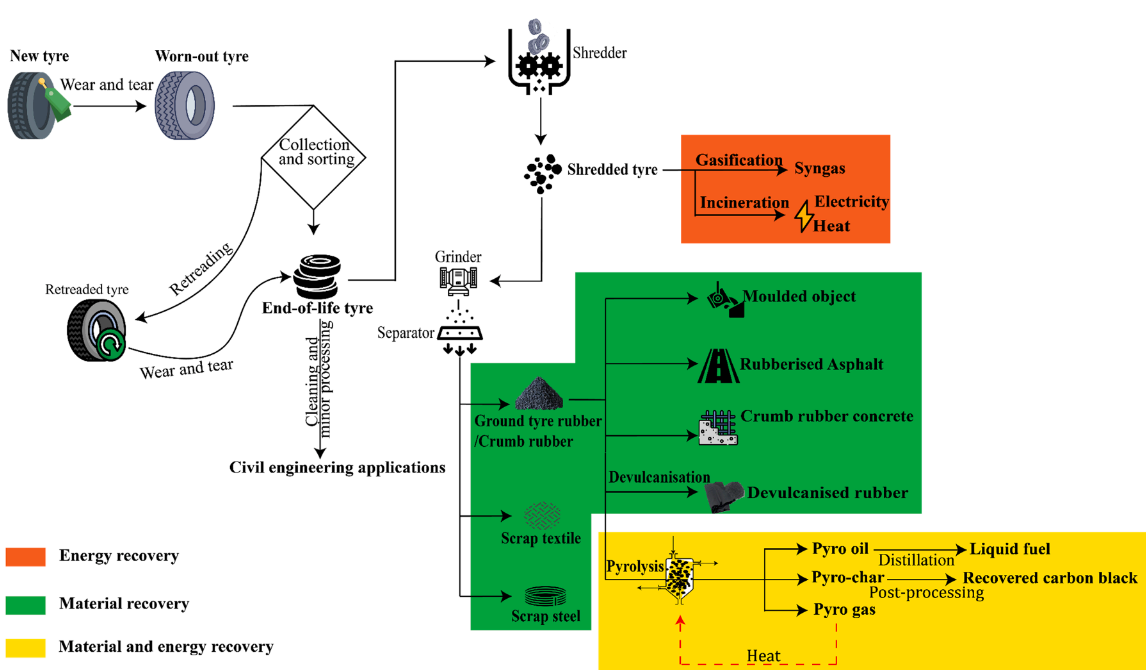

Fig. 3. End-of -life tyre valorisation routes.

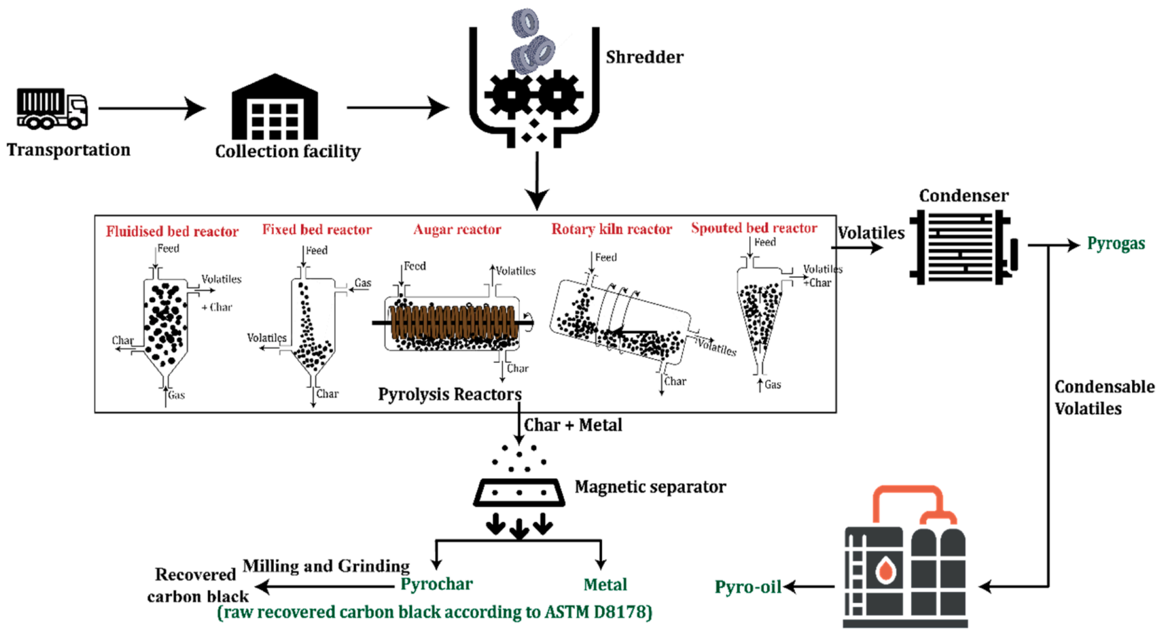

Fig. 4. Basic overview of recovered carbon black production from end-of-life tyre pyrolysis adapted from Lewandowski et al. (2019).

valuable chemicals such as limonene, styrene, and isoprene that can be extracted for chemical markets (Campuzano et al., 2023; Mello et al., 2023; Hita et al., 2016). Pyrogas typically comprises hydrogen and methane (20–25% v/v each), carbon monoxide and dioxide (4–5% v/v each), and C2-C4 hydrocarbons; these are used onsite for energy self-sufficiency.

Process outcomes depend critically on operating parameters including temperature, pressure, solid residence time, and heating rate. Slow pyrolysis, characterised by moderate heating rates (5–40 °C/min) and extended residence times (minutes to hours), favours maximum pyrochar yield and suits batch or semi-batch configurations (Mkhize et al., 2016; Cunliffe and Williams, 1998). In contrast, fast pyrolysis emphasises liquids through rapid heating, while flash pyrolysis (>700–1000 °C/s, <1 s residence time) maximises gas production and thus is unsuitable for char-focused applications (Raj et al., 2013). Reactor design further modulates performance: laboratory fixed-bed reactors enable flexible particle sizes but suffer heat transfer limitations and batch operation constraints (Laresgoiti et al., 2004). Industrial-scale continuous processing relies on rotary kilns, where rotational speed controls residence time despite moderate thermal efficiency, or auger reactors featuring internal screws for superior mixing and heat transfer (Antoniou and Zabaniotou, 2015; Martínez et al., 2013). Fluidised and conical spouted beds provide alternatives, though scale-up challenges persist.

4. Recovered carbon black

4.1. Raw recovered carbon black

The American Society for Testing and Materials (ASTM) D8178 standards defines recovered carbon black (rCB) as the "*solid product recovered via thermal decomposition from rubber goods which contain carbon black, which is free of wire and fabric, and when milled typically gives semi-reinforcing properties in rubber*" (ASTM Standard, 2022). Accordingly, pyrochar generated directly from the pyrolysis of end-of-life tyres is termed "raw recovered carbon black or raw rCB" (Martınez et al., 2021).

Raw recovered carbon black from ELT pyrolysis typically comprises 50–90 wt.% elemental carbon (from original carbon black and carbonised rubber), 1 to 3% sulphur, 5 to 20% inorganic ash, and residual organics (Martınez et al., 2021). The raw rCB also exhibits a broad particle, aggregate, and agglomerate size distribution, reflecting the mix of original commercial carbon black grades in tyres, exacerbated by pyrolysis-induced sintering and agglomeration (Cardona et al., 2018). This heterogeneity yields broader, less predictable aggregate distributions than uniform ASTM N-grades (e.g., N110, N220, N330, N660), impairing consistent reinforcing performance in rubber compounds. Surface chemistry features diverse oxygen and nitrogen- containing functional groups including acidic (carboxylic acid, hydroxyl, carboxylic anhydrite and phenol groups) and basic (pyridine, nitrile, amide, and amine) functionalities (Puri and Bansal, 1965; Boehm, 1994). These surface functional groups alongside residual organics and volatiles, hinder dispersion, wetting, and rubber-filler interactions compared to commercial carbon black (Norris et al., 2023).

4.2. Quality improvement of raw recovered carbon black by optimising the pyrolysis process

The yield and properties of the raw rCB depend strongly on the amount, grade and distribution of commercial carbon black in the ELT feed as well as the pyrolysis conditions. Decades of research have focused on optimising slow pyrolysis conditions for end-of-life tyres to generate high-quality raw rCB. The key optimisable pyrolysis parameters and their reported effect on the raw rCB production are discussed below.

4.2.1. Feedstock

End-of-life tyre composition varies with application, type and brand, which in turn strongly influences raw recovered carbon black yield and quality. Kumar Singh et al. (2018) showed that passenger car tyres, characterised by higher synthetic rubber and ash contents, give the highest raw rCB yield (≈ 43 wt.% at 700 °C), a trend confirmed by other studies (Ucar et al., 2005). Reported yields across international brands range from 37 to 42%, with specific surface areas of 71.7–83.8 m^2/g, highlighting that brand formulations also affect raw rCB structure (Kyari et al., 2005). Intra-tyre variability is equally important as Wang et al. (2019) found that sidewall pyrolysis produced raw rCB with only 6.5% ash at 500 °C and with properties comparable to the commercial N660 grade. In contrast tread pyrolysis yielded 46.5% ash under the same conditions. These compositional and structural differences critically determine raw rCB's suitability for direct replacement of commercial carbon black in tyre applications, where controlled surface area, ash content and reinforcing performance are essential. Ensuring a homogeneous and well-characterised feedstock (e.g., selective collection or pre-sorting by tyre type and section) is therefore essential to produce consistent raw rCB.

4.2.2. Particle size distribution

Particle size of ELTs critically shapes both pyrolysis performance and raw rCB quality, with direct implications for its reuse in tyre compounds. Smaller particles enhance heat transfer and heat absorption, increasing effective heating rates and intrinsic reaction rates, which shortens required pyrolysis time and reduces overall heat demand (Oyedun et al., 2012; Haydary et al., 2012). Conversely, larger particles slow conversion and tend to yield coarser raw rCB with lower surface activity, reduced carbon content and surface area and higher ash fractions (Cunliffe and Williams, 1999), limiting its applicability in replacing commercial carbon black in tyre manufacturing. Optimising pre-shredding to achieve sufficiently small, uniform particles can therefore improve consistency of raw rCB and tailor its morphology and chemistry, enabling more reliable substitution of commercial carbon black in new tyre formulations, albeit at the cost of higher grinding energy and some mass loss.

4.2.3. Temperature and heating rate

Temperature and heating rate of end-of-life tyre pyrolysis profoundly govern raw rCB yield, its carbon content, and structural quality. Carbon content rises from ~80% to 90% as temperature increases from 300 to 600 °C (Nunes et al., 2022), while volatiles drop (e.g., 16.6 wt.% to 6.3 wt.% from 450 to 650 °C (Li et al., 2004)). Lower temperatures, <450 °C boost yield via incomplete pyrolysis but leave heavy hydrocarbon deposits that block pores, significantly reducing specific surface area and activity, which could lead to critical flaws for tyre compounding (Cataldo, 2005). Higher temperatures (>650 °C) enhance surface area by volatilising deposits but risk mesopore formation, degrading reinforcement potential (Manchon-Vizuete et al., 2004). An optimal temperature range between 450 and 600 °C balances high-carbon, clean-surface raw rCB with adequate porosity and low volatiles, enabling effective partial substitution of commercial carbon black while minimising defects in new tyre formulations.

