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Life cycle assessment of vehicle tires: A systematic review

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ABSTRACT

There has been a growing awareness of the potential environmental impacts from the tire industry in the last two decades. Life cycle assessment (LCA), as an efficient technique, was applied to quantify the environmental impacts of industrial tires through the four stages of life cycle, i.e., production, transportation, use, and end-of-life. In response to the rapid development of LCA applications on tires, this article conducted a comprehensive and critical review on the related literature. The methodology, on-going trends, challenges, and future opportunities in the LCA study of tires are investigated based on a systematic review method. It is found that most studies investigated the end-of-life stage of tires, while ignoring the transportation stage. The use stage is the contributor to most environmental impacts in the entire life cycle of a tire. Notably, the carbon emissions in the use stage range from 550 kg CO_2 eq to 840 kg CO_2 eq per car tire. There are inconsistencies in several LCA aspects, i.e., functional units, impact assessment methods, impact categories, etc. To improve the environmental performance, the recovery of end-of-life tires (ELT), adoption of secondary materials, and new tire designs are recommended.

1. Introduction

The popularity of automobiles both in the developed and developing countries boosted the manufacturing of tires. During the last decade, the production of tires increased from 776 to 816 million pieces in China only (NBS, 2011, 2019). For the same period of time, an increase of 30 million tires (approximately 0.3 million tons) is reported in Europe (ETRMA, 2019b). It was reported that three billion tires were produced worldwide in the single year of 2019 (Ruwona et al., 2019). The huge amount of waste tires is a side effect. It is estimated that the global annual waste tires shall rise up to 1.2 billion tons by the end of 2030s (Liu et al., 2020). The end-of-life tires (ELT) can be reused, e.g., for civil engineering purposes or replacement of fossil fuel (USTMA, 2017). The countries (or regions) that recover the largest amounts of ELT are China, India, the United States and Europe (WBCSD, 2019). In the United States, 81% of scrap tires were recycled or reused and the figure was 92% in Europe (ETRMA, 2018). China had approximately 330 million scrap tires phased out in 2019, whereas the rate of recycling or reuse was about 60% (MIIT, 2020b).

The life cycle of a tire can be delineated into four stages, namely (i) production, (ii) transportation, (iii) use and (iv) ELT (Bras and Cobert, 2011; Korínek et al., 2012). The manufacturing processes of tires, in particular the processes to produce natural rubber, may generate nitrogen oxides (NO_x), benzene, and polycyclic aromatic hydrocarbons (PAH), which are pollutants threatening to human health (Sun et al., 2016). The manufacturing of tires also consumes large amounts of water and electricity (Shanbag and Manjare, 2020), while the upstream processes of electricity generation consume natural resources and have various environmental degradations. Transportation of tires can lead to dust emission and fuel consumption. In the use phase, the environmental problems caused by tire abrasion are relatively negligible as compared to those by fuel consumption (Li, 2011), which accounts for almost 89% of the environmental impacts during the whole life cycle (Wu, 2012). The conventional treatment method for the non-biodegradable ELT material is to dispose in landfills, which potentially leads to disease spreading and fire disasters (Taleb et al., 2020).

To regulate or reduce the environmental pollutants, standards and guidelines for the tire industry have been released, especially on ELTs. Series of directives were published in Europe, such as Directive 1999/31/EU (to prohibit landfilling of waste tires) and Directive 2000/53/EU (to prevent waste from vehicles and their components) (EN, 1999, 2000). An ELT management scheme was proposed by European Tyre Recycling Association (ETRA), combining tax models, free market and producer responsibility in a single framework (Antoniou and Zabaniotou, 2013). In addition, there are regulations on the eco-labelling of tires (ETRMA, 2019a). In China, the “Industrial Standard Conditions for Comprehensive Utilization of Waste Tires” was released, which provides technological

