

From environmental hotspots to strategic action: a life cycle assessment of solid tyre manufacturing in Sri Lanka under EU sustainability pressures

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Keywords

*Environmental Hotspots, European
Union, Life Cycle Assessment, Solid
Tyres, Sustainability Pressures*

ABSTRACT

This study evaluates the cradle-to-gate environmental performance of solid tyre production in Sri Lanka, focusing on raw material extraction and manufacturing stages. A Life Cycle Assessment (LCA) was conducted in accordance with ISO 14040 and 14044 standards using the SimaPro Faculty version. The ReCiPe 2016 Midpoint (H) method was employed to quantify 18 environmental impact categories. Primary data were collected from a leading Sri Lankan solid tyre manufacturing facility and supplemented with secondary data from Ecoinvent V3.11. This study is the first to assess the environmental impacts of solid tyre production in Sri Lanka. The total global warming potential was 160.94 kg CO₂-eq per solid tyre produced. The study finds that key raw materials such as carbon black, SBR, crumb rubber, and chemical additives, along with energy-intensive processes, drive most impacts. The findings suggest replacing high-impact materials with cleaner or bio-based ones and shifting to renewable energy like solar can greatly reduce environmental impacts. These changes are environmentally and strategically beneficial, helping Sri Lanka maintain access to markets like the EU and strengthening its position as a sustainable tyre producer.

INTRODUCTION

Tyres are one of the most significant products of the global rubber industry. As demand continues to rise sharply, several factors have reshaped competition within the industry, with sustainability among the most important. For instance, the European Union has implemented stringent environmental and chemical regulations on its exports, increasing sustainability compliance for products consumed in those countries. Major EU regulations include the Deforestation Regulation (EUDR), Chemical Regulation (REACH), EU tyre labelling (Regulation (EU) 2020/740), EU Microplastics Regulation, Extended Producer Responsibility (EPR) (UN Environment, 2024), and the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2025a; European Commission, 2025b). These evolving regulatory requirements and policy instruments make it mandatory for manufacturers to embed sustainability in strategic decision-making and long-term competitiveness.

Sri Lanka has been ranked as the world's largest solid tyre manufacturer in 2023, meeting nearly 28% of global demand, which accounts for 3.61% of Sri Lanka's total exports. According to the records, the European Union is one of the major destinations for Sri Lankan solid tyres (Sri Lanka Export Development Board (SLEDB), 2025; Sri Lanka Rubber Industry Master Plan – 2017 – 2026 | EDB Blog, 2017). According to the International Trade Centre's Trade Map, in 2024, solid and cushion tyres accounted for the largest share

of Sri Lanka's rubber exports to the EU27, at 49.4%. To sustain this competitive position, the industry must align with international environmental performance standards. Despite this importance, comprehensive life-cycle data for Sri Lankan solid tyre production remain unavailable, hindering informed decision-making to support cleaner production and global regulatory compliance.

Although global interest in tyre-related research is strong, with a concentration in the US, China, and Europe, Asia receives less attention (Wang et al., 2023). Moreover, several data gaps on tyre pollution have been identified in developing countries, limiting understanding of global complexities and hindering risk management within the industry (Mayer et al., 2024). Globally, tyre-related studies have predominantly focused on the use and disposal phases (Torretta et al., 2015; Harrison-Obi, 2019; Sharma et al., 2000; Daniela et al., 2013; Shanbag & Manjare, 2020). No research has examined the environmental impact of raw material extraction on the manufacturing phase of solid tyres. Nevertheless, there is considerable potential to reduce the environmental impact by closely analyzing the other life cycle stages of solid tyres. Rethinking how products are offered has become a market trend, driven by the advent of sustainability and green concepts. Nowadays, businesses are reengineering their products to make them more environmentally friendly.

Given these gaps, there is a pressing need to establish baseline life-cycle data for Sri Lankan solid tyre production and to plan strategic actions

to address stringent EU regulatory pressures by identifying and addressing critical environmental hotspots. Accordingly, this study aims to evaluate the cradle-to-gate environmental performance of solid tyres manufactured in Sri Lanka by quantifying material and energy flows, and to analyze the strategic and managerial implications required under EU sustainability pressures.

LITERATURE REVIEW

According to the literature review, although numerous research studies have been conducted in the tyre industry, several data gaps remain. Defining the complete quantitative chemical compositions of tyre rubbers, variations of tyre particles across commonly used brands, and tyre types are critical research needs (Mayera, et al., 2024). Furthermore, Mayera et al. identified data gaps in fate and transport, biological and ecological effects, management and remediation, recycling, reuse, and disposal, as well as data management and toxicity assessment in tyres. Additionally, no research was found during the literature review that focused explicitly on the environmental impact of the life cycle of solid tyres. Despite the growing global interest in tyre-related research—particularly concentrated in the US, China, and Europe—Asia has received comparatively less attention (Yunxia Wang, 2023). Most existing studies focus on the use and disposal phases of tyres (Torretta et al., 2015; Harrison-Obi, 2019; Sharma, Fortuna, Mincarini, Berillo, & Cornacchia, 2000) or on the life cycle of pneumatic tyres (Daniela, Recca, & Cicala, 2013; Shanbag & Manjare, 2020). However, research examining the environmental impact of raw material extraction through to the manufacturing stage of solid tyres and the risk to the sustainability of Sri Lankan solid tyres under EU pressures is virtually absent. Addressing this gap presents an opportunity to mitigate environmental impacts by closely analyzing these overlooked life cycle stages. As sustainability and green business concepts grow, companies are increasingly reengineering products to deliver environmentally friendly alternatives, making this research timely and relevant. Therefore, this research aims to identify and quantify the cradle-to-gate life cycle impact of tyres, especially solid tyres, in the Sri Lankan context, given their high global demand.

