Life cycle assessment of carbon neutral tires designed with recycled end-of-life materials: A systematic review of environmental performance, circularity pathways, and carbon reduction potential

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Abstract:
There is mounting pressure on tire sector to minimize its impact on the environment because of the heavy dependence on fossil-based raw materials, energy-intensive manufacturing processes, and rising difficulties in end-of-life tires (ELT) disposal. To overcome these challenges, principles of the circular economy are applied to combine different methods of material recovery like pyrolysis, and mechanical recycling. The paper uses a Systematic Literature Review (SLR) with PRISMA guidelines, which summarizes 40 peer-reviewed publications (2005-2025) to evaluate the potential of a carbon-neutral tire design based on recovered carbon black (rCB) and crumb rubber. The review concludes that although use-phase emissions have the biggest contribution to the impact of tire lifecycle (60-75% of GWP), the substitution of rCB can diminish production emissions by 15-30, and the inclusion of renewable electricity energy can decrease cradle-to-gate emissions by up to 40. Major methodological discrepancies in functional unit, system boundaries and definition of carbon neutrality are detected. The approach to this is a conceptual carbon-neutral tire framework that would lead manufacturers and policymakers in their direction, towards increased circularity.

Keywords:
Life Cycle Assessment, End-of-Life Tires, Recovered Carbon Black, Carbon Neutrality, Circular Economy, Sustainable Manufacturing

1. Introduction:

1.1 Background of the topic:

The treatment of end-of-life tires (ELTs) has emerged as a critical global environmental issue, with over one billion tires reaching their service life annually. The traditional tire manufacturing paradigm is resource-intensive, relying on complex supply chains of fossilderived and petrochemical-based materials. Virgin carbon black a major reinforcing agent derived from heavy petroleum fractions synthetic rubbers, and steel reinforcements form the backbone of tire production. The energy-intensive vulcanisation process further amplifies the carbon footprint of each tire at the manufacturing stage.

1.2 Importance of the research area :

International sustainability frameworks and climate mitigation goals are demanding a shift of focus from operational emissions to the full lifecycle implications of industrial products.

The tire sector, in particular, must decouple performance from petroleum dependence. Life Cycle Assessment (LCA), as standardized under ISO 14040 and ISO 14044, provides the systematic, cradle-to-grave methodology required to quantify environmental burdens across five major lifecycle stages: raw material extraction, manufacturing and vulcanisation, logistics, use phase (rolling resistance and tailpipe emissions), and end-oflife processing.

1.3 Current industry situation :

ELT recycling now has a variety of technological directions: mechanical grinding of tires to crumb rubber used in asphalt and sports surfaces, thermal decomposition of tires by pyrolysis as the recovery of oil, gases, and recovered carbon black (rCB), devulcanisation to break cross-linkages of the rubber and reuse the material, less desirable on the circular economy hierarchy, but still in practice, is energy recovery by incineration. The re-used carbon black is also becoming useful as a high-value alternative to the virgin carbon black, thus forming a possible material recycle loop.

1.4 Research gap :

Regardless of the emerging body of literature on individual interventions, a systematic overview of how high recycled content and renewable energy interact to produce tires that are carbon neutral has not been conducted. Existing LCAs have fragmented methodologies, with varying functional units and system boundaries and allocation processes, which complicates the process of making direct comparisons of environmental claims. More so, little is known about the long-term, industrial scale of high-rCB tires.

1.5 Objectives of the study :

The paper aims to: (1) to test in a systematic way the lifecycle emission of recycles tires including their content; (2) to measure and quantify carbon benefit of rCB substitution; (3) to test how significantly a renewable energy is integrated in terms of emissions; (4) to propose a unified and carbon-neutral tire system that could be applied to manufacturers and policymakers.

1.6 Structure of the paper :

The structure of the paper is as follows: Section 2 presents the literature review of the available literature in five thematic areas. In section 3, the gap in research is determined. Section 4 is the statement of objectives of the study and Section 5 is the hypothesis. The research methodology is presented in Section 6. In section 7, the results of data analysis are provided. Section 8 discusses findings. Conclusions and implications in the practical sense are covered in Section 9 and 10 respectively, whereas limitations are mentioned in Section 11.

2. Literature review :

theme 1: Ica methodology in tire studies :

One of the unresolved problems of the current literature is the absence of uniform application of LCA methods, which severely constrains the interstudy comparability. Researchers differ in the selection of their functional unit: some prefer to use the impact per tire unit, others per kilometer travelled, and systems boundaries are cradle-to-gate or cradle-to-grave. Both mass and economic value allocation decisions reverse once again inferences of the sustainability of recycled tire products.