4.2.4. Pressure

Pyrolysis pressure influences raw rCB yield, surface area, and purity, with implications for tyre-grade reinforcement. Most studies use ambient pressure in the pyrolysis process. However, elevated pressures (1–2 MPa) reduce reaction heat demand and limits volatile release. It also affects the surface area; 64.3 m^2/g at 0.1 MPa drops to 58.1 m^2/g at 1 MPa, then rises to 59.8 m^2/g at 2 MPa (Wang et al., 2021). Vacuum pyrolysis (3–10 kPa), conversely, accelerates volatile evolution, minimises secondary reactions and carbon deposition, boosting pore size and specific surface area (Roy et al., 1990). Roy et al. (1999) achieved 33–39% raw rCB yield for pyrolysis of ELTs under vacuum at 600 °C. Properties were akin to commercial N330 (with a specific surface area of 76 to 80 m^2/g; refer to Table 2), due to cleaner surfaces free of unconverted hydrocarbons.

4.2.5. Residence time

Literature suggests that the residence time of the end-of-life tyre particles in the reactor (solid residence time) is a key parameter affecting the yield and quality of raw rCB. Longer residence times (minutes to hours) at moderate heating rates promote complete disintegration of tyre particles and removal of condensed volatiles, enhancing surface cleanliness and activity desirable for reinforcement (Putra et al., 2019). However, excessively long exposure at elevated temperatures can cause carbon burn-off or gasification, lowering carbon content while increasing ash and sulphur fractions (Gao et al., 2022).

4.3. Modified recovered carbon black

Despite optimising pyrolysis conditions, inherent variations in pyrolysis feedstock and the complexities in handling ELTs means that considerable variations in surface properties of raw rCB persist. In addition, the presence of impurities such as ash and sulphur, means that the direct substitution of commercial carbon black in tyre formulations with raw rCB is technologically limiting. This underscores the need for tailored post-pyrolysis processing of raw rCB to restore structure, purity, and functionality matching virgin grades.

Raw rCB, when subjected to further physical and chemical modification to generate recovered carbon black partially suitable to substitute commercial carbon black in tyre compounds and other rubber-reinforcing applications, is termed as modified rCB. Similar to commercial carbon black, modified rCB is also characterised by its elemental composition, morphology and surface chemistry. There are two broad pathways to produce modified rCB from raw rCB for the potential replacement of commercial carbon black in tyre manufacturing: (1) physical modification and (2) chemical modification.

4.3.1. Physical modifications

Thermal treatment combined with mechanical milling represents a mature, widely adopted strategy to produce modified rCB (Martínez Ángel et al., 2013; Martínez et al., 2019). Heating raw rCB to 400–800 °C volatilises organic residues, while subsequent milling homogenises particle distribution and eliminates nodular formations. This dual process elevates specific surface area by 10 to 20%, reduces average particle diameter, and improves dispersibility in rubber matrices, closely mimicking commercial carbon black performance. Reported energy consumption is moderate at approximately 1–2 kWh/kg, primarily from drying, heating, and grinding operations (Anupabphan et al., 2025).

Electron beam irradiation offers a targeted alternative, employing high-energy beams (e.g., 10 MeV) to fragment oversized aggregates into finer, more uniform particles. Zhong et al. (2020) demonstrated a modest surface area gain from 40 to 42.1 m^2/g, alongside enhanced uniformity conducive to better filler-polymer interfacial bonding (chemical and physical interactions between modified rCB and rubber polymer chains at their boundary enhancing reinforcement). However, adoption remains constrained by high capital costs and energy use (~0.5 to 1 kWh/kg), limiting it to niche applications.

Plasma modification, though underexplored for modified rCB, shows substantial promise through surface etching and functionalisation. Argon plasma reduces particle sizes from 1.85 to 1.05 μm (Ma et al., 2022) while subsequent air jet milling reduces it further from 25.9 to 19.4 nm (Zhao et al., 2023). Plasma modification introduces polar groups and increases surface area (60 to 63 m^2/g), markedly boosting wear resistance in tyre composites (Ma et al., 2022). Environmental advantages include combustion-free operation with inert gases; yet plasma generation demands 5 to 15 kWh/kg, potentially offsetting gains via indirect emissions (Mountouris et al., 2006).

Collectively, these physical routes improve raw rCB's morphological and chemical attributes for viable substitution of virgin carbon black, with scalability hinging on energy efficiency advancements. However, the physical treatments are limited in terms of removing ash and other chemical impurities off the rCB surface and hence necessitate further chemical treatment.

4.3.2. Chemical modifications

Chemical modification of raw rCB typically follows physical modification as an additional step. Following physical modification by pre-milling and/or thermal pretreatment solid–liquid extraction with acids (hydrochloric acid (HCl), sulphuric acid (H_2SO_4), and nitric acid (HNO_3)) and/or bases (sodium hydroxide (NaOH) and potassium hydroxide (KOH)) are carried out, followed by thorough washing, and drying (Costa et al., 2022). These agents solubilise metal oxides, silicates, and sulphides, substantially lowering ash content while optimising porosity and functional group distribution of the modified rCB. The aim is to eliminate inorganic ash and refine surface chemistry, generating modified rCB akin to commercial carbon black (e.g., N330) suitable for tyre reinforcement (Anupabphan et al., 2025; Ariyadejwanich et al., 2003).

Ariyadejwanich et al. (2003) reduced ash content from 14.7 wt.% in raw rCB to 6.2 wt.% in modified rCB using 1 M HCl. Martínez et al. (2019) attained a similar ash reduction from 13.2 wt.% to 7.1 wt.% using 4 M HCl and from 13.2 wt.% to 3.1 wt.% via sequential acid–base treatment, although they deemed the latter environmentally and economically unviable. Cardona-Uribe et al. (2021) established HNO_3–NaOH as a superior treatment method to HCl–NaOH for ash removal from raw rCB. While demineralisation using 5 M HCl and 2 M NaOH sequentially reduced the ash content of the recovered carbon black from 13.5 wt.% to 6.1 wt.%, sequential use of 5 M HNO_3 and 2 M NaOH reduced the ash content to 5.2 wt.%. Anupabphan et al. (2025) achieved 2.3 wt.% ash in modified rCB from 17.2 wt.% ash in raw rCB with subsequent 6 M HCl and 2 M NaOH treatment, introducing hydroxyl/carbonyl groups and improving modified rCB's rubber matrix compatibility. Jiang et al. (2022) advanced HCl - phosphate fertiliser acid (PFA) (mixture of fluosilicic acid and hydrofluoric acid) dual treatment, yielding 99.6 wt.% carbon purity alongside HCl recycling and fluosilicic acid (H_2SiF_6) recovery.

Specific surface area increments in demineralisation, although modest (increment of 5 to 15 m^2/g), are critical for filler-polymer interfacial bonding (Martínez et al., 2019; Laithong et al., 2025). Laithong et al. (2025) demonstrated that phosphoric acid modified rCB showed an improved surface area (80 m^2/g) as compared to base (KOH) modified rCB (64.8 m^2/g). Energy requirements were modest (~0.5 to 1 kWh/kg, dominated by heating and agitation), conferring scalability advantages over niche physical alternatives like electron beam irradiation or plasma treatment (Anupabphan et al., 2025). However, a comprehensive life cycle assessment at pilot or commercial scale is necessary to effectively compare the sustainability of the different modification techniques, which is currently lacking in literature. This is further discussed in Section 5.

Table 3 details physical and chemical data for different raw and modified rCBs available in the literature.

4.4. Comparison of raw and modified rCBs with commercial carbon black

In order for modified rCB to be able to effectively replace commercial carbon black in tyre manufacturing, must be not only be similar in properties but also ensure maintain similar mechanical and rheological properties of the rubber compound (Costa et al., 2022). It must also prevent clumping of particles during mixing with natural and synthetic rubber and show adequate wetting of the rubber (Anjum, 2021).

A graphical comparison of properties of raw and modified rCBs with commercial carbon black is shown in Fig. 5. Pyrolysis of end-of-life tyre sidewalls, coupled with heating and pulverisation, yielded modified rCB with surface areas akin to N550 (~45 to 60 m^2/g) (Wang et al., 2019). However, in general, chemically modified rCBs have been demonstrated to have properties closest to commercial carbon black. For instance, Martínez et al. (2019) reported modified rCB with 93.4 wt.% carbon and 3 wt.% ash and a specific surface area of 73.4 m^2/g following initial heating and HCl treatment. The carbon and ash content closely matched N550 carbon black grade while the specific surface area was comparable to N330. Acidic oxygen-containing groups such as carboxylic acid (–COOH) and hydroxyl (–OH) of chemically modified rCB, improve compatibility with synthetic rubbers like styrene-butadiene rubber (SBR) and butadiene rubber (BR), however, unremoved residues continue to block key adsorption sites on the modified rCB surface (Anjum, 2021). Consequently, 15–25% of the modified rCB remains undispersed in the rubber matrix during the mixing process, in contrast to the near-complete uniformity achieved with commercial carbon black. Treatments such as plasma etching or advanced dispersion methods like atomisation dispersion and high-temperature sputtering drying (ADSD) improve particle separation, achieving a dispersion index above 85% and higher levels of bound rubber (Tian et al., 2021; Wen et al., 2025). However, the energy requirement of these novel techniques brings forth the sustainability issue into question which has not been investigated in the literature.

The rheological or flow properties of the rubber compound include thickness measured as Mooney viscosity, curing time for 10% and 90% completion (t_{c10} and t_{c90}) in minutes, lowest and highest torque developed during mixing (M_L and M_H), which indicates the stiffness of the rubber matrix at the starting and ending of the curing process (Hess and Klamp, 1983). The rheological properties are not significantly impacted by the incorporation of modified rCB in the rubber matrix. For example the Mooney viscosity, increases minimally from 50.4 to 51.7 kPa due to friction between its particle clumps; however, this does not negatively impact how easily the rubber can be shaped or processed (stable cure start and end times, t_{c10}/t_{c90}) (Cataldo, 2005). The torque values (M_L and M_H) are comparable for commercial carbon black and modified rCB compounded rubber matrices (Dwivedi et al., 2020).

The static mechanical behaviour of the reinforced rubber matrix, however, shows significant divergence of properties between commercial carbon black and modified rCB. For instance, the tensile strength of styrene butadiene rubber compound reduced from 15.11 MPa (using commercial N330 carbon black) to 6.36 MPa (using modified rCB prepared by sequential acid-base treatment) (Anupabphan et al., 2025). This could be attributed to ash and leftover residues in modified rCB which results in the formation of weak spots, which can build up stress. This also leads to cracking when the rubber is stretched 200–300% showing less flexibility as compared to commercial carbon black-compounded rubber (Anjum, 2021). Chemically modified rCB has shown to improve the mechanical characteristics of the reinforced rubber as compared to physically modified rCB. Martínez et al. (2019) used demineralised rCB, treated using 4 M HCl and 5 M NaOH subsequently in a styrene butadiene rubber (SBR) matrix, and observed an increase in tensile strength to 17.5 MPa compared with 16.8 MPa for a formulation using N550 carbon black. This improvement comes from removing surface dirt, allowing more rubber to tightly bond with the filler particles. It is worth mentioning here that the heated and pulverised modified rCB also performed well as a reinforcing filler in SBR (Norris et al., 2014; Silva et al., 2025). Several researchers have also proposed a mixture of modified rCB and commercial carbon black for rubber reinforcement to facilitate improved rubber matrix properties while improving the circularity of the tyre value chain (Dwivedi et al., 2020; Costa et al., 2022). Table 4 summarises the rheological and static mechanical properties of rubber matrices prepared using commercial carbon black and/or modified rCB fillers.

