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DOI
10.1016/j.resconrec.2025.108169

Publication date
2025

Document Version
Final published version

Published in
Resources, Conservation and Recycling

Resources, Conservation & Recycling 216 (2025) 108169

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Full length article

Lifecycle assessment of end-of-life tire recycling through pathways of transitioning the recycling industry to renewable energy sources

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ARTICLE INFO

Keywords:
Tire recycling
Crumb rubber
Micronized rubber powder
Reclaimed rubber
Lifecycle assessment
Global warming potential
Renewable energy

ABSTRACT

While recycling technologies offer solution to the challenges associated with end-of-life tires (ELT), the reliance of the industry on nonrenewable sources raises concerns. The objective of this cradle-to-gate lifecycle assessment study was to quantify the potential environmental impacts due to recycling of ELT into multiple outputs: crumb rubber (CR), micronized rubber powder (MRP), and reclaimed rubber (RR). Thirty-six scenarios were analyzed including three products and two ELT sources using six electricity mix scenarios transitioning the nonrenewable to renewable sources. The global warming potential due to the production of CR, MRP, and RR from domestic ELT were 1.13×10^4, 3×10^4, and 3.63×10^4 kg CO_2 eq., respectively, while 50 % transition to renewables reduced them by 10–15 %. Further, MRP showed the highest land occupation and water consumption potential. Overall, this research provided a holistic overview of current and future impacts of tire recycling industry supporting sustainable practices.

1. Introduction

Worldwide, the disposal of end-of-life tires (ELT) is one of the major challenges faced by the waste management industry that has been witnessing discarding of over one billion tires annually (Arulrajah et al., 2019; Thomas and Gupta, 2016). This pervasive trend is a multifaceted problem causing land and water pollution, fire hazards, and the release of toxic chemicals, which has resulted in a significant damage of the ecosystem (Dong et al., 2021; Formela, 2021; Moasas et al., 2022; Ortíz-Rodríguez et al., 2017). Fortunately, recycling has emerged as one of the most commonly adopted measures of mitigating the environmental consequences associated with discarded tires, which addresses the concerns of scarcity of resources through material recovery and reuse (Farina et al., 2017; Surehali et al., 2023). According to the circular economy paradigm, waste recycling and deployment of renewable energy are two pillars of modern economy used to conserve the environment and improve the standard of living (Circular Economy Action Plan - European Commission, 2025). Thus, the nexus encompassing recycling, deployment of renewable energy, and sustainable development becomes critical in achieving long-term environmental stewardship and economic resilience (Cerqueira et al., 2021), thereby supporting the broader objectives of the United Nations Sustainable Development Goals (UN SDG), particularly SDG 12 that targets responsible consumption and production. In a nutshell, waste recycling and adoption of renewable energy concurrently contribute to the reduction of environmental degradation and conservation of natural resources (Cerqueira et al., 2021; Raman et al., 2024).

Nationally Determined Contributions (NDCs), 2025 In alignment with the Paris agreement, countries outlined goals as nationally determined contributions (NDC) that set forth emissions reduction targets across sectors such as energy, land use, and waste management to limit further global warming (INDC, 2015, 2025; Powell et al., 2018). As one of the largest non-CO_2 greenhouse gas sources, the waste-sector faces challenges with adapting infrastructure to meet the climate change mitigation goals, with NDC showing a notable gap between current mitigation efforts and adaptation planning. Studies have reported that only 3–15 % of the total ELT are recycled annually, whereas 20–30 % are either landfilled or stockpiled, and 25–60 % get incinerated (Alfayez

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https://doi.org/10.1016/j.resconrec.2025.108169
Received 13 November 2024; Received in revised form 10 January 2025; Accepted 2 February 2025
Available online 13 February 2025
0921-3449/

et al., 2020; Moasas et al., 2022). However, a lack of comprehensive plan in ELT management practices has entailed an unsustainable resource recovery, thereby resulting in rebound effect, thus counteracting the intended environmental benefits. Therefore, it is imperative to explore solutions that allow for systematic allocation of ELT and recover recycled products that can be used as alternatives to virgin materials for design and fabrication of sustainable systems. For example, ELT management practices include retreading, energy recovery, pyrolysis, product recycling, and material recycling. Amongst these, material recycling involving mechanical grinding of tires that yields rubber materials of different sizes is one of the most common means of ELT management globally (Sienkiewicz et al., 2012). To summarize, research studies have indicated that recycling can reduce the quantities of disposed waste, alleviate carbon dioxide emissions, conserve virgin material consumption, and mitigate landfill contamination (Alfayez et al., 2020; Formela, 2021; Mwanza, 2021).

Crumb rubber (CR) is one of the many products produced through material recycling of ELT. Typically, the ELT undergo breakdown and processing in multiple units such as granulator, cracker-mill, micro-mill, ambient shredder, and cryogenic shredder (Valente and Sibai, 2019). Depending on the type of equipment, CR can be produced in different particle sizes, texture, and gradations. Ambient grinding produces CR with characteristics such as lower density, large specific surface area, rough texture, and irregular shape compared to cryogenic grinding. Notwithstanding, studies have also focused on the use of novel recycling technologies, including water jet grinding and ozone cracking, but which require high operational energy and have practical complications such as difficulty in controlling jet properties and ozone concentration levels (Bowles et al., 2020; Lapkovskis et al., 2020; Tushar et al., 2022). Further, researchers have documented the potential environmental impacts of tire recycling process alone (Maga et al., 2023; Meng et al., 2023; Tushar et al., 2022), while others considered tire recycling as part of the raw material extraction phase of various systems leading to the development of products such as asphalt-rubber (AR) binder for roadway applications, artificial turfs, concrete filler, road-safety barrier, and tire retreading (Farina et al., 2017; Fiksel et al., 2011; Miller, 2016; Monteiro et al., 2022; Nanjegowda and Biligiri, 2023a,b; Tanhadoust et al., 2023; Thomas et al., 2016; Venudharan and Biligiri, 2017; Venudharan et al., 2018; Way, 2025). It is noteworthy that the lifecycle impacts of CR production as a raw material in AR binder have been reported to be in the range of 100–500 kg CO_2 eq./metric ton of emissions (Farina et al., 2017; Tushar et al., 2022; Wang et al., 2020).

Reclaimed Rubber (RR) is another product that can be recovered from ELT by reclaiming the rubber either through physical or chemical method. In the reclaiming process, the three-dimensional cross links of rubber are broken down with the help of external sources such as heat, mechanical/microwave energy and/or chemical agents, thereby reducing the molecular weight of rubber chains (Adhikari et al., 2000; Bockstal et al., 2019). Several studies have explored the performance characteristics of various composites with RR and its applications in manufacture of conveyor belts, automobile tires and tubes, but without environmental impact assessment (Dobrotă and Dobrotă, 2018; Markl and Lackner, 2020). Similarly, micronized rubber powder (MRP), which is produced by grinding ELT to rubber particles down to the scales of tens of microns is incorporated in various new rubber compounds of automotive tires, composite particle board, and epoxy coatings to improve their performance (Adesina et al., 2020; Ayyer et al., 2013; Genovés et al., 2022). Limited literature is available pertaining to MRP, while the existing information on rubber powder lacks clarity regarding the type of powder and the assessment techniques to understand the impacts of particulate matter without delving deep into the comprehensive environmental aspects of its production (Buadit et al., 2023; Formela, 2021).