MATERIALS AND METHODS

This study focuses on experimental assessment of the cradle-to-gate environmental impact of solid tyres and on analysing environmental hotspots in relation to EU environmental regulations. To achieve this purpose, we employed a quantitative approach. Environmental Life Cycle Assessment was the primary tool used to quantify the environmental impact of a solid tyre. All conclusions are based on analysis of quantified primary and secondary data. The study complies with ISO 14040:2006 and ISO 14044:2006 (ISO, 2023) and uses recognized LCA tools, specifically the SimaPro Faculty version. Additionally, this software supports developing product-system models based on logic and transparency (Goedkoop et al., 2016). To quantify the impact, this study uses the ReCiPe characterization method. Because the assessment is conducted in the Sri Lankan context, the ReCiPe method is the most suitable option, as no region-specific characterization models are available. Moreover, it is the only method that covers the most midpoint impact categories. The qualification follows the following systematic approach.

The goal of the study is to calculate the adverse environmental impact of an average solid tyre from raw material extraction to manufacturing. Figure 1 shows the average solid tyre considered.



Figure 1 An average resilient solid tyre

The study was conducted within the cradle-to-gate boundary level. The declared unit is one industrial solid tyre weighing 46.5 kg, with a sectional width of 7.00 inches and a rim diameter of 12 inches. The study is conducted within the boundary, from the extraction of primary raw materials to the factory gate of the solid tyre. Figure 2 below presents a detailed system boundary of an average industrial solid tyre.

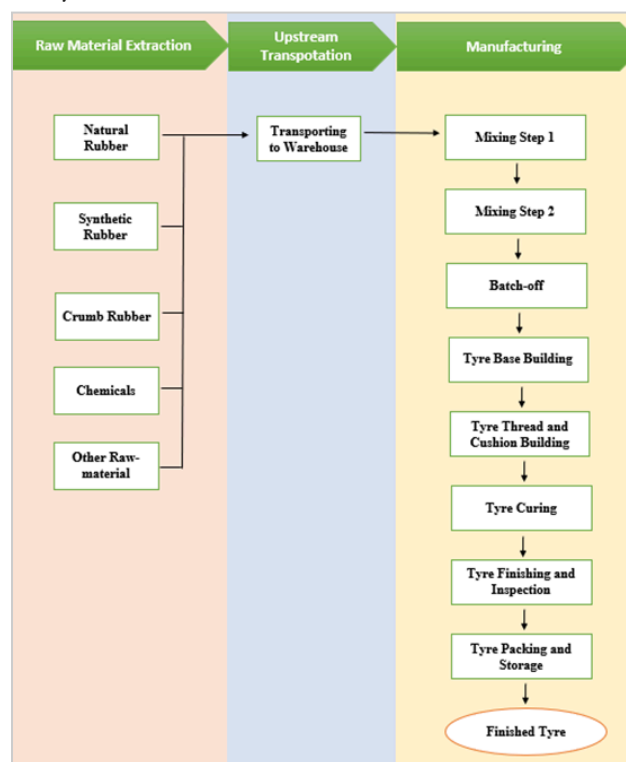


Figure 2. Detailed system boundary of an average industrial solid tyre (Developed based on the information gathered during the study-2026)

According to Figure 2, the natural rubber extraction includes the SLR-20 (Standard Lanka Rubber) rubber type. The synthetic rubber manufacturing stage includes SBR (Styrene-butadiene rubber). The crumb rubber is a type of recycled rubber. Chemicals include all the antioxidants, stabilizers, plasticizers, etc., used in solid tyre manufacturing. Other raw materials used in solid tyre manufacturing include steel, carbon black, and textile materials.

After raw materials from several locations are transported to the manufacturing plant, production begins. The manufacturing phase encompasses mixing, batch-off, tyre base building, tyre tread and cushion building, curing, finishing, inspection, and packing and storage. In each phase and process, emissions to water, soil, and air should be examined. Figure 3 represents the summarized system

boundary of the study. Tyre inspection, packaging, and storage are excluded from the analysis.

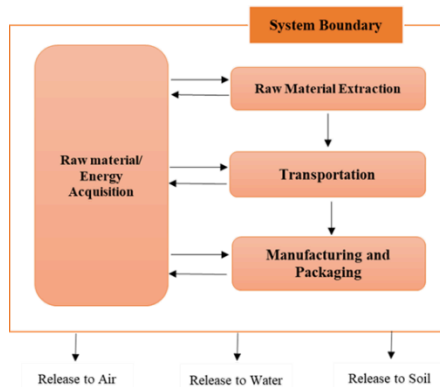


Figure 3. Summarized System boundary of the LCA study of the referenced solid tyre (Developed based on the information gathered during the study-2026)

After precisely defining the goal and scope of the study, the required data should be gathered to achieve the defined goal successfully within the demarcated boundary. All input data, including raw materials, energy, and other resources used, and output data, including products, co-products, and emissions to air, water, and soil, in quantities (activity data), should be collected for each unit process, as shown in Figure 4, using primary or secondary sources.

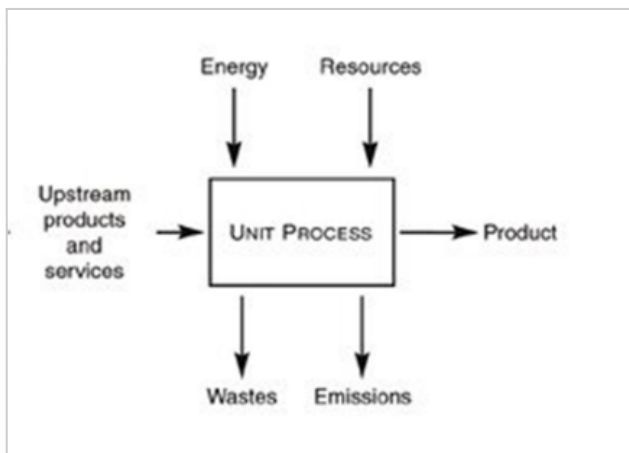


Figure 4. Life cycle inventory of unit process

Source: (Kuczenski, Geyer, & Boughton, 2010)

For instance, in SLR-20, the natural rubber manufacturing process, the amount of natural latex used, water consumption, electricity, diesel, packaging used, etc., are identified as inputs and wastewater generated and greenhouse gas emissions are identified as wastes.