Other modification processes of raw rCB, like plasma modification, electron bombardment and use of novel coupling agents, also improved the reinforcing ability of the rCB. Ma et al. (2022) used plasma-modified rCB in natural rubber composites and reported improved modulus at 300% elongation (from 8.7 MPa for rCB to 10.3 MPa for Argon plasma-modified rCB), but other mechanical properties did not have any significant changes. Zhang et al. (2023) used a novel coupling agent of (Z)-4-((4-aminophenyl) amino)-4-oxobut-2-enoate which significantly improved the reinforcing effect of modified rCB in rubber formulation. Tian et al. (2021) evaluated the atomisation dispersion and high temperature sputtering drying (ADSD) mixing method to improve the performance of the rubber matrix and observed an increased Shore A hardness compared to the values obtained in traditional dual roller mixing.

Taken together, these studies indicate that modified rCB can, under appropriate processing and modification conditions, partially replace commercial carbon black in tyre and rubber applications. Indeed, Laithong et al. (2025) have suggested that up to 50% substitution of commercial carbon black with modified rCB is feasible, maintaining comparable properties of the rubber matrix. Nevertheless, persistent

Table 3
Elemental composition and morphological properties of recovered carbon black.

Recovered carbon black: Tyre type	Pyrolysis condition: Reactor type	Temperature (°C)	Yield (wt %)	Production/ Modification method	Elemental composition: Ultimate analysis (wt. % dry basis): C	H	N	S	Ash (wt %)	Surface and pore properties: Specific surface area (m^2/g)	Pore volume (cm^3/g)	Average primary particle size (nm)	oil absorption number (OAN) (ml/100 g)[c]	Reference
-	Fluidised bed	500	-	None	90.3	0.3	0.2	1.2	8.4	63	-	-	-	(Murillo et al., 2006)
-	Fixed bed	500	23.2	None	93.3[b]	0.8	0.8	3	11.4	151.5	-	-	-	(Roy et al., 1995)
-	Fluidised bed	550	35	None	89.4	0.3	0.1	0.9	7.7	-	-	-	-	(Napoli et al., 1997)
-	Rotary kiln	420 ± 20	45 ± 4	None	83.9	1.3	0.4	3	11.75			61.5–84.5	107.7	(Xu et al., 2021)
-	Conical spouted bed	425 – 600	33.9–35.8	None	86.5-86.9	0.7-0.8	0.3-0.5	3.6-2.1	7.3-7.1	46.5- 116.3		-	-	(López et al., 2010)
Side wall	Fixed tubular bed	500	41.8	None	88.8	0.6	0.5	0.5	6.5	44.7	0.17	14.7	-	(Wang et al., 2019)
Tyre tread	Furnace		32.4		50.6	0.4	0.5	1	46.5	121.5	1.10	36.2	-	
-	Rotary kiln	400	35	None	89.9[b]	3.1	0.3	1.9	10.4	22.4	0.17	-	-	(Ayanoǧlu and Yumrutaş, 2016)
Passenger car	Fixed bed	550	33	None	94.4[b]	0.4	0.3	3.0	6.7	74.9		-	-	(Roy et al., 1999)
Truck tyre	Fixed bed	485	39	None	-	-	-	0.5	0.7	95	1.02	-	-	
-	Continuous auger	550	40.5 ± 0.3	None	83	0.5	0.3	2.7	14.9	72.4	0.3	-	-	(Martínez et al., 2019)
				Heating at 700 °C followed by HCl treatment	92.9	0.6	0.3	1.1	4.9	76.3	0.5	-	-	
Automobile tyre	Fixed bed	500	30	None	87.3	0.8	1.9	2	16.8	51.5	0.8	176	-	(Zhong et al., 2020)
				High energy electron bean irradiation of 180 kGy	-	-	-	-	17.3	42.1	0.68	166	-	
				High energy electron bean irradiation of 360 kGy	-	-	-	-	16.3	40.6	0.68	178	-	
				Hydrochloric acid treatment	-	-	-	-	8.4	93	-	-	-	
				Heat treatment at 1000 °C	-	-	-	-	21.8	94	-	-	-	
Light motor vehicle	Fixed bed	500		Pulverisation	73.1	-	-	4.3	21	44	-	-	60	(Dwivedi et al., 2020)
	Fixed bed	500		Pulverised and treatment with 30% (v/v) H_2O_2	-	-	-	4.3	-	-	-	-	-	
Passenger car tyre	Fixed bed	450	35.1 ± 0.3	Mechanical grounding with ball mill followed by ultrasonic dispersion	82[b]	0.8	0.4	2.2	19.6	52.9	-	-	87	(Tian et al., 2021)
Blend of passenger car and truck tyres	Rotary kiln	400	35	None	80.8	1	<0.01	3	13.4	32	.1	-	-	(Cardona-Uribe et al., 2021)
				Demineralisation using 5 M HCl and 2 M NaOH	89.9	1.4	1.3	1.2	6.1	39	0.3	-	-	
				Demineralisation using 5 M HNO_3 and 2 M NaOH	88.6	1.5	1	1.8	5.2	40	0.3	-	-	

[b] dry and ash free basis
[c] the oil absorption number (OAN) value is calculated based on how much (in millilitres) dibutyl phthalate 100 g carbon black can absorb (Bansal et al., 1993).

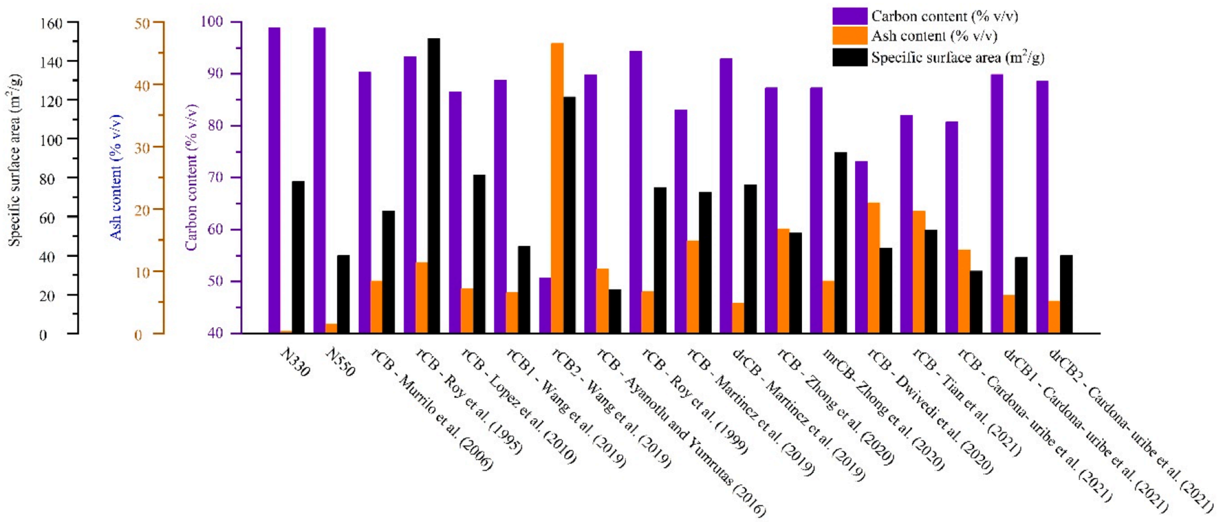

Fig. 5. Comparison of elemental composition and specific surface area of commercial and recovered carbon black.
rCB - Murillo et al. (2006); rCB - Roy et al. (1995); rCB - López et al. (2010); rCB1 - Wang et al. (2019): rCB prepared from side wall of passenger car tyre pyrolysis (Wang et al., 2019); rCB2 - Wang et al. (2019): rCB prepared from tread of passenger car tyre pyrolysis; rCB - Ayanoǒlu and Yumrutaş (2016); rCB - Roy et al. (1999); rCB - Martínez et al. (2019); drCB - Martínez et al. (2019): heating at 700 °C followed by demineralisation; rCB - Zhong et al. (2020); mrCB- Zhong et al. (2020): Demineralisation with HCl treatment; rCB - Dwivedi et al. (2020); rCB - Tian et al. (2021); rCB - Cardona-Uribe et al. (2021); drCB1 - Cardona-Uribe et al. (2021): Demineralisation using 5 M HCl and 2 M NaOH; drCB2 - Cardona-Uribe et al. (2021): Demineralisation using 5 M HNO_3 and 2 M NaOH.

challenges hinder industrial adoption of modified rCB as a substitute for commercial carbon black. Systematic optimisation of recovered carbon black properties and further comprehensive studies on filler and mixing procedures and specific modification chemistry are needed to achieve consistent performance across formulations at a large scale. Scale-up demonstrations remain limited, and demineralisation (chemical treatments) generates contaminated effluents from non-recyclable leaching agents laden with dissolved inorganics, elevating costs and environmental risks (Xu et al., 2021). Parallel advancements in effluent recycling and pilot-scale validation are imperative for broader implementation.

5. Life cycle assessment of recovered carbon black

Life cycle assessment (LCA) is an important framework for evaluating the sustainability of rCB as a replacement for commercial carbon black. As discussed in Section 2.1, the furnace black process is the predominant method for commercial carbon black production, where the precursor hydrocarbons are thermally decomposed in a reactor to produce high-quality carbon black grades (Fan et al., 2020). These precursors are derived from fossil fuels, and their incomplete combustion leads to environmental impacts including the depletion of non-renewable fossil fuel resources. The production of one tonne of carbon black following the conventional route results in around 3.5 tonnes of $CO_{2\text{-eq}}$ emissions (Rosner et al., 2024 with natural gas consumption of around 8.3 GJ and oil consumption of 33.8 GJ (Abdallas Chikri and Wetzels, 2020). Recovered carbon black, on the contrary, uses end-of-life tyres as feedstock and produces other value-added products like pyro-oil and pyrogas in the pyrolysis process. Various researchers have investigated the life cycle assessment of raw rCB; however, limited research exists on the LCA of the various modification methods of rCB and the incorporation of modified rCB in tyre production.

Comparing the ELT pyrolysis process with other end-of-life treatment methods where the functional unit is the mass of the end-of-life tyre processed has been the goal and scope definition of most of these studies (Fiksel et al., 2011; Duval et al., 2024; Buadit et al., 2020). Describing the system boundary and allocation is another pivotal aspect of LCA studies (Yasin et al., 2024). According to ISO 14,044 (2006) guidelines system expansion and substitution-based allocation approaches that consider the main product (raw or modified rCB) and the co-products (pyro-oil and pyrogas) as replacements of their conventional alternatives have been the most common method to cater for the multi-functionality of rCB production (Yasin et al., 2022). Fig. 6 illustrates the system boundary that should ideally be utilised while conducting a life cycle assessment of rCB production from end-of-life tyres. In LCA studies, recovered carbon black is most commonly considered to replace commercial carbon black with no mention of specific grades, the pyro-oil is considered to replace diesel (Banar, 2015), naphtha (Maga et al., 2023) or bunker fuel (La Rosa et al., 2019) and pyrogas is considered to either directly replace natural gas or used in combined heat and power to supply energy to the pyrolysis process (Maga et al., 2023) as shown in Fig. 6(a).