Despite the potential for utilizing recycled rubber products as substitutes to virgin raw materials, it is worth mentioning that collection, transportation, and processing of ELT require significant amount of electricity and fuel (Dobrotă and Dobrotă, 2018). Therefore, it is essential to report the environmental impacts associated with recycling the ELT, which can be scientifically accomplished through lifecycle assessment (LCA). Fundamentally, LCA involves compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product/system throughout its lifecycle conforming to procedures laid down by the international standards organization (ISO 14040, 2006a; ISO 14044, 2006b). For instance, in a cradle-to-gate LCA study, Clauzade et al. (2010) found that the impacts associated with ELT collection, sorting, and shredding stages were compensated due to the recovery of products that could be used as alternatives to virgin raw materials. Another investigation Sun et al. (2016) reported that the use of RR to produce passenger vehicle tires resulted in a reduction of total Global Warming Potential (GWP) by 0.60 %, while the acidification potential and photochemical oxidant potential increased by 0.012 kg SO_2 eq. and 0.001 kg C_2H_4 eq.

Since the magnitudes of environmental impacts pertaining to emissions were majorly attributed to production stage, investigations on ELT treatment/recycling technologies have focused on strategies that allow energy reduction during consumption phase (Li et al., 2010; Moasas et al., 2022). As an example, a study reported that recycling 1 metric ton ELT resulted in GWP of 404.88 kg CO_2 eq. and 130 kg CO_2 eq. for production of rubber powder and RR, respectively. Notably, 86.19 % of the total impacts were attributed to the energy consumption in the form of electricity during production (other than collection and transportation stages), which indicated that the transformation to renewable energy is essential for minimizing the impacts associated with recycling (Meng et al., 2023). Consequently, the handling of ELT must be undertaken with technologies that either utilize the existing power supply efficiently or harness clean energy from renewable sources (Buadit et al., 2023; Tushar et al., 2022).

On another note, renewable energy is a source that is continuously replenished by nature and that could be harnessed for sustainable energy production, which is either directly or indirectly derived from the sun through thermal, photochemical, and photoelectric processes or from other natural environmental mechanisms such as wind, hydropower, geothermal, and tidal forces. Studies show that renewable energy was steadily increasing its share in the global energy portfolio, indicating an increase in the commitment to reduce dependence on fossil fuels and mitigate the impacts of climate change (Demirbas, 2009; Manzano-Agugliaro et al., 2013). Previous literature reported that ELT recycling using ambient grinding to produce granulated rubber crumbs had high energy cost (Dobrotă et al., 2020; Xiao et al., 2022), indicating that the process consumes significant amounts of fossil fuels. Thus, it must be replaced with replenishable renewable energy sources to bring down the carbon emissions and environmental impacts of the ELT recycling. More so, the integration of renewable energy into recycling operations can enhance the sustainability of infrastructure projects. Recycled materials, when produced with renewable energy, embodies a lower carbon footprint, making them more environmentally friendly alternatives for construction and other infrastructure applications (Cerqueira et al., 2021; Tushar et al., 2022). This shift not only supports the reduction of carbon emissions but also promotes energy efficiency and resource conservation, which are key components of UN SDG 12.

To summarize, research is still emerging to quantify the potential environmental impacts associated with the production of CR, a promising strategy for recycling of ELT, which otherwise will be landfilled and burden the ecosystem. Further, though investigations are underway in evaluating the performance characteristics of RR- and MRP-composites, a comprehensive LCA impregnated with primary data sourced from the industry was unavailable. In addition, the hotspots or processes that are responsible for the highest share of environmental impacts during the production of CR, RR, and MRP are yet to be identified. Not just that, there exists a significant gap in exemplifying the environmental benefits associated with recycling of ELT into secondary rubber products for different applications. Very importantly, there is an impending need to understand the lifecycle impacts of producing various types of recycled rubber products (CR, RR, and MRP), especially that the energy sector is transitioning towards the use of renewable energy sources in concert with the government evolving the electricity supply framework for efficient policy development. Further, while the recycling industry is often seen as a vital conglomerate accounting for sustainable practices, its dependence on electricity generated through nonrenewable energy sources have raised concerns about resource extraction. Therefore, there is a need to study the impact of transitioning from nonrenewable to renewable energy sources, which is yet to be addressed.

Thus, the major objective of this research was to perform a comprehensive LCA to quantify the potential environmental impacts associated with the production of CR, RR, and MRP from ELT. The scope of the effort involved: (i) collection of primary data from a rubber recycling industry, (ii) undertake cradle-to-gate LCA by analyzing six different scenarios, namely, business-as-usual (BAU) and shifts of 10, 20, 30, 40, and 50 % energy supply from conventional fossil-based electricity grids (nonrenewable) to renewable sources considering NDC goals (Sudharmma Vishwanathan et al., 2023; Wang and Chen, 2019), and (iii) compare and summarize the impacts associated with recycling ELT procured from domestic and international sources, chiefly to streamline the necessity for efficient resource utilization. It is envisioned that this research will serve as an inventory to evaluate the impacts during the lifecycle of composite products designed with CR, RR, and MRP as important constituents and pave the way for formulation of strategies that promote sustainable waste management.

The novelty of this research lies in the integration of transition to renewable energy sources in the recycling process of ELT, thus presenting a transforming pathway in the realm of environmentally sustainable recycling industry. While researchers have reasonably assessed the CR recycling from the ELT, this study further attempted LCA involving the production processes of MRP and RR, which are the other two major types of ELT recycling. Further, the tradeoffs amongst the potential environmental impacts were assessed to underscore the importance of understanding the burden shift across the impact categories. Additionally, the environmental burdens of the recycled products were estimated using primary data at unit process level of a real full-scale ELT recycling facility. Notably, the findings provided insights into the need for mobilizing stakeholders toward more sustainable practices in the ELT management sector. Overall, this first-of-its-kind research contributed critical insights into the significant environmental impacts of ELT recycling processes, identified the hotspots in the unit processes, and evaluated the role of renewable energy sources in enhancing sustainability of the ELT recycling systems.

2. Methodology

2.1. Goal and scope definition

In India, about 0.27 million ELT are discarded within the country everyday while 3 million ELT are imported to generate recycled rubber products that are used as secondary raw materials due to high demand of recycled goods, promoting resourceful consumption (Gaidhane et al., 2022). Continuing, the power sector in India has been found to contribute to about 50 % of the overall CO_2 emissions, and is transitioning to the use of renewable energy sources, as the nation has pledged to achieve net-zero emissions by 2070 (International Energy Agency, 2021). In alignment with the Paris Agreement, the Government of India has committed to achieving approximately 50 % cumulative electric power installed capacity from non-fossil fuel energy sources by 2030 (IPCC, 2023AR6 Synthesis Report, 2023; INDC, 2015), reflecting a pursuit of a more ambitious and optimal energy mix encompassing wind, hydro, and tidal instead of relying on thermal energy alone. As a country moving towards its net-zero targets, it is important to understand the energy requirements and trends in various sectors including the recycling industry that has huge potential in various infrastructure applications.