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List of abbreviations

AD	Abiotic Depletion
AP	Acidification Potential
BUWAL	Swiss Agency for Environment, Forests and Landscape
CC	Climate Change
CLCD	Chinese Life Cycle Inventory Database
CBA	Cost-Benefit Analysis
CE	Carcinogenic Effect
CED	Cumulative Energy Demand
CML	Institute of Environmental Sciences (University of Leiden)
CO_2 eq	Carbon Dioxide Equivalent
EC	Energy Consumption
EDIP	Environmental Design of Industrial Products
EI-95	Eco-Indicator 95
EI-99	Eco-Indicator 99
ELT	End-of-Life Tires
EN	European Standards
EP	Eutrophication
EPR	Extended Producer Responsibility
ESM	Ecological Scarcity Method
ET	Ecotoxicity
ETRA	European Tire Recycling Association
ETRMA	European Tire and Rubber Manufacturer's Association
EU	European Union
EVA	Economic Valuation Analysis
FA	Freshwater Acidification
FAT	Freshwater Aquatic Toxicity
FE	Freshwater Eutrophication
FRD	Fossil Resource Depletion
FU	Functional Unit
GWP	Global Warming Potential
HH	Human Health
HLCA	Hybrid Life Cycle Assessment
HME	Heavy Metal Emissions
HT	Human Toxicity
I-LCA	Italian Database to Support Life Cycle Assessment
IMPACT	IMPact Assessment of Chemical Toxics
IO-LCA	Input-output based Life Cycle Assessment
IPCC	Intergovernmental Panel on Climate Change
IR	Ironizing Radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
MAT	Marine Aquatic Toxicity
ME	Marine Eutrophication
MIIT	Ministry of Industry and Information Technology of the People's Republic of China
MRD	Mineral Resource Depletion
NBS	National Bureau of Statistics of the People's Republic of China
NG-WBT	New-generation Wide-base Tires
NI	Noise Impact
NO_X	Nitrogen Oxides
OD	Ozone Depletion
PAH	Polycyclic Aromatic Hydrocarbons
PAS	Publicly Available Specification
PICO	Participants, Interventions, Comparisons, Outcomes
PLCA	Process-based Life Cycle Assessment
PMF	Particulate Matter Formation
POC	Photochemical Oxidant Creation
REI	Respiratory Effects Inorganics
REO	Respiratory Effects Organics
RSE	Radioactive Substance Emissions
SDA	System Dynamic Approach
STARR-LCA	Standardized Technique for Accessing and Reporting Reviews of Life Cycle Assessment
SW	Solid Waste
TA	Terrestrial Acidification
TE	Terrestrial Eutrophication
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
TT	Terrestrial Toxicity
USLCI	U.S. Life Cycle Inventory Database
USTMA	U.S. Tire Manufacturers Association
WBCSD	World Business Council for Sustainable Development
WD	Water Depletion
WP	Water Pollutants

references to retreading and recycling of ELTs with environmental requirements (MIIT, 2020a).

Besides the existing standards and regulations, the quantitative analysis of the environmental impacts of tires throughout the life cycle is extremely important to understand the sustainability performance in the tire industry. Life cycle assessment (LCA) is an efficient technique which provides quantitative assessments of a product (or a process) from cradle to grave (ISO, 2006a, b; Walker and Rothman, 2020). The application of LCA in the tire industry can be dated back to 1990s, such as for the comparison of filler types (Saur et al., 1997) and the evaluation of the environmental impacts of a tire (Krömer et al., 1999). Since the 2010s, the research interests have been shifted towards the comparative LCA studies of ELTs with new treatment methods (Landi et al., 2020; Neri et al., 2018). Although dozens of studies have been published on the topic of LCA on tires in the last two decades, the lack of consistency in methodology and the misunderstanding of sustainability results pose challenges for further LCA applications in the industry (Gomes et al., 2019; Torretta et al., 2015).

Review articles on tires related to LCA can be found in literature. For example, Torretta et al. (2015) reviewed approaches of tire treatment and disposal in Europe, and noted that LCA was applied in comparing recovery technologies of ELTs. Mohajerani et al. (2020) reviewed the applications of waste tires and recommended comprehensive life cycle analyses for applying recycling rubber in pavement materials as well as in other applications. However, there has not yet been a review endeavored to the topic of LCA studies on tires. A detailed and comprehensive literature review is therefore needed to provide a full scale picture of the state-of-art applications of LCA in the tire industry and to summarize the environmental impacts of tires from a life-cycle perspective. Such a review study can not only improve the understanding of tires' sustainability performance, but also promote in-depth LCA applications and benefit future LCA researches in the tire industry.

Based on a systematic review method, this study aims to understand the applications of LCA in the tire industry and unveil the environmental impacts of tires throughout the life cycle. The paper is organized as follows: Section 2 describes the approach adopted in this systematic review and defines the selection procedures and criteria. Section 3 presents the outcomes of the review in accordance with the standard four phases of LCA. Section 4 discusses the challenges of LCA on tires and research opportunities in the future. Section 5 concludes this reviewing study.

2. Materials and methods

2.1. Design of the review

In contrast to a traditional literature review, a systematic review is a self-contained research project to investigate a clearly specified question based on the existing studies (Denyer and Tranfield, 2009). The process in a systematic review is scientific and transparent, which guarantees reliability and minimizes bias of the literature review (Denyer and Tranfield, 2009; Huang et al., 2017). According to Pullin and Stewart (2006), there are mainly three steps in a systematic review: planning the review, conducting the review, and reporting and dissemination of results. Moreover, Denyer and Tranfield (2009) proposed a more detailed systematic review method that consists of five steps: (i) question formation, (ii) locating studies, (iii) selection and evaluation, (iv) analysis and synthesis, and (v) reporting and using the results. This study adopts the systematic review method of Denyer and Tranfield (2009), which is suitable for the purpose of the study.

To facilitate a successful review and ensure quality of the results, the STARR-LCA checklist (Zumsteg et al., 2012) is employed in the systematic review. STARR-LCA is an abbreviation for Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data. STARR-LCA checklist contains nine items that are essential for LCA reviews (Zumsteg et al., 2012). Fig. 1 demonstrates the procedures of the systematic review of this study in accordance with the STARR-LCA checklist.