Banar (2015) conducted an LCA of end-of-life tyre pyrolysis with one tonne of shredded end-of-life tyre following a system expansion approach where the output of the system replaces a conventional product. This study considered that one kg of raw rCB can only replace 0.5 kg of commercial carbon black in tyre production, and the steel present in the end-of-life tyres can be recycled fully. The results showed a saving of 510 kg $CO_{2\text{-eq}}$/tonne of end-of-life tyres processed (global warming potential (GWP)) but saving only 2.92 kg SO_2 equivalent/tonne of end-of-life tyre (acidification potential). Maga et al. (2023) also found an emission savings of 703 kg $CO_{2\text{-eq}}$/tonne of end-of-life tyres processed as various products, namely physically modified rCB, pyrolysis oil, steel and textile generated in the process offer substantial emission credits. La Rosa et al. (2019) considered a different system boundary (shown in Fig. 6b) comprising of rubber vulcanisation, tyre production and end-of-life tyre pyrolysis with avoided products comprising syngas, heavy and light fuel oil and steel. A greenhouse gas emission of 7.39 kg $CO_{2\text{-eq}}$/kg of physically modified rCB is reported. If the environmental impact of tyre production is ignored, then the rCB production provides an emission savings of 0.44 kg $CO_{2\text{-eq}}$/kg of rCB produced.

Studies specifically focusing on the life cycle assessment of different modification methods of rCB, including heating, pulverisation, demineralisation and others are limited. Wu et al., (2024) conducted an extensive LCA study of tyre manufacturing using three types of modified rCB, namely physical modification (heating and pulverisation), nitric

Table 4
Rheological and mechanical properties of commercial carbon black and modified recovered carbon black reinforced rubber.

Type of reinforcement	Representative rubber compound	Properties of vulcanised rubber													Reference
		Rheological properties							Mechanical properties						
		Mooney viscosity (kPa)	t_{c10} (min)	t_{c90} (min)	t_{s1} (min)	t_{s2} (min)	M_L (dNm)	M_H (dNm)	Elongation at break (%)	Tensile strength (MPa)	Tensile stress at 10% (MPa)	Tensile stress at 100% (MPa)	Tensile stress at 300% (MPa)	Shore hardness (Shore A)	
N330	NR	47.2	1.83	27.11			1.64	10.65	472	26.97	0.94	4.26	16.61	72.5	(Zhong et al., 2020)
rCB		52.7	2.86	21.48			1.6	6.73	465	15.57	0.389	2.29	7.96	60.8	
N550	SBR	80.6	6.45	21.53	4.25	6.96	2.61	19.64	320	16.8	-	-	15.5	69	(Martínez et al., 2019)
rCB		98	4.81	22.08	3.35	5.17	3.21	20.22	319	14.1	-	-	13	68	
drCB		91.8	3.52	17.81	1.87	3.89	3.04	28.81	350	17.5	-	-	-	69	
N339	NR	50.4	5.48	14.31	5.52	6.32	2.68	12.41	463	13.15		2.22	7.76	62	(Cataldo, 2005)
rCB		51.7	4.90	11.82	5.41	6.3	1.9	8.13	411	3.51		1.19	2.79	50	
rCB30% N300 70%	NR	-	-	5.7	-	-	0.56	7.11	600	27		3	9.5	64	(Dwivedi et al., 2020)
rCB 50% N300 50%		-	-	5.6	-	-	0.57	7.13	640	29		2.8	9	63.5	
rCB 70% N300 30%		-	-	5.5	-	-	0.57	7.33	610	27		2.8	8.1	61	
rCB 100%		-	-	5.4	-	-	0.48	7.67	680	28		2	6	57	
rCB mixed by TMM 100%	NR	-	5.87	12.6	-	-	0.54	12.07	596	24.28		1.6	7.68	55	(Tian et al., 2021)
rCB mixed by TMM 60% rCB mixed by ADSD 40%		-	5.12	11.87	-	-	1.65	15.87	552.6	25.89		2.31	11.81	63	
rCB mixed by TMM 80% rCB mixed by ADSD 20%		-	4.98	11.62	-	-	1.87	17.05	544.6	26.71		2.47	12.73	65	
rCB mixed by ADSD 100%		-	4.87	11.43	-	-	2.01	18.41	531.4	27.58		2.64	13.81	67	
N234 52% rCB 48%	NR	-	0.47	3.98	-	-	1.10	4.70	759.3	23.25		1.96	6.06	64	(Xu et al., 2021)
N234 45% rCB 55%		-	1.37	4.43	-	-	1.40	4.50	790.9	22.05		1.71	5.32	65	
N234 40% rCB 60%		-	1.80	4.28	-	-	1.10	3.90	932.3	23.59		1.14	3.34	57	

t_{ci}: curing time for i% vulcanisation; t_s: scorching time; NR: Natural rubber; SBR: Styrene-butadiene rubber; TMM: Traditional method mixing; ADSD: atomisation dispersion and high temperature sputtering drying.

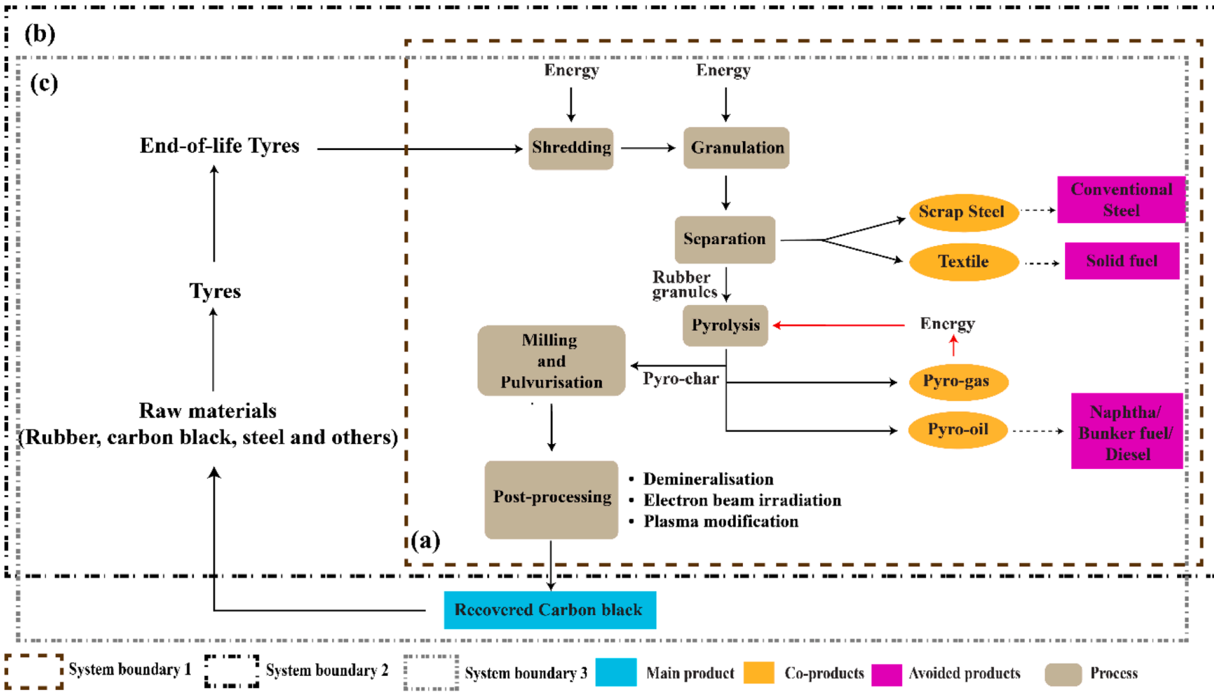

Fig. 6. (a)-(c). System boundary for life cycle assessment of recovered carbon black production from end-of-life tyre pyrolysis (Banar, 2015; Maga et al., 2023; La Rosa et al., 2019; Briones-Hidrovo et al., 2025).

acid demineralisation and plasma modification. It was assumed that 30%, 40% and 50% of the total carbon black could be replaced by these modifications, respectively, in new tyres. The physical modification showed 55% less abiotic depletion potential and 15% less global warming potential compared to the nitric acid treatment. Using plasma-modified rCB and demineralised rCB in a new tyre formulation reduced the global warming potential by 500 kg $CO_{2\text{-eq}}$/tonne of ELT treated, whereas the physical modification reduced the global warming potential by 800 kg $CO_{2\text{-eq}}$/tonne of ELT treated. However, in other environmental impact categories like abiotic depletion potential, acidification potential, ozone depletion potential and eutrophication, the plasma-modified rCB showed higher savings because of the non-toxic nature of the plasma generation technique. Briones-Hidrovo et al. (2025) compared the environmental impacts of different rCB modification processes along with the consequence of increasing carbon black supply in the market due to rCB modification. Nitric acid, hydrochloric acid and acetic acid were chosen as the demineralising agents. The nitric acid treatment significantly increased the global warming potential from saving 972 kg $CO_{2\text{-eq}}$/tonne of rCB for physically modified rCB to an emission of 2850 kg $CO_{2\text{-eq}}$/tonne of rCB. The highest global warming potential was recorded for acetic acid treatment (4760 kg $CO_{2\text{-eq}}$/tonne of rCB) and the lowest for hydrochloric acid (1340 kg $CO_{2\text{-eq}}$/ tonne of rCB) treatment. The high GHG emissions are due to the high volume of acid (~14 tonne/ tonne of rCB) used for the demineralisation process. This underscores the importance of an effluent recycle process to recover the acid. A summary of life cycle assessments conducted on modified rCB is provided in Table 5.

The varied results across different source of literatures suggest that the functional unit and system boundary have significant effect on the environmental impact. Avoided impacts are another deterministic factor. Therefore, it is essential to maintain the quality of all the products to qualify them as potential alternatives and foster circular economy through end-of-life tyre pyrolysis and rCB recovery. The authors could find only two studies where the environmental burden of rCB modification have been tested (Briones-Hidrovo et al., 2025; Wu et al., 2024b). This area, thus, should be stressed in further studies. Also, it is essential to quantify the environmental benefits of using modified rCB in tyre manufacturing which will further consolidate the premise of using modified rCB in new tyres. Therefore, a scenario shown in Fig. 6(c) should be investigated where modified rCB is included as replacement of commercial carbon black in tyre formulations. The functional unit should be standardised according to the European Commission's product environmental footprint guide as "**1 kg recovered carbon black in tyre manufacturing providing equivalent reinforcing performance of commercial carbon black over the average tyre lifetime"** (EC-JRC, 2012). Sensitivity of varying substitution rates, effluent recycling and energy sources should also be considered.