Thus, the goal of this study was to quantify the environmental impacts of ELT recycling processes to produce CR, RR, and MRP. Further, an attempt was made to understand the impacts of each recycled product during a transition from nonrenewable to renewable energy source for recycling in the southern electricity grid of India. In this attributional cradle-to-gate study, the unit processes relevant to the production of three distinct recycled rubber products and the transportation of ELT to the processing plant were included. The primary data for the recycling processes was collected directly from the industry in the southern state of Tamil Nadu, India, while the electricity data for the southern grid available in the Ecoinvent™ database was used for modeling the impacts (Ecoinvent Database, 2022). In the absence of precise information regarding the manufacturing, use, and disposal, it was assumed that the ELT entered the system boundary as burden-free and cut-off approach at the point of entering the recycling facility. Literature mentions that since electricity was the major source of recycling process, the increase in proportion of the renewable energy sources could influence the efficiency and effectiveness of the recycling processes (Das et al., 2023; Sawhney, 2021; Trudeau et al., 2011). Thus, this study considered two sources of ELT: domestic and imported, which could provide insights into resource allocation and the results may well contribute to the development of policies and regulations in the supply chain management of ELT from both sources.

As per ISO 21,930, a declared unit is the quantity of product that can be used as a reference to express the potential environmental impacts in LCA and need not cover the complete lifecycle (ISO 21,930:2007). In this study, the declared unit was defined as the production of 100 metric tons of each recycled ELT product at the end of the recycling process undertaken at the facility. The quantity of ELT required to produce recycled products was back calculated considering the loss of 5 % bead wire (a component of ELT) for all the three products and an addition of 4 % silica for MRP production to modify the mechanical properties. Irrespective of the end-product, the ELT first underwent four common processes in the recycling plant: (a) tire cutting, (b) removal of bead wire, (c) loading onto the shredder, and (d) shredding. The shredded products were then transported to their respective processing units within the recycling facility, and the associated unit processes are shown in Fig. 1, as a system boundary schematic.

Note that multifunctionality was also addressed in this study by analyzing each product separately. As indicated in the system boundary, three individual mass flows were adopted for each final product that followed the physical allocation approach. The scrap tire quantity required for each product was added individually to avoid double counting, an approach adopted to evaluate the environmental impacts specific to the declared unit of each product separately.

2.2. Recycling process

The ELT collected at the recycling facility was first cut into pieces using two mechanical tire cutters with a power of 15 hp. The tire pieces were then separated to remove the bead wires, which were then moved using a bobcat to load onto the conveyor belt and then to the shredder. Two shredders with a power requirement of 90 hp were used to shred the tire pieces to lower sizes using mesh #5 (4 mm), mesh #20 (0.841 mm), mesh #30 (0.595 mm), and mesh #40 (0.4 mm). The shredded rubber was then directed into three distinct processing units to produce CR, RR, and MRP. Regarding CR production, the shredded tires underwent further crumbing in a breaker/mechanical roller with a magnetic system. The output was subsequently conveyed using a screw conveyor system before transporting it into a Zyro, which functioned as the sieving equipment, wherein the CR was segregated into different sizes and subsequently packed as per the demand.

Likewise, to produce RR, the shredded rubber was first fed into an autoclave, where it was subjected to devulcanization to break the three-

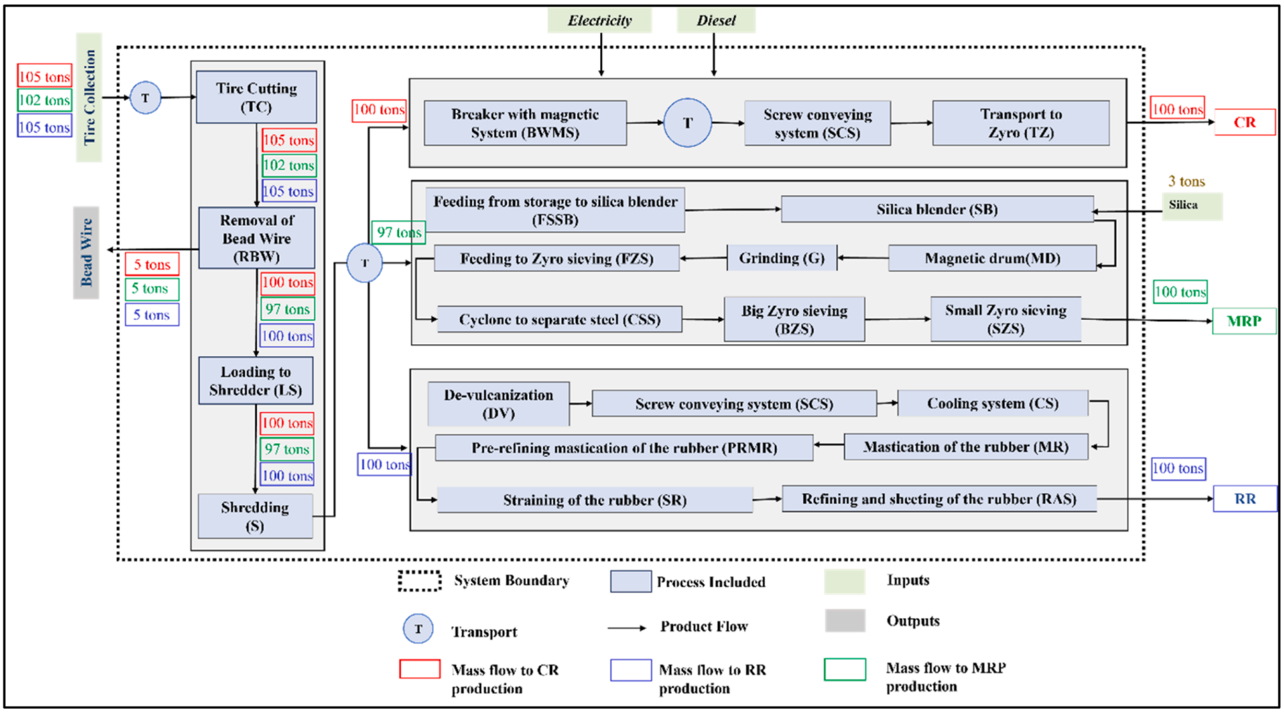


Fig. 1. System boundary for producing end-of-life tire products.

dimensional network of the cross-linked rubber products. Subsequently, the devulcanized products were transported via a screw conveying system to a cooling system to dissipate the heat. The output was then masticated to break down the molecular chain by means of a mechanical shear, and the masticated rubber was pre-refined and strained into a thread form. At the end, the strained material was fed for refining to get the final sheet, which was ultimately cut and packed to the required sizes. In the case of MRP production, the shredded rubber was fed from the storage unit to a silica blender using the bobcat. A 15 hp silica blender with a capacity of 0.35 metric tons was used to blend the shredded rubber with 3–5 % silica by weight of shredded rubber. A magnetic drum was used to remove any further metallic impurities in the mix and subsequently, the mix was ground in two stages of grinding to achieve a particle size of less than 100 μm. The resultant product was then fed into the Zyro using a blower pipe with a power of 20 hp. The material fed into the Zyro was run through cyclone separation to remove large particles from the mix, which was then followed by big and small Zyro sieving. Finally, the product from the Zyro was packed as per the client requirement.