Both primary and secondary data were used to develop the life cycle inventory. Secondary data were sourced from the Ecoinvent database (version 3.11, cut-off) to model upstream processes, including the production of synthetic rubber, carbon black, and chemical additives.

Next, the collected data were analyzed using sophisticated software (SimaPro – Faculty Version). Among many other LCA tools, such as GaBi and OpenLCA, SimaPro is preferred for academic- and professional-level Life Cycle Assessments. It allows modelling and systematic analysis of complex life cycles (Hillege, 2025). SimaPro is one of the most widely used software applications for Life Cycle Assessment, particularly in academic and consulting domains, due to its comprehensive modelling capabilities and integration with databases such as Ecoinvent (Hauschild et al., 2018). Moreover, SimaPro is more flexible and easier to edit and access LCI databases (Chen et al., 2024). ReCiPe 2016 Midpoint (H) and ReCiPe 2016

Endpoint (H) methods were used to evaluate environmental impacts and damage categories, respectively. These methods were chosen because they can pinpoint particular environmental hotspots, enabling more focused management actions.

The results are presented as characterized figures, normalized figures, tables, and networks. In this phase, the potential environmental impacts embedded in the inputs and outputs identified in the previous stage are evaluated. The environmental impacts are characterized by 18 impact categories, including climate change, resource depletion, human carcinogenic toxicity, and water pollution. To assess the broader implications of these impacts, endpoint damage categories were used, covering damage to human health, ecosystems, and resources. This analytical approach enhances understandability for both technical and managerial audiences.

Finally, the resulting data are interpreted and analyzed to derive meaningful conclusions about the product, process, or system. At this phase, the extent to which the impact can be reduced or avoided can be compared across alternatives to inform recommendations and improvements.

In addition, a separate scenario analysis assessed potential pathways for reducing environmental impact. Under this analysis, researchers compared a transition from conventional energy (grid electricity) to renewable energy (solar power) in the manufacturing stage of solid tyre production, holding other parameters constant. This comparison provides information on potential reductions in environmental impact for relevant sustainability expectations of export markets, as well as practical insights for managerial and strategic decision-making.

RESULTS AND DISCUSSION

Cradle-to-gate life cycle inventory and process overview of an average solid tyre

One foundational requirement for understanding the strategic actions needed to meet strict global customer requirements is quantifying the environmental impact of an average solid tyre manufactured in Sri Lanka. In this pursuit, understanding the production flow and developing the life-cycle inventory are critical. Figure 5 below illustrates the process for manufacturing resilient solid tyres in Sri Lanka.

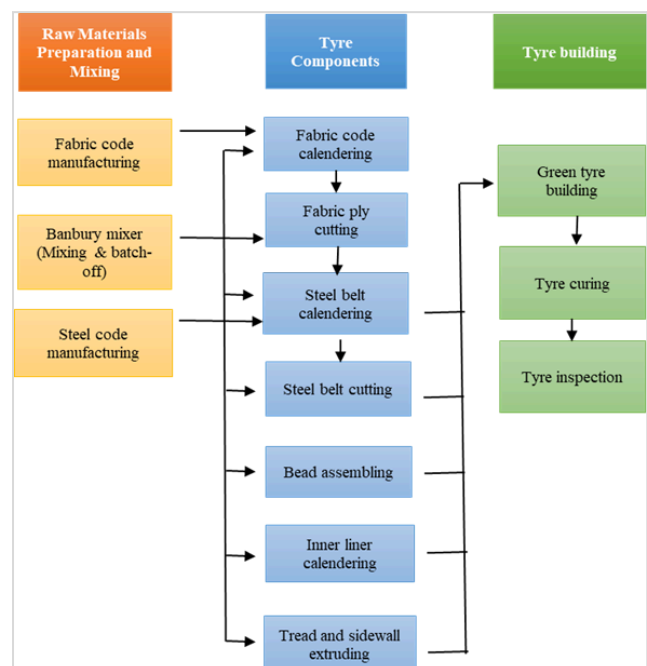


Figure 5. Manufacturing process of resilient solid tyres

As shown in Figure 5, manufacturing solid tyres is a complex, time-consuming process. Generally, solid tyres are built around a metal frame that can be mounted to a specific vehicle (Apexway, 2022). The raw materials needed to build the basic structure of a solid tyre are steel rings and rubberized fabric sheets. The beads are coils of monofilament steel wires (Nideost & Walters, 2000). Overall, the manufacturing process can be summarized in four main stages: Mixing, Batch-off, Tyre Building, and Tyre Curing. The analysis excludes the tyre inspection, packaging, and storage stages.

At the mixing stage, the required materials and chemicals are combined in specific proportions to prepare the compounds needed for the different sheets/layers of the tyre. Compounding is done to enhance the tyre's solid properties. The factory manufactures steel rings separately. The rubberized fabric sheets/layers are cooled in the batch-off stage. A green tyre, which is a semi-finished solid tyre, is built using steel rings and cooled rubberized fabric sheets/layers. This consists of three layers: the base layer, the cushion layer, and the tread layer. Then the green tyre is put into a mould and heated, allowing the rubber to vulcanize. This process is known as tyre curing. The cured, or finished, tyre can then be sent for tyre inspection. Each sub-process adds value to the final output. Based on these summarized production processes, the life cycle inventory is developed as shown in Table 1 below.