6. Economic assessment of recovered carbon black

End-of-life tyre pyrolysis is generally regarded as a commercially attractive technology due to its potential for energy self-sufficiency through the use of the pyrogas as an internal fuel, relatively low maintenance requirements, straightforward operation and environmental benefits (Rahman et al., 2022). Assessing the profitability of this process typically relies on a detailed economic assessment, which calculates various economic indicators like minimum product selling price, net present value (NPV), internal rate of return (IRR), and payback period from a discounted cash flow analysis over the plant's lifetime. Discounted cash flow analysis is conducted using the capital and operating expenditure data and revenue. The minimum product selling price corresponds to the break-even selling price (or levelised cost) at zero profit; NPV is the cumulative cash flow after tax at the end of the plant's operation; IRR is the discount rate at which the NPV becomes zero, and payback period is the time at which the fixed capital investment is recovered (Pati et al., 2023).

Xu et al. (2021) conducted a simple profit-loss calculation for an ELT pyrolysis plant with 2–3 tonne per hour plant capacity. The study reported a profit of 7.6–154.14 €/tonne of end-of-life tyre processed with revenues from physically modified rCB, pyro-oil and recycled steel. This study also found that physically modified rCB can replace 40–50% of commercial carbon black with very little or no compromise with the rubber quality. Goksal (2022) calculated a revenue of €195.8/tonne ELT processed with a processing cost of €178/tonne in a midsize plant that

Table 5
Life cycle assessment studies on ELT pyrolysis and recovered carbon black.

Location	Functional Unit	Allocation method	Avoided products	rCB modification step	Assessment method	Impact assessment						Reference
Turkey	1 t of ELT	System expansion	Steel, carbon black (1 kg rCB replaces 0.5 kg cCB), Diesel (1 kg Pyro-oil replaces 0.5 kg Diesel)	None	CML-IA baseline	Abiotic depletion (element)	kg Sb_{eq}	-2390				(Banar, 2015)
						Fossil resource scarcity	MJ	-2.16E+04				
						Acidification potential	kg SO_{2-eq}	2.92				
						Eutrophication potential	kg PO_{4-eq}	-0.391				
						Global warming potential	kg CO_{2-eq}	-510				
						Ozone depletion potential	kg CFC-11_{eq}	-2.66E-4				
						Human toxicity	kg 1,4-DB_{eq}	-778				
						Fresh water aquatic ecotoxicity	kg 1,4-DB_{eq}	-254				
						Marine aquatic ecotoxicity	kg 1,4-DB_{eq}	-3.63E+05				
						Terrestrial ecotoxicity	kg 1,4-DB_{eq}	-0.656				
						Photochemical oxidation	kg C_2H_{4-eq}	5.15E-03				
Italy	1 kg rCB	System expansion	Steel, light fuel oil, heavy fuel oil	None	CML 2.0 Baseline	Abiotic depletion potential	kg Sb_{eq}	0.081				(La Rosa et al., 2019)
						Acidification potential	kg SO_{2-eq}	0.028				
						Eutrophication potential	kg PO_{4-eq}	0.0071				
						Global warming potential	kg CO_{2-eq}	7.39				
						Ozone depletion potential	kg CFC-11_{eq}	1.5E-6				
						Human toxicity	kg 1,4-DB_{eq}	2.72				
						Fresh water aquatic ecotoxicity	kg 1,4-DB_{eq}	1.00				
						Marine aquatic ecotoxicity	kg 1,4-DB_{eq}	2492				
						Terrestrial ecotoxicity	kg 1,4-DB_{eq}	0.014				
						Photochemical oxidation	kg C_2H_{4-eq}	0.0012				
Germany	1 t of ELT	System expansion	Steel, textile fibre, naphtha and carbon black	Heating and milling	Environmental footprint	Global warming	kg CO_2 eq.	-703				(Maga et al., 2023)
						Stratospheric ozone depletion	kg CFC-11 eq.	3.0 E-08				
						Fine particulate matter formation	Disease incidents	-6.2E-5				
						Acidification	Mole of $H+_{eq}$	-2.59				
						Freshwater eutrophication	kg P_{eq}	7.8E-04				
						Marine eutrophication	kg N_{eq}	-0.26				
						Terrestrial eutrophication	Mole of N_{eq}	-2.71				
						Ionising radiation, human health	kBq $U235_{eq}$	13.78				
						Photochemical ozone formation	kg $NMVOC_{eq}$	-1.16				
						Land use	Pt	-1232				
						Mineral resource scarcity	kg Sb_{eq}	9.1E-06				
						Fossil resource scarcity	MJ	-29252				
						Water consumption	m^3	3.76				
China	1 kg of rCB	System expansion	Metal, rCB	None	eFootprint system	Global warming	kg CO_{2-eq}	-1.59				(Wu et al., 2024)
						Stratospheric ozone depletion	kg CFC-11_{eq}	-2.54E-7				
						Acidification	kg SO_{2-eq}	-1.28E-2				
						Photochemical ozone formation	kg $NMVOC_{eq}$	-1.33E-2				
						Abiotic depletion potential	kg Sb_{eq}	-2.56E-5				
						Fossil resource scarcity	MJ	-0.628				
Portugal	1 t of rCB	System expansion	Commercial carbon black and Fuel oil	Demineralisation with HNO_3(S1), Demineralisation with acetic acid (S2), Demineralisation with HCl (S3), heating, milling and palletisation (S4)				S1	S2	S3	S4	(Briones-Hidrovo et al., 2025)
						Global warming	kg CO_{2-eq}	2850	4670	1340	-972	
						Acidification	Mole of $H+_{eq}$	26.5	25.2	13.3	-11.5	
						Freshwater ecotoxicity	CTUe	1.82E+05	2.40E+05	7.53E+04	-6.28E-4	
						Freshwater eutrophication	kg P_{eq}	1.2	3.99	2.49	-0.232	
						Marine eutrophication	kg N_{eq}	5.84	5.36	3.02	-0.923	

(*continued on next page*)

Table 5 (*continued*)

Location	Functional Unit	Allocation method	Avoided products	rCB modification step	Assessment method	Impact assessment						Reference
						Terrestrial eutrophication	Mole of N_{eq}	118	77.5	29.3	-9.3	
						Photochemical ozone formation	kg $NMVOC_{eq}$	3.91	14.1	2.54	-4.54	
						Mineral resource scarcity	kg Sb_{eq}	-2.22E-03	-0.01	-1.98E-03	-1.87E-3	
						Fossil resource scarcity	MJ	-6.82E+04	1.21E+04	-8.02E+04	-1.13E-5	

kg Sb_{eq}: kg of antimony equivalent; kg $SO_{2\text{-}eq}$: kg of sulphur dioxide equivalent; kg $PO_{4\text{-}eq}$: kg of phosphate equivalent; kg $CO_{2\text{-}eq}$: kg of carbon dioxide equivalent; kg $CFC\text{-}11_{eq}$: kg of chlorofluorocarbon-11 equivalent; kg 1,4-DB_{eq}: kg of 1,4-dichlorobenzene equivalent; kg $C_2H_{4\text{-}eq}$: kg of ethylene equivalent; Mole of $H+_{eq}$: moles of hydrogen ions equivalent; kg P_{eq}: kg of phosphorus equivalent; kg N_{eq}: kg of nitrogen equivalent; Mole of N_{eq}: moles of nitrogen equivalent; kBq $U235_{eq}$: kilobecquerels of uranium-235 equivalent; kg $NMVOC_{eq}$: kg of non-methane volatile organic compounds equivalent; CTUe: comparative Toxic Unit for ecosystems (freshwater).

can process 30–40 tonnes of ELT per day. Qi et al. (2025) conducted a techno-economic assessment of molten salt ELT pyrolysis of 100,000 tonne/year and 200,000 tonne/year capacities, respectively. The authors reported a net present value of € 14.63 million and € 41.7 million, respectively, with 19.6% and 26.6% of respective pre-tax IRRs. The smaller capacity plant recovered the fixed capital investment in 5.9 years, while the time was 4.9 years for the larger plant.

The economics of raw rCB modification which is a prerequisite for tyre-grade quality matching N330/N550 carbon black, remain largely unquantified, representing a critical knowledge gap. Physical treatments such as heating and milling appear compatible with profitability, while chemical demineralisation necessitates validation of effluent recycling to offset reagent costs. Integrated processing could elevate modified rCB market value by 20–50% (to €800–1200/tonne), preserving competitiveness against commercial carbon black priced at €1500/tonne.

The economic benefits of having a commercial pyrolysis process focused on carbon black production can further be enhanced with subsidies from government and tyre manufacturers and carbon credits earned by mitigating carbon emissions and generating additional energy with the help of a combined heat and power unit (Oliveira Neto et al., 2019). The extended producer responsibility scheme adopted by most countries in the European Union provides a certain processing fee for treating ELTs in pyrolysis plants. Europe hosts over 10 operational rCB-focused pyrolysis plants (plants with capacity more 1000 tonne/year are included in Table 6), though capacities typically fall below 100 kt/year due to feedstock competition. Co-pyrolysis with biomass or plastics presents a viable scale-up strategy. However, the principal barrier to commercialisation lies in tyre manufacturer reluctance. Despite laboratory evidence supporting 20–50% commercial carbon black substitution without performance compromise, industrial rCB predominantly serves lower-specification applications such as conveyor belts, gaskets, and mats rather than tyres (Costa et al., 2022). Therefore, the need for research and development is imminent in this area, followed by the development of policies and regulations to generate acceptability and demand of modified rCB within tyre manufacturers.

7. Perspective and future direction

This review has brought together previously fragmented work on rCB production from end-of-life tyres, together with its modification, utilisation and sustainability assessment and has aimed to provide a roadmap based on the limitations and opportunities identified in the literature. It is evident that raw rCB produced from tyre sidewall has more favourable characteristics compared to the raw rCB prepared from tyre tread in terms of the carbon content, ash content and surface properties. This underscores the need for selective shredding/sorting

Table 6
List of commercially active companies on ELT pyrolysis in Europe.

Company	Location	Capacity	Key products	Status
Pyrum Innovations	Germany	~20,000 tonne/year	High purity rCB Pyrolysis oil Steel wire	Active
Scandinavian Enviro Systems	Sweden	~15,000–30,000 tonne/year	rCB pyrolysis oil Steel	Active
Anglo United Environmental ltd.	UK	15,000 tonne/year		Active
Splainex Ltd.	Netherlands	20 tonne/day	rCB	Active
Black Bear Carbon	Netherlands	~20,000 tonne/year	rCB (branded as Black bear carbon black	Active
DG Engineering	Germany	~10 tonne/day	rCB Pyrolysis oil Steel	Active
PYReco	UK	200 tonne/day	-	Active

protocols tailored to high-reinforcement fractions. Pyrolysis control measures (like moderate temperatures (450–600 °C), slow heating, extended residence, and vacuum conditions) can enhance yield of cleaner, smaller particles with enhanced porosity, and can minimise sintering while balancing energy costs against grinding demands. Vacuum pyrolysis merits revival, given its proven N330-like morphology.

Chemically modified rCB has properties closer to commercial carbon black. Immediate priorities should encompass pilot- and industrial-scale validation of modified rCB production via demineralisation to quantify scalability, effluent recycling efficiency (e.g., HCl recovery), and net energy burdens. Life cycle hotspots such as the acidification potential of chemical modification, should also be addressed. On the application side, laboratory rubber compounds must progress to full prototype tyres, subjected to rigorous independent testing for rolling resistance, wet grip, and durability in accordance with EU tyre labelling regulations, thereby building tyre manufacturer confidence. A combination of modified rCB and commercial carbon black formulations must be tested to provide a low-risk alternative for tyre manufacturers, potentially accelerating market penetration to 30% by 2030.