2.3. Lifecycle inventory

Lifecycle inventory (LCI) analysis is the second phase of LCA involving the compilation and quantification of inputs and outputs for the product system throughout its lifecycle (ISO 14040, 2006a). In this study, the product systems were modeled using the OpenLCA© Green-Delta software with Ecoinvent™ v3.9.1 as LCI database (Ecoinvent Database, 2022). The modeling was initiated by creating flows representing the material and energy inputs and outputs corresponding to each product system. Later, the unit processes were created including all the product/elementary flows corresponding to the system, which were then used to build the product systems for each recycled product. Additionally, domestic and imported sources of ELT were also compared. The generation of high voltage electricity and consumption mix for the 2012–2022 timeframe was selected as the secondary data for electricity consumption from the database, which was imported to the OpenLCA©. Further, data was collected for three products with two ELT sources and six scenarios of electricity production starting from BAU (nonrenewable sources) transitioning to 10, 20, 30, 40, and 50 % renewable energy resulting in a total of 36 product systems.

2.3.1. Primary data

Primary data was specific to the recycling processes occurring in the plant and over which the practitioner had direct control. The primary data for this study was collected by conducting meetings and interviews with the industry representatives relevant to energy consumption due to the use of electricity and fuel during the different stages of manufacturing the recycled products (see Table A.1 through Table A.3 in Appendix A). For instance, the quantity of electricity consumed by equipment during shredding of the tire cut pieces, which assumed that at any stage of processing in the recycling facility, there would be no loss of the material or energy except the bead wire that was a byproduct during the bead removal stage of recycling. Note that this study did not consider the direct stack emissions from the industry because of data unavailability.

2.3.2. Secondary data

This study employed secondary data sourced from Ecoinvent™ (regionalized) database with a cutoff system model, which encompassed production processes of electricity, diesel, and activated silica. The electricity grid dataset used for this study was a combination of both nonrenewable and renewable energy sources from various sources, and considered all the operations and maintenance activities along with materials of the power plants to create the aggregated process dataset (Ecoinvent Database, 2022). In the absence of reliable data for the diesel consumption associated with the various stages of tire recycling, proxy data was used for modeling the LCA impacts ascribed to the transportation of: (a) ELT by truck, (b) tire pieces to the shredder, and (c) shredded rubber to a breaker with inbuilt magnetic system. Owing to the complexity in obtaining data from the oil refineries as well as modeling and allocation, this study utilized secondary data with actual unit process in a separate refinery model and subdivided into product-specific datasets.

The truck types used in the domestic and imported tire transport were PRIMA LX 2525 K and MAN LE 280 B, respectively, which were considered equivalent to EURO 4 and EURO 3 standard vehicles for modeling purposes (see Table B.1 in Appendix B). Further, the sea transport data of ELT was assumed to be equivalent to transporting any dry goods in the bulk carrier. The activated silica datasheet from Ecoinvent™ was used in the silica blending process during MRP production, which included raw material consumption, energy use, and infrastructure and emissions during the production process. To summarize, this study used “allocation, cut-off by classification” system model for the background in which the primary material production was always allocated to the primary user of the material. Tables C.1 and C.2 in Appendix C includes the secondary data used in this study covering renewable and non-renewable electricity sources. Note that the electricity generation data was sourced from the All-India Electricity Statistics and Central Electricity Authority with regional import calculated based on the Grid Controller of India limited. The diesel dataset used in this study included product-specific analysis (impact of an individual product in contrast to the macroeconomic or sector-level assessments) of a refinery model, which was calibrated with country specific information.

2.3.3. Limitations

The limitations associated with the study are listed as follows.

- Primary data from industry was only available for the energy consumed during rubber recycling operations and context-specific emissions data was not available. Further, all the secondary data was obtained from Ecoinvent™ database, which included country specific inputs that are inherited from global dataset by taking the weighted average and multiplying them with efficiency scaling factors. Thus, energy consumption may not represent the actual mix production of a country under consideration. Also, the application of production grid mix instead of consumption mix may represent underestimates or overestimates of the environmental impacts related to electricity consumption. Additionally, due to complexity in obtaining the data as well as modeling and allocation of oil refineries, the global diesel data from Ecoinvent™ was used.
- The study adopted 10 % linear increase of renewable energy sources for the tire recycling industry, which was essential to simplify the complexity of dynamic energy transition that can be influenced by a variety of factors such as policy changes in investments, technological advancements such as grid infrastructure developments and energy storage facilities, market conditions, and consumer behavior. Thus, this study was focused on potential impacts due to transition without accounting for the uncertainties in forecasted energy transition due to market strategies, energy demand, projections and policies. The models provided by the databases are dedicated scenarios based on energy supply and demand, markets, technology costs, and policies. Further, the scope of this study was region-specific, whereas the database models provide macro-level forecast for global trends. Therefore, the adoption of linear assumption approach helped avoid the uncertainties of these complex forecast models and reduced ambiguity in understanding the impacts.
- A detailed uncertainty assessment was not considered, which involved the variability in each outcome based on the uncertainty of all the parameters in the modeled product system. However, it is noteworthy that the study incorporated data quality assessment of the primary data, which is still acceptable for large data used in this study.
- It was assumed that there was no loss of material at any stage other than the by-product such as removal of the bead wire. However, the material losses inevitably occurring during the processes of shredding, grinding, and transportation will affect the mass balance of the system boundary, which will have to be accounted for in future studies.

2.3.4. Data quality assessment

The data quality was determined using the pedigree matrix approach described in the International Life Cycle Data (ILCD) system (European Commission, 2010). The LCA data included secondary data from Ecoinvent™ database and ELT recycling process data collected from the recycling facility. Six independent indicators were used to assess the data quality, which included: (i) technological representativeness (TeR), (ii) geographic representativeness (GR), (iii) time-related representativeness (TiR), (iv) completeness (C), (v) precision (P), and (vi) methodological appropriateness and consistency (M). Each indicator was then rated on a scale of 1 through 5 as per the methodology laid out in the ILCD handbook. In order to aggregate the data into a single score, the expression for data quality rating (DQR) given in the ILCD handbook was used, as shown in Eq. (1).

$$DQR = \frac{TeR + GR + TiR + C + P + M + X_w \times 4}{i + 4} \tag{1}$$

Where:

i = 6, which indicates the number of applicable data quality indicators, and

X_w= indicates the weakest quality level obtained.

Since the LCA model developed in this research was based on secondary data obtained from the Ecoinvent™ database, a semi-quantitative data quality assessment was carried out to ensure the reliability of the study. A pedigree matrix of data quality assessment following ILCD guidelines was developed using a score range of 1–5 for each indicator (see Table D.1 in Appendix D). The single data quality rating was then aggregated to obtain DQR. The primary data quality assessment for all the products indicated that the data used in this research was of basic quality and conformed to the ILCD guidelines.

2.4. Lifecycle impact assessment

Technically, Lifecycle Impact Assessment (LCIA) translates the emissions and resource extractions compiled in LCI into a limited number of environmental impact categories by means of characterization factors. This study used characterization factors of ReCiPe 2016 LCIA method at midpoint level, which strongly correlated with the environmental flows and located the point after which the environmental mechanism was identical for all the environmental flows assigned to that impact category. All the eighteen impact indicators of ReCiPe 2016 midpoint (Hierarchist) method (Huijbregts et al., 2017) with the updated values of GWP from IPCC 2021 were used in the impact assessment. Amongst different impact categories per ReCiPe 2016 (H), the land use change refers to the loss of relative species due to local land usage that covers the complete cycle of land transformation, occupation, and relaxation. Land occupation potential (LOP) is the impact characterization factor representing transformation and occupation phases, where the land is made suitable for its new function and utilized for a certain period of time. Further, the Hierarchist method in general relies on scientific consensus and considers both short- and long-term impacts whereas individualist method prioritizes short-term interests and technological optimism. Thus, the Hierarchist method was adopted in this study to cover a 100-year timeframe considering the relative significance of impact categories and also referenced in the ISO standards (Huijbregts et al., 2017; ISO 14044, 2006b).