Table 1. Inputs and outputs of the solid tyre manufacturing phase

Process	Input Name	Unit	Quantity	Output Name	Unit	Quantity
Mixing	Natural Rubber	kg	15.777	Compound Waste	kg	1.648
	SBR	kg	6.852	Waste Water	l	5.645
	Crumb Rubber	kg	5.101			
	FRC (10mm)	kg	2.480			
	Cotton Flock	kg	0.571			
	Carbon Black	kg	13.860			
	VN3	kg	0.571			
	Zinc Oxide	kg	0.862			
	Stearic Acid	kg	0.498			
	ZDEC	kg	0.030			
	TETD	kg	0.014			
	CBS	kg	0.303			
	Struktol A 95	kg	0.950			
	Si69	kg	0.288			
	TMQ	kg	0.138			
	6PPD	kg	0.344			
	Wingstay 100	kg	0.047			
	PVI	kg	0.025			
	Sulfur	kg	0.510			
	C5 Resin	kg	0.229			
	40MS	kg	0.154			

	MJP	kg	0.549			
	Steel	kg	0.486			
	Water (Cooling)	l	5.645			
	Electricity	kWh	26.315			
Batch-off	Soap	kg	0.011	Waste Water	l	5.113
	Water (Dipping)	kg	2.345			
	Water (Cooling)	l	2.768			
	Electricity	kWh	15.760			
Tyre Building	Electricity	kWh	0.441	Compound Waste	kg	2.01
Tyre Curing	Electricity	kWh	1.476	Flash	kg	0.45
	Steam	kg	45.481			

Table 1 presents all inputs and outputs for manufacturing a resilient solid tyre. Mass balance closes to within 0.1%: total material input is 50.65 kg (50.64 kg of compounding materials plus 0.01 kg of soap), against 4.11 kg of solid process losses (3.66 kg compound waste and 0.45 kg curing flash), giving a finished tyre mass of 46.54 kg (declared as 46.5 kg). Water is assumed to leave each stage entirely as effluent, with 10.76 L input and 10.76 L wastewater across mixing and batch-off; evaporative losses and cooling-water recirculation are not modelled, which is a conservative assumption for plant water consumption. The primary raw materials used in manufacturing solid tyres are natural rubber (SLR-20, Standard Lanka Rubber), SBR (Styrene-butadiene rubber), a synthetic rubber, crumb rubber, a recycled form of rubber, and carbon black. Natural rubber and crumb rubber are sourced from Sri Lanka, and SBR is sourced from Poland. FRC (Fibre-reinforced rubber compound) is a type of upcycled rubber. Carbon black, Cotton flock, and VN3 (precipitated silica) are used as fillers in the manufacturing of solid tyres. Zinc oxide, Stearic acid, ZDEC (Zinc Diethyl Dithiocarbamate), CBS (Cyclohexyl Benzothiazole Sulfenamide), and TETD (Tetraethylthiuram disulfide) are accelerators used in the compounding process. Struktol A 95 and Si69 (Silane) are coupling agents, and TMQ (2,2,4-trimethyl-1,2-dihydroquinoline), 6PPD (N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine), and Wingstay 100 are antioxidants. Pre-Vulcanization Inhibitor (PVI) is a retarder, and Sulfur is a curing agent. As Hydrocarbon resins, C5 resin, and 40MS are used. MJP is a plasticizer used in rubber compounding. Additionally, steel is used to manufacture rings that form part of the base layer. Steel is imported from China. All other raw materials are imported from India. Water is used mainly for washing and cooling purposes.

Grid electricity powers the process. Steam energy is used for tyre curing. The process outflows are identified as compound waste and water waste in the mixing, batch-off, and tyre-building processes. It is assumed that the total amount of water used as input leaves the process as wastewater, with no losses. Furthermore, it is assumed that there are no electricity losses during the process. Flash is the excess amount of tyre particles that are melted during the tyre curing process. The total weight of all materials used to manufacture the solid tyre is 50.6 kg. After deducting all the waste, the net weight of the solid tyre is 46.5 kg. This life cycle inventory lays the basis for the environmental impact assessment presented in the following section.

Overall environmental impact profile

Table 2 below presents the characterized environmental impact of a solid tyre from raw material extraction to manufacturing.

Table 2. Total Characterized Cradle-to-Gate Environmental Impact of a Solid Tyre

Impact category	Unit	Total
Terrestrial ecotoxicity	kg 1,4-DCB	466.4289
Global warming	kg CO ₂ eq	160.9458
Human non-carcinogenic toxicity	kg 1,4-DCB	115.6244
Fossil resource scarcity	kg oil eq	61.1829
Water consumption	m ³	30.8527
Land use	m ² a crop eq	11.5502
Human carcinogenic toxicity	kg 1,4-DCB	5.3858
Marine ecotoxicity	kg 1,4-DCB	4.8284
Freshwater ecotoxicity	kg 1,4-DCB	3.5960
Ionizing radiation	kBq Co-60 eq	2.1654
Terrestrial acidification	kg SO ₂ eq	0.9629
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.6419
Ozone formation, Human health	kg NO _x eq	0.6127
Mineral resource scarcity	kg Cu eq	0.5510
Fine particulate matter formation	kg PM _{2.5} eq	0.3568
Marine eutrophication	kg N eq	0.0484
Freshwater eutrophication	kg P eq	0.0409
Stratospheric ozone depletion	kg CFC11 eq	0.0001

According to Table 2, the global warming impact of the solid tyre under study is 160.9458 CO₂ eq. Water consumption is recorded as 30.8527 m³ per solid tyre under study. The human carcinogenic impact is equivalent to 5.3858 kg of 1,4-DCB per one solid tyre. According to the normalized impact categories, which are comparable (unitless), respectively, human carcinogenic toxicity (0.5230), freshwater ecotoxicity (0.1428), water consumption (0.1157), marine ecotoxicity (0.1111), freshwater eutrophication (0.0630), fossil resource scarcity (0.0624), ozone formation - terrestrial ecosystems (0.03614), terrestrial ecotoxicity (0.03069), ozone formation - human health (0.0298), terrestrial acidification (0.0235), and global warming (0.0201) showed the highest significance. The results indicate that environmental impacts are significant and multidimensional, with both climate- and human-health-related implications.