To align with circular economy objectives, and to adhere to recent EU policies like the Green Deal (Fetting, 2020) and the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) guidelines (Hunt et al., 2025) the following roadmap is proposed: (1) Establish pilot-scale integrated pyrolysis-modification facilities (10–20

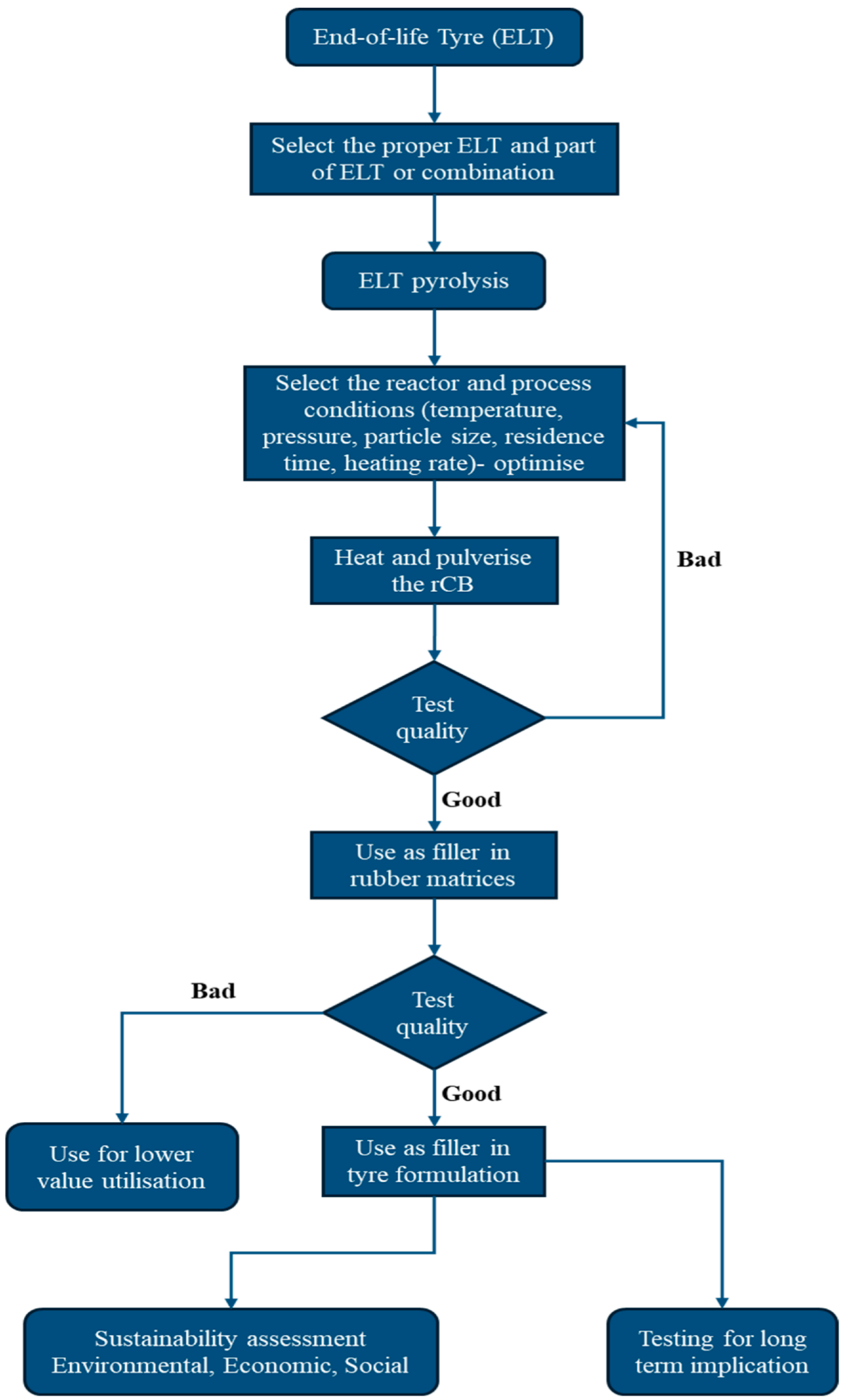

Fig. 7. Possible decision flow diagram on the future direction of research in recovered carbon black.

kt/year) to benchmark full-chain costs. (2) Fabrication and independent testing of prototype tyres incorporating 30–50% modified rCB blends against EU labelling criteria. (3) Leverage carbon credits (reflecting 79–85% CO_2 reductions) and extended producer responsibility premiums alongside original equipment manufacturer (OEM) offtake agreements; and (4) Implement policy mandates targeting 10–20% sustainable carbon material content in tyres by 2030, analogous to existing EU battery regulations (Melin et al., 2021).

With the absence of tyre manufacturer's adoption, modified rCB risks relegation as a niche recycled material. Targeted research and development in plasma treatment scalability and artificial intelligence optimised mixing promises additional gains, while cross-sector collaboration among end-of-life tyre pyrolysis companies, modifiers, and tyre producers will ultimately close the end-of-life tyre loop and reduce fossil fuel dependency across the sector. Fig. 7 shows a decision flow diagram on the prospective avenue of modified rCB, integrating feedstock choice, process optimisation modification strategies and sustainability assessments as key elements in advancing modified rCB toward wider industrial use.

8. Conclusion

This review consolidates progress across production, modification, application, and sustainability assessment of recovered carbon black produced from the slow pyrolysis of end-of-life tyres. It enables the reader to comprehend the progress on recovered carbon black research and provides a clear outlook on the avenues to take this research further. Physically and chemically modified rCB shows substantial promise based on technical, environmental and economic indicators on its suitability to replace commercial carbon black in tyre reinforcement. Tailored feedstocks (e.g., sidewalls), optimised pyrolysis conditions, and post-treatments like demineralisation enable modified rCB properties approaching N330/N550 grades of commercial carbon black, supporting 20–50% substitution while maintaining rubber compound performance. Environmentally, end-of-life tyre pyrolysis delivers net benefits across key LCA categories, particularly 79–85% lower global warming potential through co-product credits and avoided virgin production burdens. Techno-economic analyses affirm profitability (NPVs €14–42 M, IRRs 20–27%), bolstered by extended producer responsibility fees and carbon credits, though modified rCB upgrading costs require pilot validation. Tyre manufacturers' adoption continues to remain as a principal barrier in adopting modified carbon black in tyre manufacturing. Future efforts should prioritise integrated pilot facilities, prototype tyre testing, comprehensive LCAs, and policy mandates for sustainable carbon content to and close the tyre circularity loop.

CRediT authorship contribution statement

Soumitra Pati: Writing – original draft, Methodology, Investigation, Conceptualization. **Conor Goggin:** Writing – review & editing. **Richard O'Shea:** Writing – review & editing, Supervision, Project administration. **Claire McManus:** Writing – review & editing. **Bill Collins:** Writing – review & editing. **Jerry D. Murphy:** Writing – review & editing, Funding acquisition. **Gillian Collins:** Writing – review & editing, Supervision, Project administration. **Archishman Bose:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

References

Abbas-Abadi, M.S., Kusenberg, M., Shirazi, H.M., Goshayeshi, B., Van Geem, K.M, 2022. Towards full recyclability of end-of-life tires: challenges and opportunities. J. Clean. Prod. 374. https://doi.org/10.1016/j.jclepro.2022.134036.
Abdallas Chikri, Y., Wetzels, W., 2020. Decarbonisation Options For the Dutch carbon Black Industry. The Hague.
Anjum A. Recovered carbon black from waste tire pyrolisis. 2021.
Antoniou, N., Zabaniotou, A., 2015. Experimental proof of concept for a sustainable End of life tyres pyrolysis with energy and porous materials production. J. Clean. Prod. 101, 323–336. https://doi.org/10.1016/j.jclepro.2015.03.101.
Anupabphan, T., Narischat, N., Theinnoi, K., Hartley, U.W., Wongkhorsub, C., 2025. Chemical process enhancement of pyrolytic carbon black from waste tires. ACS Omega 10, 42451–42460. https://doi.org/10.1021/acsomega.5c02908.
Ariyadejwanich, P., Tanthapanichakoon, W., Nakagawa, K., Mukai, S.R., Tamon, H., 2003. Preparation and characterization of mesoporous activated carbon from waste tires. Carbon N. Y. 41, 157–164.
ASTM Standard, 2022. Standard terminology relating to recovered carbon black (rCB). Annu. B. ASTM Stand.
Ayanoǧlu, A., Yumrutaş, R., 2016. Rotary kiln and batch pyrolysis of waste tire to produce gasoline and diesel like fuels. Energy Convers. Manage 111, 261–270. https://doi.org/10.1016/j.enconman.2015.12.070.
Banar, M., 2015. Life cycle assessment of waste tire pyrolysis. Fresenius Environ. Bull. 24, 1215–1226.
Banasiak L., Chiaro G., Palermo A., Granello G. Recycling of end-of-life tyres in civil engineering applications: environmental implications 2019.
Bansal, R.C., Donnet, J.B., Wang, M., 1993. Carbon black. Sci. Technol. 133.
Bing, W., Hongbin, Z., Zeng, D., Yuefeng, F., Yu, Q., Rui, X., 2021. Microwave fast pyrolysis of waste tires: effect of microwave power on product composition and quality. J. Anal. Appl. Pyrolysis. 155, 104979.
Bockstal, L., Berchem, T., Schmetz, Q., Richel, A., 2019. Devulcanisation and reclaiming of tires and rubber by physical and chemical processes: a review. J. Clean. Prod. 236. https://doi.org/10.1016/j.jclepro.2019.07.049.
Boehm, H.P, 1994. Some aspects of the surface chemistry of carbon blacks and other carbons. Carbon. N. Y. 32, 759–769.
Briones-Hidrovo, A., Costa, S.M.R., Maganinho, C., Silva, C.M.C., Rocha, J., Dias, A.C., et al., 2025. Recovering carbon black from end-of-life tires: a consequential life cycle assessment. Environ. Impact Assess Rev. 115. https://doi.org/10.1016/j.eiar.2025.108044.
Buadit, T., Rattanapan, C., Ussawarujikulchai, A., Suchiva, K., Papong, S., Ma, H.W, 2020. Life cycle assessment of material recovery from pyrolysis process of end-of-life tires in thailand. Int. J. Environ. Sci. Dev. 11, 493–498. https://doi.org/10.18178/ijesd.2020.11.10.1296.
Campuzano, F., Martínez, J.D., Agudelo Santamaría, A.F., Sarathy, S.M., Roberts, W.L, 2023. Pursuing the end-of-life tire circularity: an outlook toward the production of secondary raw materials from tire pyrolysis oil. Energy Fuels. 37, 8836–8866. https://doi.org/10.1021/acs.energyfuels.3c00847.
Cardona, N., Campuzano, F., Betancur, M., Jaramillo, L., Martínez, J.D, 2018. Possibilities of carbon black recovery from waste tyre pyrolysis to be used as additive in rubber goods-a review. In: IOP Conf. Ser. Mater. Sci. Eng., 437 IOP Publishing, 12012.
Cardona-Uribe, N., Betancur, M., Martínez, J.D, 2021. Towards the chemical upgrading of the recovered carbon black derived from pyrolysis of end-of-life tires. Sustain. Mater. Technol. 28. https://doi.org/10.1016/j.susmat.2021.e00287.
Cataldo, F., 2005. Preparation of pyrolytic carbon black from scrap tire rubber crumb and evaluation in new rubber compounds. Macromol. Mater. Eng. 290, 463–467.
Chen, K.S., Yeh, R.Z, 1996. Pyrolysis kinetics of epoxy resin in a nitrogen atmosphere. J. Hazard. Mater. 49, 105–113.
Chicu, N., Prioteasa, A.-L., Deaconu, A., 2020. Current trends and perspectives in tyre industry. Stud. Univ. Vasile Goldiș Arad. Ser. Științe. Econ. 30, 36–56.
Chikri, Y.A., Wetzels, W., 2019. Decarbonisation Options For the Dutch tyre Industry. PBL Netherlands Environmental Assessment Agency.
COM E. A new circular economy action plan–for a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2020.
Commission E. For the circular economy of tyre domain: recycling end of life tyres into secondary raw materials FOR tyres and other product applications 2024. https://cordis.europa.eu/article/id/454286-end-of-life-tyres-from-waste-to-a-valuable-resource.