Firstly, to propose a research question, a preliminary review was conducted on the title, keywords and abstract through a traditional review process. Then, the rationale of this review study was formed and the review question was raised (in next subsection). The aims and objectives of this study were proposed. A review protocol was designed, including the details of the search engine, databases, search strings, etc. for locating the studies. In the next step, the selection and evaluation of the individual studies were carried out and the irrelevant individual studies were filtered out based on the inclusion and exclusion criteria. The analyses and syntheses of the selected studies were conducted through quantitative and qualitative methods. Lastly, the results were summarized and the limitations and future research opportunities were discussed.

2.2. Question formation

As mentioned in the introduction section, this study aims to understand the applications of LCA in the tire industry and unveil the environmental impacts of tires. The question of this review was constructed following the PICO format (product/process, impacts of interest, flows or economic sectors included, and types of LCA) (Zumsteg et al., 2012), which was based on the PICO structure proposed by Liberati et al. (2009). The studied product is tires (including original tire products and waste tires). The impacts of interest are environmental impacts caused by the tire industry to air, water, and soil (midpoint) and to human health, ecosystem, and natural resources (endpoint). The flows or economic sectors of this study are the tire industry as well as the participants in the upstream life cycle stages. There is no constraint on the types of LCAs in this review, indicating this study will encompass LCA studies on tires for the whole life cycle (“cradle-to-grave”), partial life cycle (e.g., “cradle-to-gate”) in terms of the scope; the process-based, input/output-based and hybrid LCAs in terms of inventory; and the midpoint and endpoint methods in terms of impact assessment; the attributional and consequential LCAs in terms of interpretation. The question of this systematic review is defined as *“What do the existing LCA studies tell us about the environmental impacts of tires?“*.

2.3. Locating the studies

The search engines Web of Science, Science Direct, CNKI and WanFang were employed to collect the relevant literature articles. The strings for searching in the literature were (“Life cycle assessment” or “LCA”) and (“tire” or “tires” or “tyre” or “tyres”). The titles or abstracts of the articles retrieved should contain the keywords. To guarantee the comprehensiveness of this review, there was no constraint on the time of publication. The search was completed on May 9, 2020.

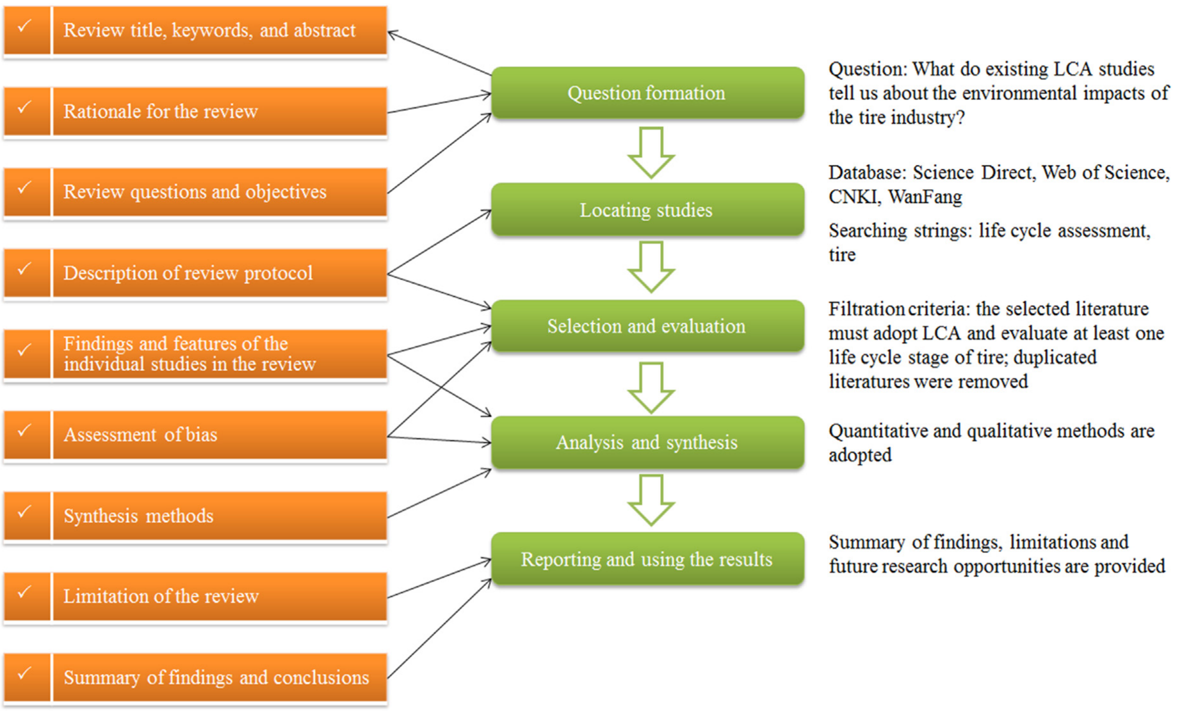


Fig. 1. Five steps (green boxes) of the systematic review and their relations with STARR-LCA checklist items (orange boxes). Black arrows represent information flows.