3. Scenario development

The study analyzed six scenarios of the southern electricity grid in India to determine how the efforts to recycle ELT are aligned with the goals of Paris Agreement. Since the country has set a target of generating about 50 % of the cumulative electric power from non-fossil-based energy sources by 2030, this study considered a 10 % linear increase in the shift to use renewable energy through the BAU scenario, as already introduced in the LCI. The LCIA of recycled products from the domestic as well as imported ELT was carried out with different proportions of renewable energy starting from the BAU (called S1), which had about 75.2 % nonrenewable sources (see Table C.1 in Appendix C) and 24.8 % renewable energy sources (see Table C.2 in Appendix C). Further, the scenarios of transforming nonrenewable to renewable energy by 10 % (S2), 20 % (S3), 30 % (S4), 40 % (S5), and 50 % (S6) were created separately and applied on each product. The contributions of each energy source to different scenarios along with their trends in renewable and nonrenewable sources are depicted in Fig. E.1 in Appendix E. The renewable energy resources encompassed wind energy, hydro run-of-river, hydro reservoir, hydro pumped storage, and combined heat and power generation from wood chips. Conversely, nonrenewable energy sources comprised nuclear energy, oil, natural gas, lignite, and hard coal. Note that the increase in renewable sources was assumed to be equally distributed amongst all the resources. For each scenario, the recycling processes to produce CR, RR, and MRP from both domestic as well as imported tires were analyzed. The implications of changes in the indices, especially the GWP, were verified with varying proportions of electricity sources.

4. Results

As an initial step, the interpretation of LCIA results explained that each recycling process gave rise to different environmental impacts, specifically in the areas of global warming, water consumption, and land use. The total global warming impact in terms of GWP attributed to the production of CR, MRP, and RR from domestically sourced tires were estimated as 1.13×10^4, 3×10^4, and 3.63×10^4 kg CO_2 eq., respectively. Further, the GWP ascribed to produce CR, MRP, and RR due to the recycling of imported tires were found to be 2.78×10^4, 4.56×10^4, and 5.28×10^4 kg CO_2 eq., respectively. As expected, the import of ELT to produce CR, MRP, and RR caused 2.46, 1.51, and 1.45 times higher global warming than recycling domestically sourced tires. Upon comparing the three products, it was evident that the production of RR caused the highest global warming, whereas the corresponding impacts for CR production were the lowest. The change in the environmental impact depicted that it is important to decide on the type of recycled product to be produced so the stakeholders can reduce the environmental burden of recycling processes. Furthermore, the results indicated that until the common stage of shredding, the potential environmental impacts were almost similar for the three recycled products. However, the stages followed during the shredding process were responsible for the production of different recycled products and caused differences in the environmental impacts. The detailed LCIA results to produce CR, MRP, and RR are presented in the following sections.

4.1. Lifecycle impact assessment of ELT recycling to produce CR

As mentioned earlier, the CR production from domestic ELT resulted in the lowest environmental impacts compared to RR and MRP (see Table F.1 through F.3 in Appendix F). Fig. F.1 in Appendix F presents the percent contribution of each unit process involved in the CR production using domestic ELT. About 42 % of the total GWP for CR production was derived from the unit process involving breaker with magnetic system (BWMS) available with the ELT recycling plants that crushed shredded tires and separated steel from the rubber fragments using magnets. Also, in BWMS, the CR of different sizes were segregated ensuring production of high quality of the recovered material. Further, it contributed to more than 40 % of the impacts that were shared between acidification, ecotoxicity, eutrophication, and particulate matter generation. Similarly, the overall water consumption potential (WCP), which in this case represented the quantity of water consumed during the production of CR was reported as 52.98 m^3. Amongst the unit processes, >50 % of the WCP was attributed to the shredding phase, while the contribution of BWMS to WCP was only 1.83 % remarking that despite the lower GWP of shredding process compared to BWMS, it can lead to higher extraction of water resources. The WCP for CR production from imported ELT was about 1.3 times higher than that originating due to the processing of domestic ELT. Further, it was found that the screw conveyor system, which transports different sized CR had the least environmental impacts. The LOP, which provides an overview of the land use and depletion of productive land area resource should also be considered while transitioning to the use of renewable resources since the infrastructure setup may need acquiring additional land area.

4.2. Lifecycle impact assessment of ELT recycling to produce micronized rubber powder

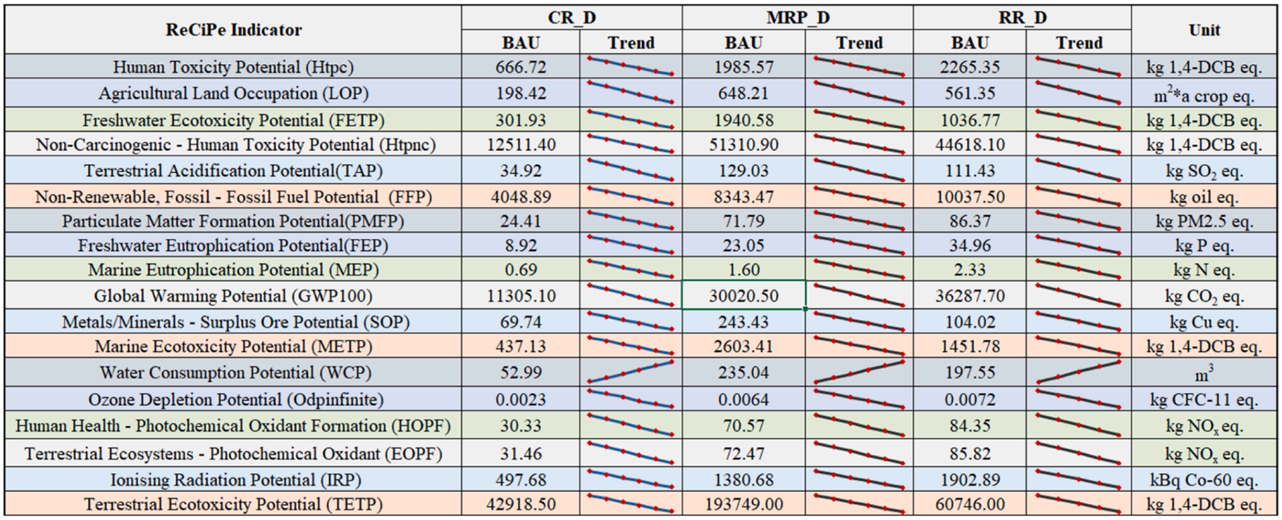
Fig. F.2 in Appendix F presents the percent contribution of each unit process involved in the MRP production using domestic ELT. Amongst the different unit processes, the silica blending phase was a significant contributor constituting 70 % of the ecotoxicity (freshwater, marine, and terrestrial) and 54 % of WCP within the entire product system of MRP. The production of MRP by recycling domestic ELT resulted in 3×10^4 kg CO_2 eq., which was 2.66 times higher than that for CR production. For the imported ELT, the kg CO_2 eq. was 1.64 times greater than the CR produced from domestic tires ascribed to the high impacts associated with long transportation distance while importing. Similarly, the WCP associated with MRP was 1.2 times that of CR production, which indicated that there was high extraction of water resource due to MRP production. In general, the impacts associated with MRP production were higher than CR for the different indicators considered in this study. Further, rubber grinding had the highest contribution (41.2 %) to the GWP in the entire product system of MRP. Additionally, MRP production from domestic ELT attributed to LOP of 648.209 m^2 *annual crop eq., which was three times more than that of CR production from domestic tires, implying that the production of MRP would cause significant utilization of agricultural land when compared to CR.