Costa, S.M.R., Fowler, D., Carreira, G.A., Portugal, I., Silva, C.M, 2022. Production and upgrading of recovered carbon black from the pyrolysis of end-of-life tires. Mater. (Basel) 15. https://doi.org/10.3390/ma15062030.

Cunliffe, A.M., Williams, P.T, 1998. Composition of oils derived from the batch pyrolysis of tyres. J. Anal. Appl. Pyrolysis. 44, 131–152.

Cunliffe, A.M., Williams, P.T, 1999. Influence of process conditions on the rate of activation of chars derived from pyrolysis of used tires. Energy Fuels 13, 166–175.

Czajczyńska, D., Krzyżyńska, R., Jouhara, H., Spencer, N., 2017. Use of pyrolytic gas from waste tire as a fuel: a review. Energy 134, 1121–1131.

Dai, X., Yin, X., Wu, C., Zhang, W., Chen, Y., 2001. Pyrolysis of waste tires in a circulating fluidized-bed reactor. Energy 26, 385–399.

Duval, L., Majeau-bettez, G., Saunier, F., Maréchal, F., Margni, M., 2024. Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts. J. Ind. Ecol. 28, 512–526. https://doi.org/10.1111/jiec.13474.

Dwivedi, C., Manjare, S., Rajan, S.K, 2020. Recycling of waste tire by pyrolysis to recover carbon black : alternative & environment-friendly reinforcing filler for natural rubber compounds. Compos B 200, 108346.

EC-JRC, 2012. Product Environmental Footprint (PEF) Guide. Eropean Commision Jt Res Cent, p. 154.

Fan, Y., Fowler, G.D., Zhao, M., 2020. The past, present and future of carbon black as a rubber reinforcing filler - a review. J. Clean. Prod. 247, 119115.

Fazli, A., Rodrigue, D., 2020. Recycling waste tires into ground tire rubber (Gtr)/rubber compounds: a review. J. Compos. Sci. 4. https://doi.org/10.3390/jcs4030103.

Fetting C. The European green deal. ESDN Report, December 2020;2:53.

Fiksel, J., Bakshi, B.R., Baral, A., Guerra, E., Dequervain, B., 2011. Comparative life cycle assessment of beneficial applications for scrap tires. Clean Technol. Environ. Policy 13, 19–35. https://doi.org/10.1007/s10098-010-0289-1.

Gao, N., Wang, F., Quan, C., Santamaria, L., Lopez, G., Williams, P.T, 2022. Tire pyrolysis char: processes, properties, upgrading and applications. Prog. Energy Combust. Sci. 93, 101022.

Goksal, F.P, 2022. An economic analysis of scrap tire pyrolysis, potential and new opportunities. Heliyon 8. https://doi.org/10.1016/j.heliyon.2022.e11669.

Han, J., Li, W., Liu, D., Qin, L., Chen, W., Xing, F., 2018. Pyrolysis characteristic and mechanism of waste tyre: a thermogravimetry-mass spectrometry analysis. J. Anal. Appl. Pyrolysis. 129, 1–5.

Haydary, J., Jelemenský, Ľ., Gašparovič, L., Markoš, J., 2012. Influence of particle size and kinetic parameters on tire pyrolysis. J. Anal. Appl. Pyrolysis. 97, 73–79.

Hess, W.M., Klamp, W.K, 1983. The effects of carbon black and other compounding variables on tire rolling resistance and traction. Rubber Chem. Technol. 56, 390–417.

Hita, I., Arabiourrutia, M., Olazar, M., Bilbao, J., Arandes, J.M., Castaño, P., 2016. Opportunities and barriers for producing high quality fuels from the pyrolysis of scrap tires. Renew. Sustain. Energy Rev. 56, 745–759.

Huang, K., Gao, Q., Tang, L., Zhu, Z., Zhang, C., 2005. A comparison of surface morphology and chemistry of pyrolytic carbon blacks with commercial carbon blacks. Powder Technol. 160, 190–193.

Hunt, N., Kestens, V., Rasmussen, K., Badetti, E., Soeteman-Hernández, L.G., Oomen, A. G., et al., 2025. Regulatory preparedness for multicomponent nanomaterials: current state, gaps and challenges of REACH. NanoImpact 37, 100538.

Jiang, G., Pan, J., Deng, W., Sun, Y., Guo, J., Che, K., et al., 2022. Recovery of high pure pyrolytic carbon black from waste tires by dual acid treatment. J. Clean. Prod. 374. https://doi.org/10.1016/j.jclepro.2022.133893.

Kibria, M.A., Thomas, B.S., Bhattacharya, M., Bhattacharya, S., 2024. Processing of metal-free end-of-life tyres (EOLTs) to fuels and products: an experimental study with process simulation and economic analysis from an Australian perspective. Clean Technol. Environ. Policy. https://doi.org/10.1007/s10098-024-02825-y.

Kumar Singh, R., Ruj, B., Jana, A., Mondal, S., Jana, B., Kumar Sadhukhan, A., et al., 2018. Pyrolysis of three different categories of automotive tyre wastes: product yield analysis and characterization. J. Anal. Appl. Pyrolysis. 135, 379–389. https://doi.org/10.1016/j.jaap.2018.08.011.

Kurian, T., Mathew, N.M, 2006. Natural rubber : production, properties and applications. Biopolym. BIOMÉD. Environ. Appl. 403–436.

Kwon, E.E., Kim, S., Lee, J., 2019. Pyrolysis of waste feedstocks in CO2 for effective energy recovery and waste treatment. J. CO2. Util. 31, 173–180.

Kyari, M., Cunliffe, A., Williams, P.T, 2005. Characterization of oils, gases, and char in relation to the pyrolysis of different brands of scrap automotive tires. Energy Fuels 19, 1165–1173.

Laithong, T., Nampitch, T., Ourapeepon, P., Phetyim, N., 2025. Quality improvement of recycled carbon black from waste tire pyrolysis for replacing carbon black N330. Sci. Rep. 15, 1–17. https://doi.org/10.1038/s41598-025-08539-5.

Laresgoiti, M.F., Caballero, B.M., de Marco, I., Torres, A., Cabrero, M.A., Chomón, M.J, 2004. Characterization of the liquid products obtained in tyre pyrolysis. J. Anal. Appl. Pyrolysis. 71, 917–934.

La Rosa, A.D., Pergolizzi, E., Maragna, D., Recca, G., Cicala, G., 2019. Reuse of carbon black from end-of-life tires in new pneumatic formulations and life-cycle assessment of the thermolysis process. J. Elastomers. Plast. 51, 740–754.

Lewandowski, W.M., Januszewicz, K., Kosakowski, W., 2019. Efficiency and proportions of waste tyre pyrolysis products depending on the reactor type — a review. J. Anal. Appl. Pyrolysis. 140, 25–53.

Li, S.-Q., Yao, Q., Chi, Y., Yan, J.-H., Cen, K.-F, 2004. Pilot-scale pyrolysis of scrap tires in a continuous rotary kiln reactor. Ind. Eng. Chem. Res. 43, 5133–5145.

López, G., Olazar, M., Aguado, R., Bilbao, J., 2010. Continuous pyrolysis of waste tyres in a conical spouted bed reactor. Fuel 89, 1946–1952.

Lo Presti, D., 2013. Recycled tyre rubber modified bitumens for road asphalt mixtures: a literature review. Constr. Build. Mater. 49, 863–881. https://doi.org/10.1016/j.conbuildmat.2013.09.007.

Ma, Y., Zhao, H., Zhang, X., Fan, C., Zhuang, T., Sun, C., et al., 2022. Structure optimization of pyrolysis carbon black from waste tire and its application in natural rubber composites. Appl. Surf. Sci. 593. https://doi.org/10.1016/j.apsusc.2022.153389.

Maga, D., Aryan, V., Blömer, J., 2023. A comparative life cycle assessment of tyre recycling using pyrolysis compared to conventional end-of-life pathways. Resour. Conserv. Recycl. 199, 107255. https://doi.org/10.1016/j.resconrec.2023.107255.

Manchon-Vizuete, E., Macıas-Garcıa, A., Gisbert, A.N., Fernández-González, C., Gómez-Serrano, V., 2004. Preparation of mesoporous and macroporous materials from rubber of tyre wastes. Microporous Mesoporous Mater. 67, 35–41.

Martínez, J.D., Cardona-Uribe, N., Murillo, R., García, T., López, J.M, 2019. Carbon black recovery from waste tire pyrolysis by demineralization: production and application in rubber compounding. Waste Manage 85, 574–584. https://doi.org/10.1016/j.wasman.2019.01.016.

Martınez, J.D., Gisele Jung, C., Bouysset, J.P, 2021. Recovered carbon black: characteristics and properties in compounds. Tire Waste Recycl. 177.

Martínez, J.D., Murillo, R., García, T., Veses, A., 2013a. Demonstration of the waste tire pyrolysis process on pilot scale in a continuous auger reactor. J. Hazard. Mater. 261, 637–645. https://doi.org/10.1016/j.jhazmat.2013.07.077.

Martínez, J.D., Puy, N., Murillo, R., García, T., Navarro, M.V., Mastral, A.M, 2013b. Waste tyre pyrolysis - A review. Renew. Sustain. Energy Rev. 23, 179–213. https://doi.org/10.1016/j.rser.2013.02.038.

Martínez Ángel J.D., Murillo Villuendas R., García Martínez T. Production of carbon black from the waste tires pyrolysis 2013.

Mayer, P.M., Moran, K.D., Miller, E.L., Brander, S.M., Harper, S., Garcia-jaramillo, M., et al., 2024. Where the rubber meets the road : emerging environmental impacts of tire wear particles and their chemical cocktails. Sci. Total Environ. 927.

Melin, H.E., Rajaeifar, M.A., Ku, A.Y., Kendall, A., Harper, G., Heidrich, O., 2021. Global implications of the EU battery regulation. Sci. (80-) 373, 384–387.

Mello, M., Rutto, H., Seodigeng, T., 2023. Waste tire pyrolysis and desulfurization of tire pyrolytic oil (TPO)–A review. J. Air Waste Manage Assoc. 73, 159–177.

Mkhize, N.M., Van der Gryp, P., Danon, B., Görgens, J.F, 2016. Effect of temperature and heating rate on limonene production from waste tyre pyrolysis. J. Anal. Appl. Pyrolysis. 120, 314–320.