This result is corroborated by the damage assessment results for the cradle-to-gate life cycle of a solid tyre. According to the normalized results, the most serious damage from cradle-to-gate solid tyres is to human health (0.019895046). Apart from the high human carcinogenic toxicity recorded, all other identified impact categories have a direct or indirect adverse impact on human health. The resulting characterized damage to human health is 0.000477 Disability Adjusted Life Years (DALYs). This means the cradle-to-gate impact of one solid tyre under study can cause 0.000477 years of ill-health,

disability, or early death for human beings. However, this figure is a globally averaged indicator of potential damage based on marginal characterisation models. It does not depict observed or attributable health outcomes in any particular population and should be used primarily for comparing design options, not as an absolute measure of harm.

Understanding the difference between normalised midpoint significance and endpoint damage is essential for interpretation. When measured on a normalised midpoint basis, human carcinogenic toxicity appears highest, mainly due to the low normalisation reference for that category rather than a large absolute burden. In contrast, at the endpoint level, the total human-health damage of 4.77×10^{-4} DALY per declared unit is mainly due to fine particulate matter formation and global warming, which together make up about three-quarters of the total. Carcinogenic toxicity accounts for less than 5%. Both pathways primarily originate from coal-based grid electricity, highlighting energy substitution as the most effective intervention. Although toxicity-related categories are smaller in endpoint terms, they remain strategically important because EU chemicals regulation directly targets them.

Higher production levels lead to higher DALYs. If the average annual solid tyre production in Sri Lanka is assumed to be 100,000 units, the total damage to human health is 47.7 DALYs. This reflects the materials, energy, and processes used from raw material extraction to the manufacturing stage of one solid tyre.

Environmental impact distribution across life cycle stages

To identify the life-cycle stage-wise distribution of environmental impacts, the total result was categorized into three stages, as defined in the European standard EN 15804: A1, A2, and A3, representing the Cradle-to-Gate scope. A1 covers raw material extraction, A2 covers transport to the factory, and A3 covers the manufacturing stage. According to the SimaPro results, the normalized impacts were distributed among the defined life cycle stages. Figure 6 below depicts the graphical representation of the results. Normalized impact categories are used for comparison purposes here.

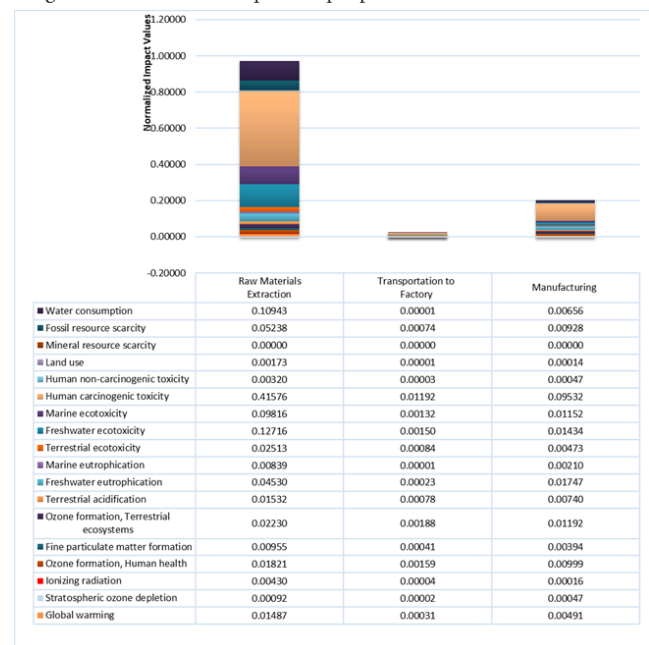


Figure 6. Cradle-to-Gate environmental Impact of a Solid Tyre (Derived by running the SimaPro Faculty version under the ReCiPe characterization method - 2026)

As shown in Figure 6, the highest environmental burden of a solid tyre within the scope of cradle-to-gate is recorded in the raw material extraction phase. Among the environmental impacts generated during raw material extraction, human carcinogenic toxicity contributes the most. The raw materials used for the manufacturing of a solid tyre generate a considerable proportion of harm to human beings in terms of cancer, as supported by the previous analysis. The second- and third-highest environmental impacts in the raw material extraction phase are freshwater ecotoxicity and water consumption, respectively. Global warming also shows a normalized impact of 0.01487.

Among the identified primary life-cycle stages of a solid tyre, the manufacturing stage is the second most significant contributor to the environmental burden. As with the raw material extraction phase, human carcinogenic toxicity contributes most. Here, during the manufacturing phase, the primary activities considered are energy and water consumption for producing a solid tyre. The two energy sources considered are electricity and steam. Freshwater ecotoxicity, freshwater eutrophication, and marine ecotoxicity are other significant environmental impacts from manufacturing a single solid tyre.

According to Figure 6, upstream transportation is less significant than the other two stages. Based on the data collected, most raw materials, except SLR-20, crumb rubber, SBR, and steel, are imported from India. SLR-20 and crumb rubber are locally sourced, and therefore, only land transportation was considered. SBR and steel are imported from Poland and China, respectively. For all foreign-sourced raw materials, sea transportation is also considered, in addition to land transportation from the supplier's location to their harbour and local land transportation (from Colombo harbour to the manufacturing plant). However, in upstream transportation, as in the other two life cycle stages, the highest-impact category recorded is human carcinogenic toxicity. In conclusion, the results indicate that upstream material choices play a more critical role than downstream processing in determining environmental performance.