2.4. Selection and evaluation

The following inclusion and exclusion criteria of screening are adopted:

2.4.1. Inclusion criteria

- Literature article should involve applications of LCA;
- Literature article should evaluate one or more life cycle stages of tires;
- Peer-reviewed literature are included;
- Literature article should be published in English.

2.4.2. Exclusion criteria

- Literature articles containing only theoretical knowledge without the application of LCA in the tire industry are excluded;
- Duplicated literature articles are excluded;
- Theses and dissertations are excluded in case of duplicated content.

Through the screening process, 50 relevant literature articles were obtained, including 42 peer-reviewed journal papers, 2 reports, and 6 conference papers. The information of the selected literature is given in Appendix A.

3. Results and discussion

Fig. 2 shows the number of LCA publications on tires over time, based on the literature review. The publications on this topic have been increased significantly in particular in the past five years, indicating a growing attention on the application of LCA in the tire industry. Fig. 3 gives the spatial distribution of publications. It is found that over half of the literature were published in Europe, with Italy alone contributing 14 publications. There are 12 articles published in Asian countries, among which China accounts for 7 publications. North America published 7 articles. On the other hand, South America and Africa have fewer publications on this topic. It is noticed that one of the articles studied two spatial contexts. Lonca et al. (2018) studied the environmental impacts caused by ELT retreading and regrooving in the context of Brazil, while they also investigated the environmental benefits of using ELT grind powder in new tire production in Europe.

In the following, the analyses are based on the four phases of LCA as required by ISO (ISO, 2006b), i.e., (i) goal and scope definition, (ii) inventory analysis, (iii) life cycle impact assessment (LCIA) and (iv) interpretation.

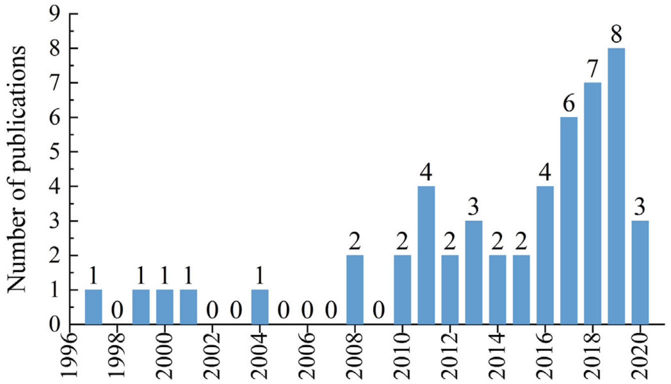


Fig. 2. Numbers of LCA publications on tire over time (the search conducted on May 9, 2020).

3.1. Goal and scope definition

3.1.1. Study aims of literature

The reviewed literature covers eight study aims as shown in Table 1. The majority of reviewed papers focused on the first five study aims, i.e., the whole life cycle of tires, ELT, comparison of designs, application of secondary materials, and new impacts, while a few studies evaluated the treatment processes of tires and the new-generation wide-base tires (NG-WBT). The whole life cycle of tires or the so-called "cradle-to-grave" stages refer to the production, transportation, use and end-of-life. The studies of A1 endeavored to analyze the environmental impacts of tires generated in all life cycle stages. A2 is to study the ELT and investigate the recovery methods of ELC with respect to the environmental impacts. For example, Corti and Lombardi (2004) made a comparative analysis of the disposal methods of waste tires using LCA, i.e., energy recovery (replacing traditional fuels in cement kilns) and material recovery (mechanical crushing and cryogenic crushing). The studies of A3 focused on the environmental impacts of new formula of tire designs, e.g., silicon dioxide being used to replace part of carbon black (Sun et al., 2017). The studies of A4 investigated the application of ELT in the production of other materials, e.g., ELC fiber-reinforced in hot mix asphalt mixtures (Landi et al., 2020). The studies of A5 focused on the new impacts, such as economic impacts and noise. For the economic impacts, life cycle costing is usually adopted (Kang et al., 2019). Using waste tires may influence the manufacturing process and this was discussed by the studies of A6, e.g., the environmental impacts of ground rubber production process from scrap tires (Li et al., 2014). A7 studied the new generation wide-base tires, which can considerably reduce fuel consumption, tire cost, and improve comfort and vehicle stability.