This complexity is attested by major empirical research. Dong et al. (2021) show that emissions at the use phase are the most significant since they are needed in the rolling resistance energy demand, and Corti and Lombardi (2018) identify raw material extraction as the main manufacturing hotspot. A combination of these works proves that there is no currently existing set of LCA frameworks that could allow benchmarking the progress towards the ultimate carbon neutrality.

theme 2: Environmental hotspots in conventional tires :

In the traditional reports on the life-cycle assessment of tire manufacturing, the use stage is always the most important stage of environmental impact- about sixty to seventy five percent of the total Global Warming Potential (GWP). This supremacy is as a result of the fuel used in overcoming the rolling resistance when the vehicle is in operation. By contrast, manufacturing, specifically the creation of carbon black is a secondary hot spot, as well, with approximately fifteen to twenty percent of all manufacturing emissions attributed to the high levels of combustion necessary to process heavy petroleum feedstocks.

Cradle-to-gate results are significantly mitigated by the nature of electricity used in the production process. Plants that are located in areas which have a high carbon energy network have significantly higher manufacturing footprints compared to plants that use cleaner energy sources. This fact highlights that successful sustainability in the tire sector requires both the decarbonisation of the material and energy sources at the same time.

theme 3: Elt recycling technologies :

Mechanical recycling is the most used form of end-of-life tire (ELT) management because it has less capital capital needs and is very simple to execute. Ambient temperature, or freeze grind at ambient temperature produces crumb rubber that can be used in rubberised asphalt, sports turf, and molded rubber products, and so this waste is not subjected to chemical treatment that would otherwise send it to landfills.

Pyrolysis, which is a thermochemical reaction that does not require oxygen, yields highvalue products, including rCB, oil, and syngas. The process of pyrolysis strongly relies on the energy source that drives the process in terms of environmental performance. Zhao et al. (2025) show that when pyrolysis is coupled with renewable electricity, this will maximise carbon savings on the production of rCB. However, some pyrolysis designs could increase the possibilities of acidification and eutrophication, which justifies the use of multi-indicator sustainability measurements. Devulcanisation, which attacks the sulfur cross-linkages in rubber, represents a higher-value recycling pathway, however, at an industrial level is technically difficult.

theme 4: Recovered carbon black (rcb) substitution :

As Costa et al. (2022) show, rCB has similar surface area and reinforcing characteristics to virgin carbon black. Life-cycle assessments have continually documented that the substitution of rCB by five to thirty percent of manufacturing gases of greater global warming potential and also decreases the depletion of fossil resources. Such gains, however, are related to the nature of quality consistency of rCB that may fluctuate in terms of ash content compared with virgin grades, and thus, posing issues with high-performance compound predictability. Although the economics of rCB is increasingly becoming efficient through technology maturity, the quality targets of an industrial scale is still a challenge.

theme 5: Renewable energy integration :

The attributes of plant energy are consistently determined to play an equal role with material selection in defining the environmental profile of a tire. Plant-level emissions can be cut by forty percent by switching to renewable electricity in manufacturing operations. Practices such as the solar-powered pyrolysis processes, specifically, can bring down the net carbon intensity of rCB by removing the inversion of thermal decomposition emissions. These benefits are damped by the intensity of carbon in the regional grids - high carbon grids absorb the gains of sophisticated recycling. This proves the fact that carbon neutrality requires a twofold approach, material and energy supply decarbonisation.

2. Research Gap

Although there is technological and environmental progress, a missing link is still very eminent as yet no study has synergistically explored the interplay of high recycled contents and renewable energy in coming up with a carbon-neutral tire. Majority of the research considers these factors as independent variables instead of parts of a combined strategy. There is no universally accepted definition of carbon neutrality to tires, which leads to the lack of organisation in reporting. The differences between functional units, system boundaries, and methodologies of allocation hinder the comparability of the studies. Furthermore, the management of high-rCB tires at industrial level, with regard to its longterm mechanical performance and safety data, are still limited, preventing extensive installations.

3. Objectives of the study :

The objectives of this study are formulated to provide a systematic analytical pathway toward the decarbonisation of the tire industry:

(1) To estimate systematically the emissions of life cycles of recycled content tires made of raw materials sourcing through end deployment.