Identification of environmental hotspots

The results above show that identifying material-based hotspots is essential for managerial decisions to avoid or mitigate environmental impact and meet global regulatory pressures. Figure 7 below compares inputs by their environmental impact contribution. Normalized impacts are used for comparison.

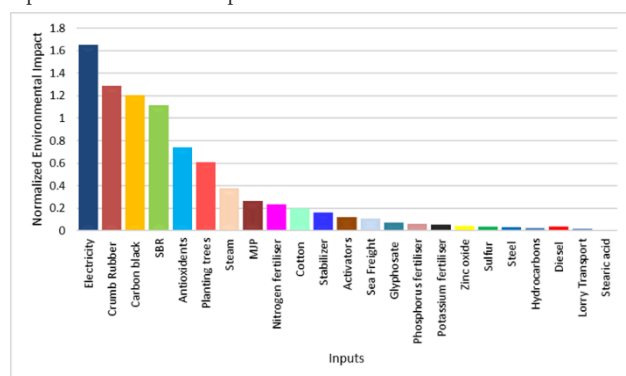


Figure 7. Comparison of Environmental Impact Contribution of Inputs used in Solid Tyre Manufacturing (Derived by running the SimaPro Faculty version under the ReCiPe characterization method - 2026)

According to the results in Figure 7, the major contributors to environmental or human health damage are electricity, crumb rubber, carbon black, SBR, and chemicals in total, as well as tree planting. The highest-impact category identified above is human carcinogenic toxicity. Grid electricity consumption is the primary contributor to this impact, a conclusion corroborated by existing literature. For

instance, coal-powered electricity generation has several detrimental impacts on human health. Persistent inhalation of pollutants generated by coal combustion can damage the lungs, immune system, heart, DNA, brain, and reproductive system in humans (Gasparotto & Da Boit Martinello, 2020; Chen et al., 2017; Weldu et al., 2017). Electricity is highly consumed throughout the solid tyre manufacturing process, including compound preparation (mixing), batch off, tyre building, and tyre curing. According to life-cycle inventory analysis, the solid tyre manufacturing process consumes 43.992 kWh of electricity. In Sri Lanka, electricity is mainly generated by burning coal.

Several studies have shown that coal-based electricity generation results in the emission of numerous toxic pollutants, including mercury, lead, sulfur dioxide, nitrogen oxides, particulates, and heavy metals, which can have a significant adverse impact on the quality of the environment and human health (Weldu, Assefa, & Jolliet, 2017). Burning coal emits toxic pollutants, including sulfur dioxide, Nitrogen Oxides, Carbon dioxide, Fly ash, and toxic metals. These pollutants can contaminate groundwater and also cause land pollution (EPA, 2025). According to the United States Environmental Protection Agency, reductions in plant biodiversity, acid rain, and changes in biological communities are among the other adverse effects of coal-fired electricity generation. These factors may contribute to the significant environmental burden associated with electricity consumption in solid tyre manufacturing in Sri Lanka.

Second, Figure 7 shows that crumb rubber is the next-highest contributor to the negative environmental impact of the cradle-to-gate solid tyre life cycle. To produce a 46.5 kg solid tyre, 5.101 kg of crumb rubber should be incorporated. Crumb rubber is a type of recycled rubber derived from used tyres. According to the results obtained, the normalized impact of crumb rubber is 1.284. Although it is considered an environmentally friendly raw material, researchers have found that crumb rubber could threaten aquatic and soil organisms (Fort et al., 2022). Studies have found that the crumb rubber manufacturing process contaminates water with BOD₅, COD, TSS, ammonia, and total nitrogen. The drying process can also cause air pollution, including SO₂, NO₂, HCl, NH₃, and other harmful emissions (Yerdianti & Aziz, 2021).

The third most significant contributor to the negative environmental impact of the cradle-to-gate solid tyre life cycle is carbon black. According to the LCIA results, 13.860 kg of carbon black is consumed in producing one solid tyre under study. The normalized environmental impact of carbon black used is 1.199. According to Coppola et al., carbon black is a carbonaceous residue with unique chemical and optical characteristics, primarily produced by the incomplete combustion of organic materials such as biomass and fossil fuels. Studies have shown that carbon black harms air quality, agriculture, forests, human health, the economy, and the environment (Tiwari, Chen, Singh, Singh, & Srivastava, 2021). Carbon black in the atmosphere, soil, glaciers, water bodies, and human bodies has detrimental effects on global carbon cycling, climate change, and human health (Coppola et al., 2022). These factors help explain the significance of carbon black's adverse environmental impact, as illustrated in Figure 7.

Additionally, SBR has a significant adverse environmental impact, as shown in Figure 7. SBR has been identified as a major source of microplastics, which have a high potential to harm the environment, including land, water, and air (Järlskog, 2020; Zhao et al., 2021). According to the LCIA, a 46.5 kg solid tyre contains 6.852 kg of SBR, most of which is in the tread layer, the tyre's outermost layer.

According to Figure 7, antioxidants are the next highest contributor to negative environmental impact. Antioxidants used in solid tyre manufacturing, including 6PPD and TMQ, are also identified as major contributors to the selected solid tyre's negative environmental impacts. The results indicate that the normalized environmental burden of antioxidants used is 0.738. Regarding 6PPD, researchers have found that 6PPD and 6PPD-Quinone, present in tyre wear dust, cause adverse environmental impacts, especially to aquatic life. Researchers have uncovered that there is a relationship between Coho salmon deaths and 6PPD. As a result, tribes in Washington requested a ban on 6PPD in 2023 (Shanbag & Manjare, 2020). In addition to that, 6PPD and 6PPD quinone have been detected in the bloodstreams of children and adults, including pregnant women in China, probably entering through the inhalation of tyre particles (Bohara et al., 2025). This evidence supports the significant human carcinogenic impact of the cradle-to-gate life cycle of the solid tyre under study. Therefore, Sri Lankan tyre manufacturers should seriously consider using antioxidants such as 6PPD in solid tyre production.