In the last category (A8-"Others"), there are five articles. Qu et al. (2013) analyzed the contribution of changing the ELT recycling mode in terms of material metabolism. Dong et al. (2017) studied the promotion of the urban industrial symbiosis in a macro scale in terms of ELT. Elkafoury and Negm (2016), La Rosa et al. (2019) and Shanbag and Manjare (2020) carried out partial LCA studies of tires on the life cycle stages excluding ELT. There are nine articles appearing twice in Table 1, as these studies cover more than one area. For example, Achilleos et al. (2011) employed life cycle costing (LCC) to study the cost saving by using steel fibers derived from ELT to replace original steel fibers in concrete pavement, so this article is categorized to both A4 and A5. In addition, it is noticed that although some studies claimed to assess the environmental performance of tire throughout a whole life cycle, a few processes were missing. For instance, Sun et al. (2016) ignored the use and transportation stages. Similarly, Meyer et al. (2017) did not include the transportation stage in the analysis.

3.1.2. System boundary

As shown in Fig. 4, the life cycle of a tire starts with the raw material acquisition of natural rubber, textiles, steel, and chemicals. Then the natural rubber and other chemicals, such as carbon black, silicon dioxide, active clay, etc., are blended in Banbury mixers and further processed in extruders. Meanwhile, textile and steel are used to manufacture fabric cord, and bead and belt steel cord. After the cutting of fabric and steel cord, the tire components are processed in tire building machines to manufacture an entire tire. Through curing press and the restrict inspection on appearance, balance, force and movement, a finished tire is made. Then tires are transported to vehicle/airplane manufacturers. After the use phase (normally up to 20 years), ELTs may be recycled as secondary tires, or reused to replace traditional energy or construction materials.

Amongst the reviewed literature, seven studies cover the whole life cycle of tires. Since the environmental impacts of the transportation phase seems less important than the other phases (Bras and Cobert,

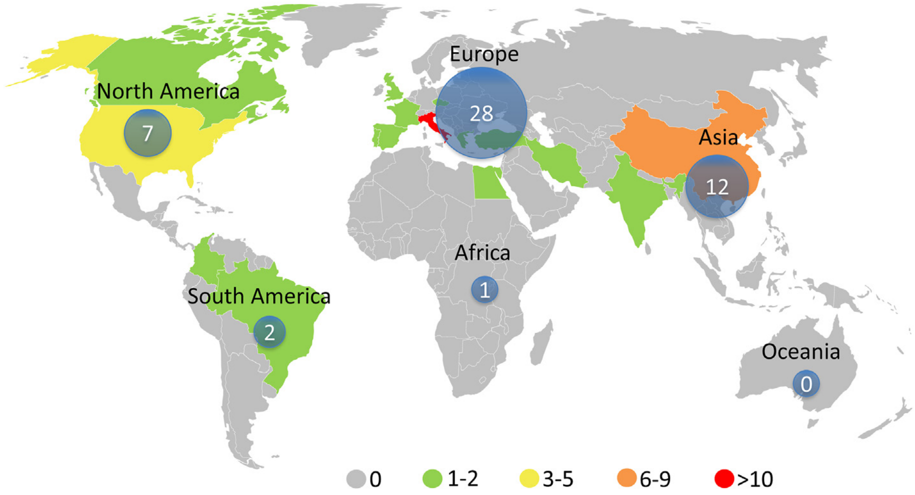


Fig. 3. Spatial distribution of LCA studies.
(Seven studies did not specify countries, of which six were based on Europe and one was based on North America).

Table 1
Categories of the selected literature based on their study aims.

Aim	Description	Authors (year)
A1: Whole life cycle of tires	To evaluate the environmental impacts of tires through a whole life cycle from the "cradle to grave"	(Beukering and Janssen, 2000; Ferrão et al., 2008; Korínek et al., 2012; Piotrowska et al., 2019; Pré Consultants, 2001; Sun et al., 2016)
A2: End-of-life tire (ELT)	Only evaluate or compare disposal scenarios for ELT and products derived from ELT but exclude other stages	(Banar, 2015; Clauzade et al., 2010; Corti and Lombardi, 2004; Feraldi et al., 2013; Georgiopoulou and Lyberatos, 2018; Gigli et al., 2019; Landi et al., 2018a; Landi et al., 2018b; Landi et al., 2016; Li et al., 2010; Malijonyte et al., 2016; Marconi et al., 2018; Neri et al., 2018; Ortiz-Rodriguez et al., 2017; Uson et al., 2012)
A3: Comparison of designs	To compare the difference caused by the change of formula on the environmental impacts of tires	(Bras and Cobert, 2011; Eranki and Landis, 2019; Krömer et al., 1999; La Rosa et al., 2015; Lin et al., 2017; Lonca et al., 2018; Saur et al., 1997; Sun et al., 2017)
A4: Secondary materials	To evaluate and compare the environmental impacts between conventional materials and secondary materials derived from ELT	(Achilleos et al., 2011; Buratti et al., 2018; Curry et al., 2011; Djadouni et al., 2019; Farina et al., 2014, 2017; Fiksel et al., 2011; Heidari and Younesi, 2020; Landi et al., 2020; Puccini et al., 2019; Simões et al., 2013)
A5: New impacts	To evaluate a new impact caused in the life cycle of a tire, such as noise and economic impact	(Achilleos et al., 2011; Beukering and Janssen, 2000; Curry et al., 2011; Gigli et al., 2019; Kang et al., 2019; Khoo, 2009; Krömer et al., 1999; Landi et al., 2018a; Meyer et al., 2017; Saur et al., 1997)
A6: Treatment processes	To evaluate the impact of a certain treatment process	(Khoo, 2009; Li et al., 2014)
A7: NG-WBT	To evaluate the environmental impacts of new-generation wide-base tires (NG-WBT) on pavement	(Kang et al., 2019; Said et al., 2020)
A8: Others	The aim of study is not included in the above	(Dong et al., 2017; Elkafoury and Negm, 2016; La Rosa et al., 2019; Qu et al., 2013; Shanbag and Manjare, 2020)