(2) To determine the carbon-reduction potential of the substitution of virgin carbon black with recovered carbon black (rCB).

(3) To determine the environmental impacts of the inclusion of renewable energy in manufacturing and recycling processes.

(4) To detect and categorize methodological inconsistency in the current LCAs, such as the variation in functional units and systems boundaries.

(5) To present a carbon-neutral tire model as a strategic reference point to the manufacturers and policymakers.

4. Hypotheses:

H1: Use of ELT recycled materials (rCB) will result in a drastic decrease of cradle-to-gate GWP in comparison to traditional manufacturing of tires using virgin materials.

H2: Adding renewable electricity will cause a strong multiplier effect on carbon reduction that enhances savings realized by material substitution.

H3: In carbon-neutral design conditions, use-phase emissions will continue to be the largest portion of the total tire lifecycle GWP with a % of 60-75 having the largest contribution.

5. Research methodology :

5.1 Research design :

The research utilises a Systematic Literature Review (SLR) adhering to PRISMA standards a qualitative interpretive-type of study, which can be used to support the reproducibility and bias minimisation of the synthesis of peer-reviewed literature regarding tire LCAs and ELT recycling technologies.

5.2 Data collection - databases used :

The sources of data were selected using Google scholar, Scopus, and Web of science because they have extensive coverage of environmental science, chemical engineering, and industrial sustainability. The inter-database cross-referencing minimized the selection bias and prevalent views.

5.3 Screening process and sample :

The screening was conducted in the form of a multi-stage: 312 initial records were accessed, 124 of them were eliminated as duplicates, and 148 records were screened, basing on the title and abstract. Following the screening of 63 articles on a full-text level, 40 peer-research papers were enrolled in the final synthesis (2005-2025). Because of the heterogeneity in methodology, meta-synthesis was used as opposed to statistical metaanalysis and it was based on thematic synthesis, quantitative aggregation of GWP data, comparative framework analysis, and conceptual framework development.

5.4 Data analysis tools :

Since the body of literature under review is characterised by the methodological heterogeneity, we took the meta-synthesis framework as opposed to the classical statistical meta-analysis.

The following were the components of the analytical toolkit:

Thematic synthesis - discovering and defining common themes of the environment on the different steps of the tire life cycle.

Quantitative aggregation - collecting global warming potential (GWP) reduction ranges on research on recovered carbon black (rCB) replacement and renewable energy usage.

Comparative framework analysis: a methodological evaluation of methodological differences in functional units, systems limits, and allocation plans in a systematic way. Conceptual framework development- Integrating the gathered findings into a rational model of a carbon-neutral tire design.

6. Data analysis and results:

6.1 Baseline gwp of conventional tires :

An analysis of the GWP measurements in the forty articles reviewed provides a baseline of 90-110kg CO 2 -eq of emissions per tire in the conventional manufacturing of tires made of petroleum. This number includes all the cradle-to-gate processes that are involved in the extraction of raw material, compounding, vulcanisation, and logistics and therefore offers a quantitative point of reference to which the environmentally beneficial outcomes of the circular interventions can be compared.

6.2 Gwp reduction from rcb substitution: (h1 testing)

In the literature reviewed, a reduction of 10- 25g CO 2 -equivalent per tire in GWP is found when recovered carbon black substitutes virgin carbon black. This is a decrease of 15-30 manufacturing-based GWP, which provides solid empirical evidence of Hypothesis 1 (H1). The resultant savings are explained by the removal of high temperature petroleum burning to produce virgin carbon black which is replaced by low-energy pyrolysis recovery reaction.

6.3 Gwp reduction from renewable energy integration: (h2 testing)

Switching to renewable power produces a separate cut in manufacturing emissions of 2040 independent of energy grids, which supports the high effect of decarbonised energy grids. Combining the advantages of rCB replacement and renewable energy adoption, the overall effect of the GWP on the life-cycle can decrease by 20-35 percent compared to the traditional baseline, which is strong evidence to support the hypothesis of a synergistic amplifier effect, which is hypothesised to occur in Hypothesis 2 (H2).