4.3. Lifecycle impact assessment of ELT recycling to produce reclaimed rubber

The impact assessment of unit processes showed that the stages of mastication, pre-refining, refining, and sheeting together constituted more than 60 % of the GWP, LOP, and WCP (Fig. F.3 in Appendix F). The production of RR by recycling the domestic ELT resulted in 3.63×10^4 kg CO_2 eq., which was 3.22 times more than the CR. Furthermore, the GWP of RR production from imported ELT was 1.46 times than CR, pointing out that import of the materials makes a significant impact due to the production of RR that was less relevant when compared to CR. Also, it is noteworthy that though the LOP due to RR production was 2.83 times greater than CR production, it was 15.47 % less than that of MRP, which implied that renewable energy sources with substantial land requirements would be more suitable for RR production compared to MRP. Albeit RR had the highest impact amongst the three products, the implementation of energy-efficient technologies and optimization of processes such as alternative refining methods would have huge potential in mitigating the environmental burden due to RR production. In this study, it was observed that for all the three products, there was a reduction in LOP by 4.68 %, 3.25 %, and 6.59 % for CR, MRP and RR, respectively with the transition to renewable electricity sources.

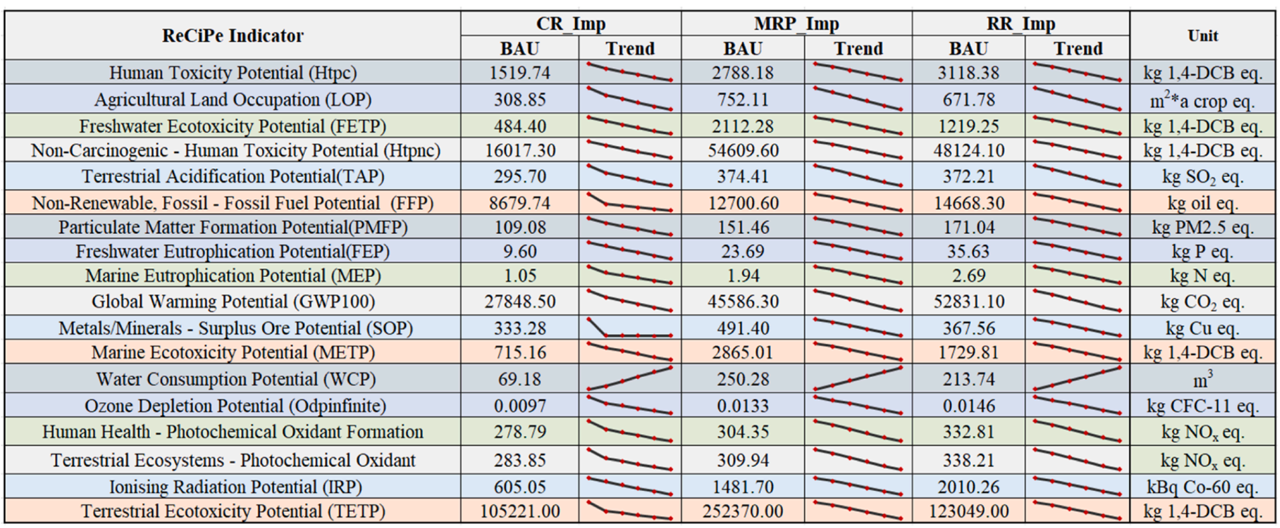
4.4. Scenario analysis

The LCIA results corresponding to the processing of ELT procured from domestic and international sites in conjunction with the transition to adopt renewable energy sources are presented in Figs. 2 and 3, respectively. All the environmental impact indicators other than the WCP exhibited a decreasing trend with an increase in the shift toward renewable energy sources. This observation is in line with NDC put forth by India in accordance with the Paris agreement that aims to reduce



ReCiPe Indicator	CR_D		MRP_D		RR_D		Unit
	BAU	Trend	BAU	Trend	BAU	Trend	
Human Toxicity Potential (Htpc)	666.72		1985.57		2265.35		kg 1,4-DCB eq.
Agricultural Land Occupation (LOP)	198.42		648.21		561.35		m^2*a crop eq.
Freshwater Ecotoxicity Potential (FETP)	301.93		1940.58		1036.77		kg 1,4-DCB eq.
Non-Carcinogenic - Human Toxicity Potential (Htpnc)	12511.40		51310.90		44618.10		kg 1,4-DCB eq.
Terrestrial Acidification Potential(TAP)	34.92		129.03		111.43		kg SO_2 eq.
Non-Renewable, Fossil - Fossil Fuel Potential (FFP)	4048.89		8343.47		10037.50		kg oil eq.
Particulate Matter Formation Potential(PMFP)	24.41		71.79		86.37		kg PM2.5 eq.
Freshwater Eutrophication Potential(FEP)	8.92		23.05		34.96		kg P eq.
Marine Eutrophication Potential (MEP)	0.69		1.60		2.33		kg N eq.
Global Warming Potential (GWP100)	11305.10		30020.50		36287.70		kg CO_2 eq.
Metals/Minerals - Surplus Ore Potential (SOP)	69.74		243.43		104.02		kg Cu eq.
Marine Ecotoxicity Potential (METP)	437.13		2603.41		1451.78		kg 1,4-DCB eq.
Water Consumption Potential (WCP)	52.99		235.04		197.55		m^3
Ozone Depletion Potential (Odpinfinite)	0.0023		0.0064		0.0072		kg CFC-11 eq.
Human Health - Photochemical Oxidant Formation (HOPF)	30.33		70.57		84.35		kg NO_x eq.
Terrestrial Ecosystems - Photochemical Oxidant (EOPF)	31.46		72.47		85.82		kg NO_x eq.
Ionising Radiation Potential (IRP)	497.68		1380.68		1902.89		kBq Co-60 eq.
Terrestrial Ecotoxicity Potential (TETP)	42918.50		193749.00		60746.00		kg 1,4-DCB eq.