2011), only eight studies involved transportation in analysis. Most of the reviewed studies (31 out of 50 studies) investigated the ELT phase. A few of them (12 out of 50 studies) compared the treatment methods of ELT with regards to the environmental impacts. For example, Clauzade et al. (2010) identified the pros and cons of nine recovery methods in terms of environmental impacts. Feraldi et al. (2013) compared the environmental burdens and trade-offs of energy and material recovery for ELT. Five studies (Gigli et al., 2019; Landi et al., 2016) investigated the improvement of environmental impacts by changing the end-of-life textile fiber materials. In addition, the reuse of the by-products from ELT, such as steel fibers and crumb rubber, are extensively discussed (in 14 out of 50 studies) (La Rosa et al., 2015; Landi et al., 2020).

3.1.3. *Functional unit*

The functional unit (FU) is the basis for quantifying the inputs and outputs in an LCA study (Aziz et al., 2019; Hafez et al., 2019; Matustik et al., 2020). Unfortunately, there is a lack of agreement in the reviewed literature, and this makes LCA results difficult to compare (Quek and Balasubramanian, 2014). Among the reviewed studies, there are four categories of FUs, namely, distance-based, mass-based, number-based, and others. Details of the FUs are provided in the Appendix A. A summary of the FUs for the selected studies is shown in Fig. 5.

It is found that 23 studies (46%) used the mass-based FUs, such as 1 ton of tires. These studies mainly aim at ELTs or evaluate the new impacts of tires. The mass-based FUs also include others, such as 787.5 ton textile fibers from ELT, 6000 kg waste textile fibers, and 29,140 kg waste tires (see Appendix A for details). There are 15 studies (30%) whose FUs were based on the number of tires, such as one tire, while these studies primarily focus on the whole life cycle of tires or the comparison of different scenarios. Other than the mass-based and number-based FUs, Elkafoury and Negm (2016) adopted the annual consumption of tires in Egypt (17,575,198 tires) as FU. In studying the environmental changes caused by the reuse of waste tires in the transportation infrastructure or the application of NG-WBT on roads, the distance-based FUs are often selected. A few studies (7 studies, 14%) adopted the distance-based FUs. Noticeably, there is no consensus on the distance length due to the subjectivity in selection. In addition, the distance-based FUs include not only the distance length, but also other variables, such as thickness, total width, service life, and the number of lanes of pavement. Finally, a few studies on the recycling of ELT used the other FUs that is hardly categorized. For example, Malijonyte et al. (2016) adopted 1 GJ of fuel input to incinerator as the FU, while Djadouni et al. (2019) used a retaining wall of 30.4 m*3.3 m as the FU.

Although most studies used the mass-based or number-based FUs, it is necessary to consider quality, service, and the functions of tires in the