Mohammad Zainol, M., Mustaffa, N., Hassan, A.H., Mustapa, A.N., Mamat, M.H., Syed-Hassan, S.S.A., et al., 2024. A mini review on carbon black production as rubber reinforcement in tyre application. Chem. Eng. Trans. 113, 235–240. https://doi.org/10.3303/CET24113040.

Mountouris, A., Voutsas, E., Tassios, D., 2006. Solid waste plasma gasification: equilibrium model development and exergy analysis. Energy Convers. Manage 47, 1723–1737. https://doi.org/10.1016/j.enconman.2005.10.015.

Murillo, R., Aylón, E., Navarro, M.V., Callén, M.S., Aranda, A., Mastral, A.M, 2006. The application of thermal processes to valorise waste tyre. Fuel Process Technol. 87, 143–147.

my-power.ie, 2026. https://my-power.ie/how-many-kwh-does-it-take-to-run-a-house/.

Napoli, A., Soudais, Y., Lecomte, D., Castillo, S., 1997. Scrap tyre pyrolysis: are the effluents valuable products? J. Anal. Appl. Pyrolysis. 40, 373–382.

Norris, C.J., Hale, M., Bennett, M., 2014. Pyrolytic carbon: factors controlling in-rubber performance. Plast Rubber Compos. 43, 245–256.

Norris, C.J., López Cerdán, A., Ter Haar, P., 2023. Understanding recovered carbon black. Rubber Chem. Technol. 96, 196–213. https://doi.org/10.5254/rct.23.76956.

Nunes, L.J.R., Guimarães, L., Oliveira, M., Kille, P., Ferreira, N.G.C, 2022. Thermochemical conversion processes as a path for sustainability of the tire industry: carbon black recovery potential in a circular economy approach. Clean Technol. 4, 653–668. https://doi.org/10.3390/cleantechnol4030040.

Oikonomou, N., Mavridou, S., 2009. The use of waste tyre rubber in civil engineering works. Sustain. Constr. Mater. 213–238.

Oliveira Neto, GC de, Chaves, L.E.C., Pinto, L.F.R., Santana, J.C.C., Amorim, M.P.C., Rodrigues, M.J.F, 2019. Economic, environmental and social benefits of adoption of pyrolysis process of tires: a feasible and ecofriendly mode to reduce the impacts of scrap tires in Brazil. Sustainability 11, 2076.

Oyedun, A., Lam, K.-L., Fittkau, M., Hui, C.-W, 2012. Optimisation of particle size in waste tyre pyrolysis. Fuel 95, 417–424.

Pati, S., De, S., Chowdhury, R., 2023. Integrated techno-economic, investment risk and life cycle analysis of Indian lignocellulosic biomass valorisation via co-gasification and syngas fermentation. J. Clean. Prod. 423, 138744. https://doi.org/10.1016/j.jclepro.2023.138744.

Pei, Y., Han, B., Kumar, D., Adams, S.D., Khoo, S.Y., Norton, M., et al., 2024. Mechanical processes for recycling of end-of-life tyres. Sustain. Mater. Technol. 41, e01050. https://doi.org/10.1016/j.susmat.2024.e01050.

Puri, B.R., Bansal, R.C, 1965. Iodine adsorption method for measuring surface area of carbon blacks. Carbon. N. Y. 3, 227–230.

Purvis, B., Celebi, D., Pansera, M., 2023. A framework for a responsible circular economy. J. Clean. Prod. 400, 136679.

Putra, A.E.E., Amaliyah, N., Syam, M., Rahim, I., 2019. Effect of residence time and chemical activation on pyrolysis product from tires waste. J. Jpn. Inst. Energy 98, 279–284.

Qi, J., Wang, Y., Xu, P., Hu, M., Huhe, T., Ling, X., Chen, Y., 2025. Coupling of molten salt heating tire pyrolysis process with carbon black modification process: technical economic evaluation and life cycle assessment. J. Cleaner Prod. 486, 144454.

Rahman, M.M., Yu, Y., Wu, H., 2022. Valorisation of waste tyre via pyrolysis: advances and perspectives. Energy Fuels 36, 12429–12474.

Raj, R.E., Kennedy, Z.R., Pillai, B.C, 2013. Optimization of process parameters in flash pyrolysis of waste tyres to liquid and gaseous fuel in a fluidized bed reactor. Energy Convers. Manage 67, 145–151.

Robertson, C.G., Hardman, N.J, 2021. Nature of carbon black reinforcement of rubber: perspective on the original polymer nanocomposite. Polym. (Basel) 13, 1–28. https://doi.org/10.3390/polym13040538.

Rosner, F., Bhagde, T., Slaughter, D.S., Zorba, V., Stokes-Draut, J., 2024. Techno-economic and carbon dioxide emission assessment of carbon black production. J. Clean. Prod. 436. https://doi.org/10.1016/j.jclepro.2023.140224.

Rothon, R., 2017. Fillers For Polymer Applications, 489. Springer, Berlin, Germany.

Roy, C., Chaala, A., Darmstadt, H., 1999. The vacuum pyrolysis of used tires: end-uses for oil and carbon black products. J. Anal. Appl. Pyrolysis. 51, 201–221.

Roy, C., Labrecque, B., de Caumia, B., 1990. Recycling of scrap tires to oil and carbon black by vacuum pyrolysis. Resour. Conserv. Recycl. 4, 203–213.

Roy, C., Rastegar, A., Kaliaguine, S., Darmstadt, H., Tochev, V., 1995. Physicochemical properties of carbon blacks from vacuum pyrolysis of used tires. Plast. Rubber Compos. Process. Appl. 23, 21–30.

Shanbag, A., Manjare, S., 2020. Life cycle assessment of Tyre manufacturing process. J. Sustain. Dev. Energy Water Environ. Syst. 8, 22–34.

Sharma, S., Ghoshal, A.K, 2010. Study of kinetics of co-pyrolysis of coal and waste LDPE blends under argon atmosphere. Fuel 89, 3943–3951.

Silva, C.M.C., Maganinho, C., Mendes, A., Rocha, J., Portugal, I., Silva, C.M, 2025. Recovered carbon black: a comprehensive review of activation, demineralization, and incorporation in rubber matrices. Carbon Resour. Convers, 100334.

Sun, X., Liu, J., Hong, J., Lu, B., 2016. Life cycle assessment of Chinese radial passenger vehicle tire. Int. J. Life Cycle Assess 21, 1749–1758.

Sunthonpagasit, N., Duffey, M.R, 2004. Scrap tires to crumb rubber: feasibility analysis for processing facilities. Resour. Conserv. Recycl. 40, 281–299. https://doi.org/10.1016/S0921-3449(03)00073-9.

Tian, X., Zhuang, Q., Han, S., Li, S., Liu, H., Li, L., et al., 2021. A novel approach of reapplication of carbon black recovered from waste tyre pyrolysis to rubber composites. J. Clean. Prod. 280. https://doi.org/10.1016/j.jclepro.2020.124460.

Ucar, S., Karagoz, S., Ozkan, A.R., Yanik, J., 2005. Evaluation of two different scrap tires as hydrocarbon source by pyrolysis. Fuel 84, 1884–1892.

Valentini, F., Pegoretti, A., 2022. End-of-life options of tyres. a review. Adv. Ind. Eng. Polym. Res. 5, 203–213. https://doi.org/10.1016/j.aiepr.2022.08.006.

Wang, F., Gao, N., Quan, C., 2021. Effect of hot char and steam on products in waste tire pressurized pyrolysis process. Energy Convers. Manage 237, 114105.

Wang, M., Gray, C.A., Reznek, S.A., Mahmud, K., Kutsovsky, Y., 2000. Carbon black. Kirk-Othmer Encycl Chem. Technol.

Wang, M., Zhang, L., Li, A., Irfan, M., Du, Y., Di, W., 2019. Comparative pyrolysis behaviors of tire tread and side wall from waste tire and characterization of the resulting chars. J. Environ. Manage 232, 364–371.

Wen, X., Zhu, X., Chen, S., Lin, J., Zhao, W., Zhao, S., et al., 2025. Improvement of tribological properties of natural rubber filled with waste tire pyrolysis carbon black treated by plasma. J. Appl. Polym. Sci. 142, e57367.

Williams, P.T, 2013. Pyrolysis of waste tyres : a review. Waste Manage 33, 1714–1728.

Wu, Q., Zhang, Q., Chen, X., Song, G., Xiao, J., 2024a. Life cycle assessment of waste tire recycling: upgraded pyrolytic products for new tire production. Sustain. Prod. Consum. 46, 294–309. https://doi.org/10.1016/j.spc.2024.02.029.

Wu, S., Wang, Z., Guo, S., Cai, Y., Zhang, J., Huangfu, C., et al., 2024b. Life-cycle-based reconfiguration of sustainable carbon black production: integrated conventional technique with waste tire pyrolysis and its future improvement potentials. J. Clean. Prod. 442, 141022. https://doi.org/10.1016/j.jclepro.2024.141022.

Xu, J., Yu, J., He, W., Huang, J., Xu, J., Li, G., 2021a. Recovery of carbon black from waste tire in continuous commercial rotary kiln pyrolysis reactor. Sci. Total Environ. 772, 145507.

Xu, J., Yu, J., He, W., Huang, J., Xu, J., Li, G., 2021b. Replacing commercial carbon black by pyrolytic residue from waste tire for tire processing: technically feasible and economically reasonable. Sci. Total Environ. 793. https://doi.org/10.1016/j.scitotenv.2021.148597.

Yasin, S., Hussain, M., Uddin, A., Zheng, Q., Shi, J., Song, Y., 2024. Recycling of binary polymer (PET/SBR) carpet into microfibrillar composites: a life cycle perspective with microplastics quantification. Sustain. Mater. Technol. 40, e00988.

Yasin, S., Hussain, M., Zheng, Q., Song, Y., 2022. Thermo-soil weathering and life cycle assessment of carbon black, silica and cellulose nanocrystal filled rubber nanocomposites. Sci. Total Environ. 835, 155521.

Yuehong, Z., Hao, W., Zhihong, X., 2006. Conceptual design and simulation study of a co-gasification technology. Energy Convers. Manage 47, 1416–1428. https://doi.org/10.1016/j.enconman.2005.08.024.

Zhang G., Jiang Y., Wang S., Zhang Y. Influence of a novel coupling agent on the performance of recovered carbon black filled natural rubber 2023;255.

Zhao, S., Tang, D., Fang, Y., Hao, X., Liu, Y., Liu, J., et al., 2023. Enhanced wear resistance of sustainable tire materials with plasma modified pyrolysis carbon black. Carbon. N. Y. 213. https://doi.org/10.1016/j.carbon.2023.118201.

Zhong, R., Xu, J., Hui, D., Bhosale, S.S., Hong, R., 2020. Pyrolytic preparation and modification of carbon black recovered from waste tyres. Waste Manage Res. 38, 35–43. https://doi.org/10.1177/0734242X19869987.

Zoroufchi Benis, K., Behnami, A., Minaei, S., Brinkmann, M., McPhedran, K.N., Soltan, J., 2023. Environmental occurrence and toxicity of 6PPD quinone, an emerging tire rubber-derived chemical: a review. Environ. Sci. Technol. Lett. 10, 815–823. https://doi.org/10.1021/acs.estlett.3c00521.