In addition to these five primary contributing inputs, planting trees, nitrogen fertilizer, glyphosate, phosphorus fertilizer, and potassium fertilizer are also used in TSR production (SLR-20 in this study). The normalized impacts are 0.609, 0.234, 0.072, 0.059, and 0.051, respectively. Several socioeconomic and environmental impacts have been identified in the rubber tree planting process, including damage to soil quality and groundwater reserves, biodiversity loss, deforestation, and microclimatic changes (Ochigbo, Lafia-Araga, & Suleiman, 2011; Panda & Sarkar, 2020). Glyphosate, a commonly used herbicide, is also relevant in this regard. The International Agency for Research on Cancer (IARC) has classified glyphosate as carcinogenic (Tarazona et al., 2017).

In terms of water consumption, SimaPro process contribution results indicate that the highest water consumption in cradle-to-gate solid tyre production is attributed to SBR production. Studies show that "about 710 million gallons of makeup water is withdrawn daily by the styrene, butadiene, styrene-butadiene rubber (SBR), and speciality-rubber industries; 88 percent of this water is used only for once-through cooling" (Durfor, 1963). Furthermore, the cotton flock used in the base layer is highly water-intensive (Demeke et al., 2024). Moreover, in crumb rubber production, if the wet process is used, the crumb rubber is mixed with asphalt at the plant before being combined with aggregate. This method may require water for mixing and cleaning (Public Works Construction, 2015). In addition, freshwater and marine ecotoxicity can occur when fertilizers and chemicals are added to waterways, as discussed above.

In conclusion, the concentration of impacts in a limited number of inputs suggests that material selection is a primary driver of environmental performance. Moreover, comparing the environmental impact contributions of individual inputs used in solid tyre manufacturing provides essential information on areas that should be the focus of further research and development by solid tyre manufacturers.

Scenario analysis: grid electricity & solar energy

The analysis above identified grid electricity use as the major driver of most environmental impacts. Ultimately, these impacts significantly harm human health. Therefore, it is important to consider replacing grid electricity with a renewable energy option to reduce the identified impacts. Figure 8 below compares the major impact variations between using solar power and grid electricity as the main energy source in the manufacturing stage of a solid tyre. When generating the

results, it is assumed that 100% coal-powered electricity is replaced with 100% solar energy, with no emissions or impacts in the installation stage.

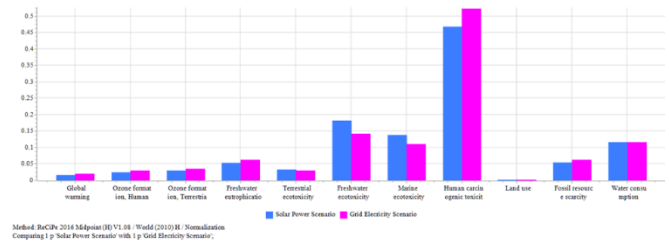


Figure 8. Comparison between using grid electricity and solar power in the manufacturing of a solid tyre

According to Figure 8, replacing grid electricity with solar energy has both positive and negative impacts, with the positive impacts more prominent. Most significantly, replacing the main energy source with solar power has decreased global warming impact by 20%, ozone formation (human health) by 18%, freshwater eutrophication by 15%, human carcinogenic toxicity by 10%, and land use by 4%. The results show that the energy transition alone can significantly reduce the carbon footprint, human carcinogenic toxicity, and numerous other impact categories, underscoring its importance as a strategic intervention.

Managerial implications for facing strategic risks under EU Sustainability Pressure

Sri Lanka, the world's leading solid tyre manufacturer, which caters to a significant share of global demand and has the EU as one of its major customers, faces multiple risks if manufacturers do not opt to switch to more environmentally and human-friendly production methods. According to the analysis, high global warming potential can increase the risk of carbon-related trade measures and buyer rejections in the future. This can directly threaten Sri Lankan solid tyre export competitiveness. High carcinogenic toxicity can expose a product to regulatory compliance risks, such as REACH, and consequently to future product restrictions. According to industry sources, EU buyers are also demanding sustainability reporting and various ESG compliance requirements, which will increase as government involvement in exports grows. Hence, environmental performance is increasingly becoming a prerequisite for market access rather than a means of differentiation. Numerous global tyre companies have publicly disclosed their objectives to reduce their carbon footprints and promote circularity in material sourcing. For example, some have set a target to increase the incorporation of sustainable materials in their products by at least 40% by the year 2030, while others have expressed their intention to transition entirely to renewable and recycled feedstock by 2045 (Bridgestone, 2023; Perto - Digital Accessibility, 2026). Under these circumstances, Sri Lanka needs to actively explore transitioning its conventional tyre offerings to greener alternatives. Therefore, Sri Lanka must implement strategic changes in raw material selection, energy sourcing, and other areas of solid tyre manufacturing to safeguard and strengthen this lucrative export market.

Based on the LCA results, carbon black, SBR, crumb rubber, and antioxidants such as 6PPD and TMQ are the primary contributors to most environmental impact categories, including human carcinogenic toxicity and global warming potential. In light of this finding, from a managerial perspective, these primary materials should be prioritised for modification or enhancement rather than pursuing unfocused, extensive sustainability initiatives. Bio-based synthetic rubbers instead of petroleum-based synthetic rubbers, bio-based fillers instead of

carbon black, self-healing materials instead of crumb rubber, bio-based fabrics and bio-based accelerators, recycled carbon black, and recycled fabrics are currently under consideration as green materials for green tyre manufacturing (Sampath et al., 2025). Substituting conventional raw materials with these cleaner materials would reduce toxicological risks and carbon emissions by a greater percentage, which will be particularly important for aligning with EU chemical regulations. Consequently, material substitution can yield multiple benefits for Sri Lankan solid tyre manufacturers, including environmental improvements and a strategic response to regulatory requirements.