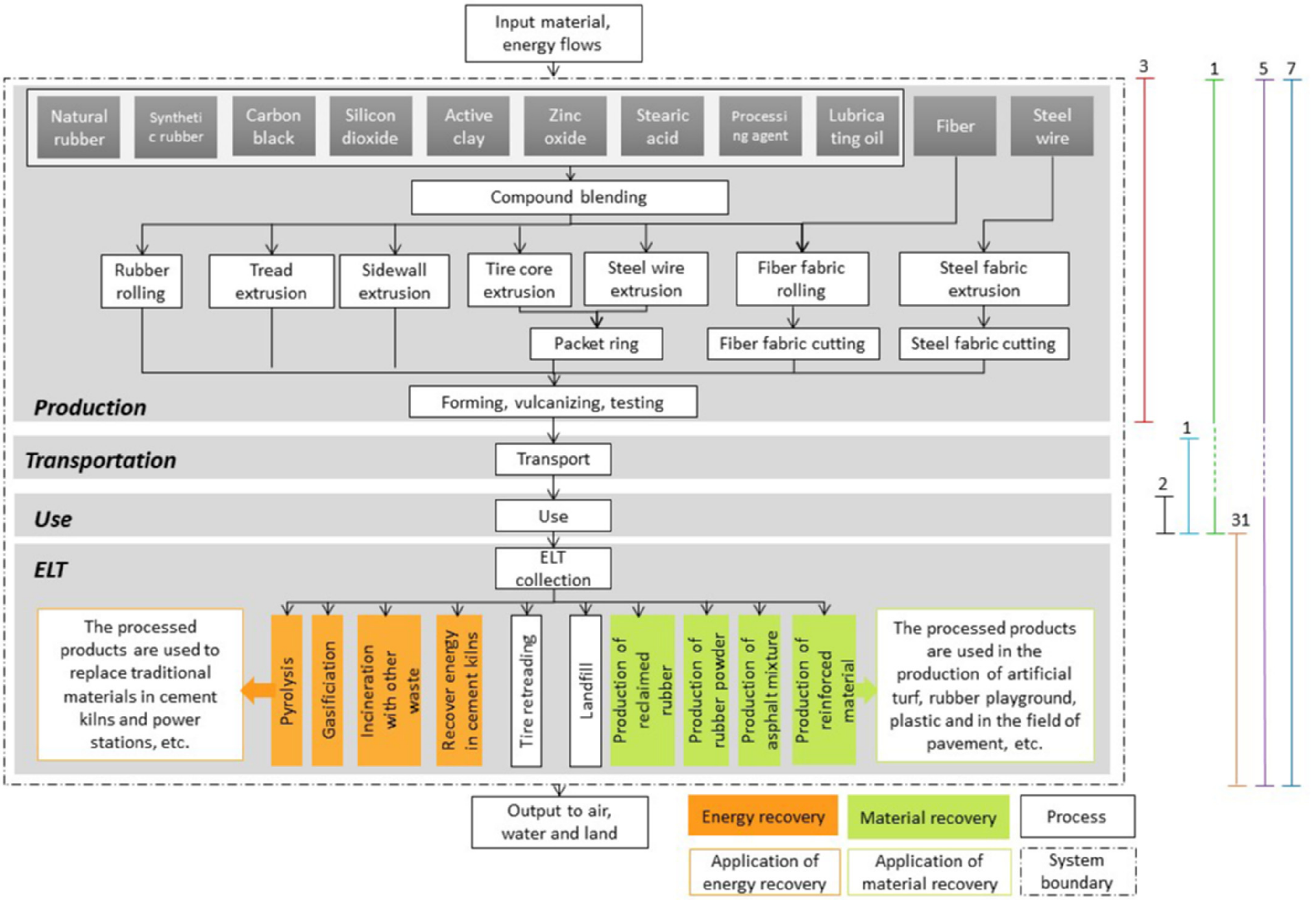


Fig. 4. System boundaries of tire LCA studies.
(On the right side, the life cycle stages covered are presented in colored lines, with the corresponding numbers of studies also shown).

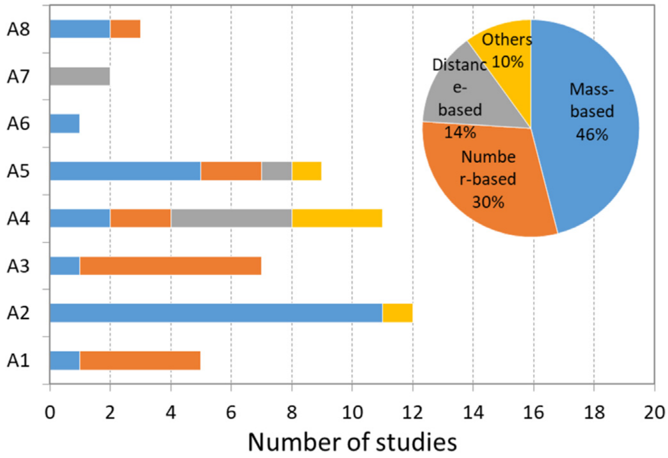


Fig. 5. Classification of FUs in literature. The pie chart shows the distribution of FUs; the bar chart shows the numbers of studies corresponding to the eight categories of study aims.

LCA evaluation. A comparison purely using a mass- or number-based FU without considering these factors can lead to biased interpretation (Sahoo et al., 2019). On the other hand, the lack of consensus on the choice of FUs introduces problems for comparing the LCA results (Deviatkin et al., 2019), which will ultimately hinder the application of LCA in tire industry.

3.2. Life cycle inventory (LCI)

3.2.1. Process-based or IO-based LCA

There are three types of LCAs regarding the source of life cycle inventory, namely the process-based LCA (P-LCA), input-output based LCA (IO-LCA) and hybrid LCA (H-LCA). As a bottom-up method, P-LCA is capable of recording the direct impacts with details all through the life cycle stages of a product, while the downside of P-LCA is the inevitable truncation error caused by the subjective determination in system boundary (Ma et al., 2018; Yang et al., 2017). In contrast, IO-LCA is a top-down method that can provide more complete analyses. However, the aggregation error can be introduced since it is difficult to conduct detailed analyses on a specific product (Chen et al., 2020; Liu, 2018). The hybrid H-LCA combines the advantages of the two methods (Feng, 2017). There are several sub-branches of H-LCA regarding the level of integration of the two methods, such as a H-LCA based on the P-LCA structure with the substitution of IO-LCA data and vice versa.