Fig. 2. Impact indicators for the BAU scenario of products CR, MRP and RR from domestic ELT and its trend with transition towards renewable energy resources. *Note: BAU – Business as Usual, CR- Crumb Rubber, MRP-Micronized Rubber, RR-Reclaimed Rubber.*



ReCiPe Indicator	CR_Imp		MRP_Imp		RR_Imp		Unit
	BAU	Trend	BAU	Trend	BAU	Trend	
Human Toxicity Potential (Htpc)	1519.74		2788.18		3118.38		kg 1,4-DCB eq.
Agricultural Land Occupation (LOP)	308.85		752.11		671.78		m^2*a crop eq.
Freshwater Ecotoxicity Potential (FETP)	484.40		2112.28		1219.25		kg 1,4-DCB eq.
Non-Carcinogenic - Human Toxicity Potential (Htpnc)	16017.30		54609.60		48124.10		kg 1,4-DCB eq.
Terrestrial Acidification Potential(TAP)	295.70		374.41		372.21		kg SO_2 eq.
Non-Renewable, Fossil - Fossil Fuel Potential (FFP)	8679.74		12700.60		14668.30		kg oil eq.
Particulate Matter Formation Potential(PMFP)	109.08		151.46		171.04		kg PM2.5 eq.
Freshwater Eutrophication Potential(FEP)	9.60		23.69		35.63		kg P eq.
Marine Eutrophication Potential (MEP)	1.05		1.94		2.69		kg N eq.
Global Warming Potential (GWP100)	27848.50		45586.30		52831.10		kg CO_2 eq.
Metals/Minerals - Surplus Ore Potential (SOP)	333.28		491.40		367.56		kg Cu eq.
Marine Ecotoxicity Potential (METP)	715.16		2865.01		1729.81		kg 1,4-DCB eq.
Water Consumption Potential (WCP)	69.18		250.28		213.74		m^3
Ozone Depletion Potential (Odpinfinite)	0.0097		0.0133		0.0146		kg CFC-11 eq.
Human Health - Photochemical Oxidant Formation	278.79		304.35		332.81		kg NO_x eq.
Terrestrial Ecosystems - Photochemical Oxidant	283.85		309.94		338.21		kg NO_x eq.
Ionising Radiation Potential (IRP)	605.05		1481.70		2010.26		kBq Co-60 eq.
Terrestrial Ecotoxicity Potential (TETP)	105221.00		252370.00		123049.00		kg 1,4-DCB eq.

Fig. 3. Impact indicators for the BAU scenario of products CR, MRP and RR from imported ELT and its trend with transition towards renewable energy resources. *Note: BAU – Business as Usual, CR- Crumb Rubber, MRP-Micronized Rubber, RR-Reclaimed Rubber.*

greenhouse gas emissions and certainly will assist in achieving the long-term goal of net-zero emissions in the country by 2070. Interestingly, the trend was similar, irrespective of the source of ELT (domestic and international) and the generated recycled products.

Amongst the 18 midpoint indicators; GWP, WCP, and LOP were found to be the most significant parameters in the context of transitioning to renewable energy. Further, a transition to renewable resources by 50 % resulted in reductions of 11.72 %, 10.02 %, and 14.53 % in the production of CR, MRP, and RR, respectively, those that were sourced from the domestic ELT. Conversely, the reductions in CR, MRP, and RR production from imported tires were 5.67 %, 6.59 %, and 9.98 %, respectively, which corroborated that the import of ELT for recycling would yield diminished benefits in the reduction of GWP due to the transition to renewable sources. Also, it is noteworthy that the GWP of CR produced (as in Table 1) from the imported tires were comparable with MRP produced from domestic tires after the transition to renewable electricity source, remarking that with transitioning to renewable energy sources to 50 % would lead to a significant reduction in GWP of MRP from domestic ELT compared to CR produced from imported ELT, obviously ascribed to the additional distance required to transport ELT.

Table 1
GWP of each product before and after transition to renewable source.

Recycled Product	Domestic ELT		Imported ELT	
	GWP at BAU (kg CO_2 eq.)	GWP after 50 % transition (kg CO_2 eq.)	GWP at BAU (kg CO_2 eq.)	GWP after 50 % transition (kg CO_2 eq.)
CR	11,300	9980.6	27,800	26,269.4
MRP	30,000	27,013.2	45,600	42,578.9
RR	36,300	31,014.3	52,800	47,557.8

Thus, it can be recommended that instead of importing tires for CR production, the manufacture of MRP from domestic tires would be more beneficial in future from an environmental sustainability viewpoint.

Further, it was observed that the increase in the shift towards renewable energy sources led to a reduction in LOP with the highest reduction in the case of RR production from domestic ELT. On another account, the maximum increase in WCP was 15.98 % when 50 % of the electricity supply was met with renewable sources to produce RR, indicating the increased demand for water resources. The increase in water demand can be credited to the large number of hydro projects to balance the nonrenewable resources that consume large quantities of water to generate electricity. It is worth mentioning that although RR had the highest environmental burden amongst the three products, the magnitude of reduction regarding the impacts with transition to renewable sources was higher than CR since all the unit processes involved in RR production required electricity, while some of the unit process operations in CR were based on consumption of diesel. Therefore, high GWP associated with RR production could be brought down significantly by means of transition to renewable electricity source.

Furthermore, other indicators such as ionizing radiation potential (IRP), non-carcinogenic human toxicity potential (Htpnc), marine eutrophication potential (MEP), particulate matter formation potential (PMFP), freshwater eutrophication potential (FEP), and surplus ore potential (SOP) were also reported in this study to understand its variation with transition to the renewable energy sources. Also, when the energy supply changed from BAU to S6, FEP to produce CR, MRP, and RR reduced by approximately 15.7, 13.8, and 15.9 %, respectively, depicting that regarding FEP, the production of MRP was least affected due to the transition to renewable sources. Further, to produce RR, reduction of 15.8 %, 14.99 %, and 14.9 % were observed in IRP, Htpnc, and MEP, respectively, noting the most substantial reduction amongst all the three recycled rubber products. In addition, it was observed that though there was a sudden reduction in the SOP of CR produced from imported ELT due to 10 % transition to renewable resources, the SOP presented an asymptotic behavior because of the minimum requirement of mineral resources, further clarifying that the transition to renewable energy sources would have a limit in reducing mineral resource extraction of CR.

Amid the various scenarios presented in this research, the production of CR resulted in the least environmental impacts while RR had the highest. The GWP of RR production was three times higher than CR, irrespective of the ELT source or proportion of renewable energy. Further, an attempt was made to understand the tradeoff between the reduction in GWP and increase in WCP for the different scenarios, as presented in Fig. 4(a) through (f). Noticeably, the reduction in GWP was higher than the increase in WCP only for the case of MRP production from domestic tires, while the reduction in GWP was outweighed by the increase in WCP for all the other scenarios due to the fact that all the unit processes except the feeding to storage in the MRP production used electricity whereas in CR several stages exist that use diesel as the fuel. Thus, the consumption of diesel will restrict the reduction in GWP in the case of CR and RR even though there would be a transition to renewable resources for electricity generation.