Intervention	GWP Reduction Range

rCB substitution (manufacturing)	15–30%
Renewable electricity (manufacturing)	20–40%
Combined rCB + Renewable energy	20–35% (total lifecycle)
Use-phase share of total GWP	60–75% (dominant factor)

Table 1: Summary of GWP Reduction Results (Meta-Synthesis of 40 Studies)

6.4 Use phase dominance: (h3 testing)

In the entire university of forty studies reviewed, the use stage has always contributed sixty to seventy-five percent of the total life-cycle global-warming potential, thus confirming Hypothesis 3 (H3). This trend still remains as the manufacturing emissions are significantly reduced by using material- and energy-based measures. This association, which is hard to change, shows that even any advances made in the confines of the factory will not be sufficient to achieve complete life-cycle carbon neutrality unless tire rolling-resistance performance is also dealt with.

6.5 Trade-offs identified :

Although quantified carbon indicators demonstrate predictable alleviation of the appearance of circular interventions, the review still reveals apparent environmental tradeoffs. Wet scrubbing is used as a method of off-gassing in pyrolysis processes, which can potentially increase the consumption of the aqueous resources. This may be worsened in some recycled -carbon-bearing (rCB) refining operations which rely on high-energy milling to increase the risk of acidification and eutrophication. The observations made herein highlight the fact that a system that is based on carbon-neutrality should be evaluated simultaneously by using a multidimensional sustainability approach.

7. Discussion :

Circularity of materials and decarbonisation of energy are some synergetic levers rather than unrelated ones since rCB has the effect of decreasing embodied carbon by replacing petroleum-based virgin materials, but its overall effect is limited due to the high intensity of the carbon recycling process itself. Cycling electricity contributed by pyrolysis through the high carbon electric energy eliminates savings; renewable electricity maximises savings-which proves again the dual fibred character of the carbon-neutral route. A very important finding is the use -phase paradox: even a tire that has been made carbon-neutral at the factory-gate can still have a major carbon footprint in its lifetime when rolling resistance is degraded. Carbon-neutral designs should hence maintain or enhance rolling resistance functionality. The heterogeneity in LCAs approaches to methodology, which include varying functional units, system boundaries and allocation, introduces an untrustworthy benchmarking landscape. In the absence of standardisation, the risk of greenwashing increases, which highlights the importance of having a universal index of carbon-neutrality of tire products.

8. Conclusion:

This review confirms that in an integrated material-energy approach, carbon-neutral tire design can be achieved with 1530% of manufacturing GWP reduction; and A renewable electricity integration can provide 2040% manufacturing GHW reduction; and 2035% of the total lifecycle GHW reduction will be obtained. Nevertheless, even absolute lifecycle carbon neutrality is limited by the use-phase preeminence (6075% of GWP) and environmental trade-offs such as augmenting water consumption and acidification during certain recycling routes. It introduces the notion of a theoretical carbon-neutral tire structure that incorporates the circular material recovery concept, decarbonised industrial energy, and low-rolling-resistance design as the pillars being mutually reliant on each other, building on a strategic roadmap between the linear take allow-result of embodied in linear-take-waste production to the truly circular, climate-positive production. In the future, it is recommended that carbon-neutrality metrics, scale rCB quality, and optimisation of compounds aided by AI be standardised and investigated.

9. Practical implications :

Manufacturers must take a 2-track approach; they must invest in rCB supply-chainintegration and at the same time invest in procuring industrial renewable energy. Green electricity retrofits and solar-based pyrolysis should not be counted as a zero cost expenditure since the returns are carbon. The government should develop Extended Producer Responsibility (EPR) policies that have financial incentives on the adoption of rCBs and minimum amount of recycled content. Universal carbon-neutrality reporting would spur openness and rivalry on true environmental performance. Carbon Border Adjustment Mechanism (CBAM) by the EU ought to be evaluated in terms of facilitating sustainable tire trade.

10. Limitations and Future Research

There are four major limitations of this study. To begin with, the fact that we are using secondary data on LCA makes the results very dependent on the assumptions made by the original authors, thus limiting us in ensuring the rigor of the principal data gathering. Second, the large geographical differences between electricity grids would mean that the 2040 per cent manufacturing emission removals could not be easily interpolated across the divergent industrial geographies. Third, the heterogeneity of the reviewed studies in terms of methodology requires a qualitative thematic synthesis and not a statistical meta-analysis only. Fourth, there is a lack of industrial-sized empirical data with regard to the production of carbon-neutral tires so that we are currently basing our findings on pilot programmes and modelling research, instead of the mass-market data on operations.

These are the gaps that the future research should cover using dynamic material-flow modelling, the creation of a Universal Carbon-Neutrality index of tires, AI-based optimisation of rubber compounds, and policy-oriented research of the effects of EPR and carbon border levies on the global trade of recycled tire derivatives.

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