In addition, the results indicate that grid electricity is a key driver of the resulting environmental impacts. The scenario analysis suggested that the transition to renewable energy sources (solar energy) could reduce numerous environmental impacts by significant percentages, for instance, global warming by approximately 20%. Amid rising carbon-related trade measures and buyer-driven sustainability requirements in the EU market, reducing carbon intensity can enhance the competitive position of Sri Lankan solid tyre manufacturers. EUDR is highly relevant to this industry, as natural rubber is one of its main raw materials. Rubber estates are highly monitored under it. The EUDR (Regulation (EU) 2023/1115) came into effect in June 2023. Its enforcement has been postponed twice, most recently through Regulation (EU) 2025/2650. It now takes effect on 30 December 2026 for large and medium operators, and on 30 June 2027 for micro and small operators. The delay does not change the core due diligence and traceability requirements. The Commission has stated it will not revisit the regulation, meaning the extra time is intended for preparation, not a delay in obligations. Therefore, after these specified dates, any product exported to the EU must be deforestation-free, traceable to the exact land where it was sourced, and legally produced under the source country's laws. Sri Lanka remains categorised as a low-risk country under the EUDR, reducing the need for risk assessments on the EU importers' side, but exporters must still submit detailed geolocation data and proof of legal land ownership for farms producing rubber. Although this process is simpler for large plantations, smallholder farmers—who manage 68.14% of the country's rubber cultivation—have not yet developed the capacity to meet these demands (TalkingEconomics, 2025). Sri Lankan solid tyre manufacturers source natural rubber from smallholder farmers and large estates, which could lead to future EUDR non-compliance issues and ultimately threaten the EU market for Sri Lankan solid tyres.

Sri Lankan solid tyres are currently outside the EU Carbon Border Adjustment Mechanism's scope. From January 2026, this mechanism will mainly cover cement, iron and steel, aluminium, fertilisers, hydrogen, and electricity. Its 2028 proposal aims to include steel- and aluminium-intensive downstream products. At present, the main carbon-related pressure on tyres comes from buyer demands and value-chain reporting, not from border taxes. The more immediate regulatory influence is the Ecodesign for Sustainable Products Regulation, which lists tyres as a key product group.

The Ecodesign for Sustainable Products Regulation (EU 2024/1781) provides a general framework, with specific requirements detailed through product-specific delegated acts. According to the ESPR and the Energy Labelling Working Plan 2025–2030 (COM(2025) 187, approved on 16 April 2025), tyres are classified as one of six priority product groups, alongside textiles, furniture, mattresses, iron and steel, and aluminium. The planned adoption window for delegated acts is around 2027, followed by an 18-month transition period. These delegated acts are expected to establish rules on durability,

recycled content, carbon disclosure, and a Digital Product Passport (Directorate-General for Environment, 2025).

Considering these outcomes, if solid tyre manufacturers act proactively, Sri Lanka can further secure and enhance its global positioning. Based on the findings of this study, a green solid tyre, a product with a reduced carbon footprint and minimized toxicological impacts, can be proposed, which needs further research. This positioning would cater to the accelerating demand for environmentally responsible products in the global market. By using LCA insights, companies can improve internal operations and communicate their environmental performance to buyers, reinforcing their value proposition in sustainability-sensitive markets.

CONCLUSIONS

This study offers a thorough cradle-to-gate Life Cycle Assessment (LCA) of solid tyre manufacturing in Sri Lanka, providing essential baseline data for one of the nation's most vital export-oriented industries. The results indicate that environmental impacts concentrate in specific inputs and processes, particularly the use of carbon black, synthetic rubber (SBR), recycled rubber (crumb rubber), and chemical additives, as well as in energy-intensive manufacturing stages. Among the impact categories, human carcinogenic toxicity, freshwater and marine water-related depletions, fossil resource scarcity, ozone formation (terrestrial ecosystems), terrestrial ecotoxicity, ozone formation (human health), terrestrial acidification, and global warming are identified as primary concerns, highlighting the significant environmental and human health implications associated with current production practices.

Beyond mere quantification, this study underscores the strategic importance of Life Cycle Assessment (LCA) as a decision-support tool under escalating global sustainability pressures. The identified environmental hotspots signal not only operational inefficiencies but also potential strategic risks, especially under European Union (EU) environmental regulations. Elevated carbon intensity could subject manufacturers to emerging carbon-related trade measures, while reliance on human labour and environmentally toxic chemicals may pose challenges under stringent chemical compliance frameworks. Therefore, companies should incorporate environmental performance into their core business strategy rather than treating it solely as a compliance exercise.

Material substitution and energy transition were identified as pathways to address the highlighted issues. Researchers have shown that reducing dependence on high-impact inputs such as crumb rubber, carbon black, SBR, and antioxidants by adopting cleaner or bio-based alternatives can significantly lower carbon emissions and toxicological risks. Likewise, shifting from conventional grid energy to a renewable source such as solar power can significantly reduce the overall carbon footprint and other major production impacts. These actions are environmentally beneficial and strategically vital for preserving access to export markets such as the EU, which prioritize sustainability. Based on these findings, positioning Sri Lanka as a green solid tyre manufacturer would create multidimensional advantages in global competition.

In conclusion, this study links environmental assessment with strategic planning by showing how LCA can guide sustainable decision-making in export-oriented industries. The results offer practical advice for manufacturers, policymakers, and stakeholders aiming to improve environmental performance and maintain long-term competitiveness. Future research should broaden the analysis to cover the entire life cycle of solid tyres, including distribution, use, and end-of-life stages, and investigate the economic

impacts of sustainability transitions to develop more comprehensive decision-making frameworks.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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