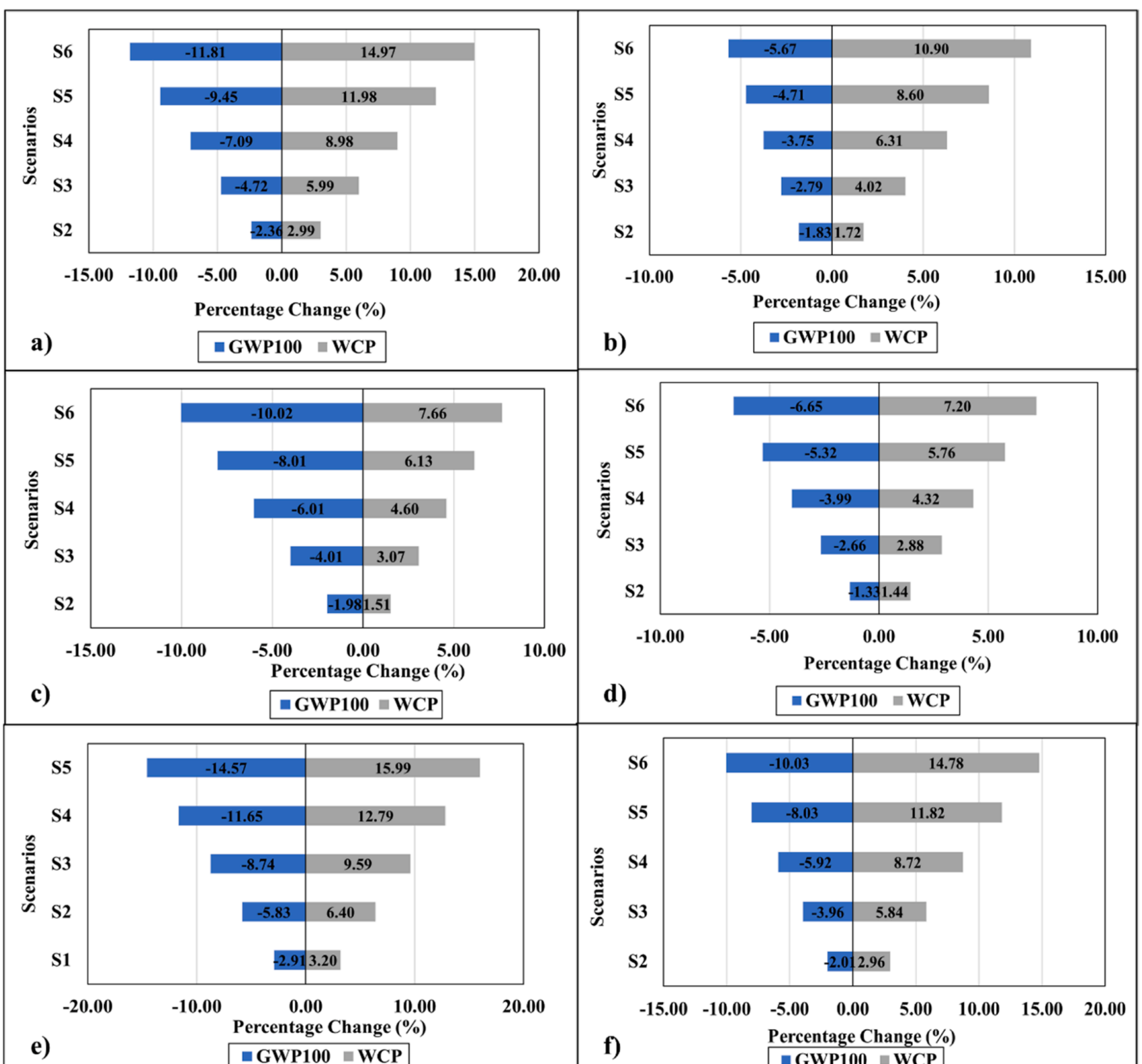


Fig. 4. Tradeoff between GWP and WCP of: (a) CR production from domestic ELT, (b) CR production from imported ELT, (c) MRP production from domestic ELT, (d) MRP production from imported ELT (e) RR production from domestic ELT, (f) RR production from imported ELT.
Note: GWP-Global Warming Potential, WCP-Water Consumption Potential, ELT-End-of-life Tire, CR-Crumb Rubber, MRP-Micronized Rubber Powder, RR-Reclaimed Rubber.

5. Discussion: research significance

The major contribution of this study was the quantification of environmental impacts associated with the production of recycled rubber products: CR, MRP, and RR. The lifecycle inventory created in this research was based on primary data, which assisted in robust evaluation and identification of hotspots specific to processes employed in the ELT recycling industry. Further, the results of this study can serve as inputs for investigations that use products obtained after recycling ELT as one of the matrix constituents. This first-of-its-kind study also demonstrated the consequences of transition to renewable energy sources on the environmental sustainability of the ELT recycling industry. Importantly, this investigation highlighted the significance of understanding the tradeoffs between GWP and WCP during transition to renewable energy sources, which is crucial in policy making. In addition, the potential for technological improvements in the recycling process of ELT were discussed. It is noteworthy to mention that the research highlighted the importance of promoting recycling efforts at the national level and fostering collaboration at the global scale to develop solutions that reduce the impacts of ELT imports. Importantly, the work laid the foundation in understanding the influence of product selection and strategic planning in ELT management. Overall, the development of improved policies and regulations based on the findings of this research study are envisioned to promote the sustainable practices within the recycling industry both at the national and global levels.

6. Conclusions & recommendations

This study addressed the research gap of energy source implications on ELT recycling industry and evaluated the environmental sustainability of recycled product options. Specifically, this research quantified the potential environmental impacts associated with the production of CR, MRP, and RR obtained from two different sources. The declared unit was production of 100 metric tons of each recycled product at the midpoint level. The impacts were quantified using the ReCiPe 2016 LCIA method, with the modified GWP based on characterization factors provided in the IPCC 2021 AR6 report. In addition, sensitivity analysis was conducted for six different scenarios with transition of electricity to renewable sources to understand the variations in the impact of energy composition on the ELT recycling process. The results indicated that CR had the lowest GWP, irrespective of ELT source and electricity scenarios, while the production of RR from imported ELT had the highest impacts. However, as the energy sector transitions to renewable resources, it is recommended that the decision-makers must prioritize the production of RR followed by MRP, owing to the significant reduction in the overall environmental impacts. To summarize, the major contributions of this first-of-its-kind study are as follows:

- The evaluation of environmental impacts due to the combined effects of the energy sector and tire recycling industry, including the source variability of ELT suggested that the integration of renewable energy could lead to significant reductions in the environmental burdens, making the tire recycling industry more sustainable.
- The contribution analysis included evaluation of unit processes in ELT recycling to produce CR, MRP, and RR, thereby offering critical insights into the environmental performance and opportunities for technological improvements.
- The procurement of ELT from domestic sources resulted in lower environmental impacts for production of recycled products compared to the international sources.
- Notably, the trade-off analysis between the GWP and WCP highlighted the importance of considering all the midpoint impacts associated with the industry to identify the future challenges with the technological changes.

In conclusions, this study provided valuable insights into the environmental impacts of the ELT recycling industry, providing essential data to come up with the design of long-term sustainability strategies. Further, this study also provided an overview of the current and future environmental impacts of tire recycling industry in India. Nonetheless, future studies must include a detailed data collection of the recycling plants across different regions to analyze the impacts in a broader manner that incorporates uncertainties associated with energy consumption. Further, this study provided a framework, where future research can evolve by incorporating the energy forecasts on the transition to renewable energy, which would focus on policy and market dynamics, including the uncertainties. It is envisioned that this work will be useful for industry, as it will allow for rational assessment of the environmental burdens associated with the production of different recycled rubber products.

CRediT authorship contribution statement

Namitha Sudan: Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Avishreshth Singh:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chaitanya Ganesh Bhat:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Krishna Prapoorna Biligiri:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgments

The authors gratefully acknowledge Tinna Rubber and Infrastructure Limited India that provided primary data and technical support to conduct the relevant research and analysis. The research activities described in this paper was sponsored by Aarvee Associates as part of the Corporate Social Responsibility project with the Indian Institute of Technology Tirupati.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108169.

Data availability

Data will be made available on request.

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