In the reviewed articles, P-LCA is the mainstream method, which has been adopted in 47 articles. The other three studies applied a H-LCA for urban industrial symbiosis analysis on tire recycling (Dong et al., 2017), IO-LCA for urban agglomeration of centralized tire recycling (Qu et al., 2013), and IO-LCA and economic evaluation of truck tires (Beukering and Janssen, 2000), respectively. Apparently, the existing studies focused on LCA in the tire industry at the micro (product) level rather than the macro (a sector or an entire economic system) level. This probably is partially due to a lack of input-output data of the tire industry and partially to the major target being product-level improvements of tires.

3.2.2. *Data source and modeling tools*

LCI includes two types of data: (i) primary data, directly acquired from the laboratory, company or a site visit, and (ii) secondary data, collected from literature and databases (Edelen et al., 2018; Hafez et al., 2019; Muteri et al., 2020; Paredes et al., 2019). Among the reviewed studies, Ecoinvent database is the most adopted due to its standardization, transparency and completeness (Saade et al., 2020). The choice of database is also related to the geographical area. For example, CLCD (IKE, 2012) is often used in studies based in China (Sun et al., 2017). It should be noted that the adoption of secondary data may undermine the accuracy of results (Dong et al., 2015b) and the using of secondary data from a database or other sources should be clearly reported.

Amongst the modeling tools, SimaPro and GaBi are the mostly applied in the reviewed studies. Other modeling tools, such as Athena and LCA-Date Manager are selected in some studies to fulfill their research needs (Ortiz-Rodriguez et al., 2017). In addition, a few studies do not apply (or not mention) a specific LCA modeling tool (Bras and Cobert, 2011).

3.2.3. *Allocation*

It is necessary to make decisions on the distribution of material and energy flows between by-products, whenever a production process generates more than one product (by-products) (Bailey et al., 2020; Maga et al., 2019; Saade et al., 2020). According to ISO standards, the allocation should be avoided by expanding the system boundary to encompass processes related to by-products (ISO, 2006b). Nevertheless, in situations where an allocation is not avoidable, the allocation should be based on relations between by-products (Hossain et al., 2018). The existing allocation methods are usually based on mass or cost. In general, the mass allocation is preferred over the cost allocation, since the cost of a product is fluctuating according to market (Muench and Guenther, 2013).

Of the 50 reviewed studies, 18 studies clearly stated the allocation methods, whereas the other 32 studies did not provide any information on allocation. Three studies (Fiksel et al., 2011; Simões et al., 2013; Sun et al., 2017) applied purely mass-based allocation methods, while one used a cost-based method (Beukering and Janssen, 2000). Most of the studies conducted system expansion trying to avoid allocation (Banar, 2015; Eranki and Landis, 2019). In some cases, system expansion is used together with a mass- or cost-based allocation. For instance, Marconi et al. (2018) used a mass allocation method to quantify the impacts of the reuse of tire textile fiber and allocate 70% impacts to clean fiber and 30% to rubber power, and also employed system expansion to avoid the allocation of polypropylene production impact. Lonca et al. (2018) adopted economic allocation to quantify trade-offs between resource and environment, as well as system expansion for circular economy solutions. Several studies define a cut-off criterion and expand the system to meet the criterion so as to avoid allocation (Landi et al., 2018b). There is one study which declared that no allocation is needed (Piotrowska et al., 2019).

3.2.4. *Inputs and outputs*

Inventory analysis is the stage where inputs and outputs are compiled and quantified throughout the life cycle of a product or service (Dong et al., 2015a; Heidari et al., 2019; Mayer et al., 2019). Different sources of inventory can lead to inconsistent results even for the same product, which ultimately weaken the comparability of studies (Jiang and Wu, 2019; Moni et al., 2020). In tire LCA, two types of inventory analyses can be found: (i) input analysis for the original tire production, and (ii) input and output analyses for the treatment methods of waste tires. Table 2 lists the inventory for the first type with a FU of passenger car tire (referring to Fig. 5, most articles selected a tire as FU when evaluating the whole life cycle of tire). The results are also shown in per tonne for the comparison purpose. It is found that the input data among the studies though different are in general comparable, and the differences are mainly caused by various tire models and regional diversity.

Table 3 gives the input and output data for the disposal methods of ELT, with the FU of 1 tonne of tires (referring to Fig. 5, mass-based FU is the mostly adopted for ELT studies). For most of the listed data, the range of discrepancy is not significant, while steel crap in ambient pulverization process and electricity in pyrolysis are two exceptions. The large difference in steel crap data is mainly caused by the different content of steel fiber in various types of tires. The electricity consumption in pyrolysis is related to the crushing of waste tires, as the smaller the tire size, the greater the electricity consumed.

Table 2
Input data for producing a passenger car tire and 1 tonne (t) of tires.

Materials and energy	Amount (per tire)	Amount[a] (per t)	Unit	Data sources
Synthetic rubber	1.928–2.471	192.8–260.1	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019; Sun et al., 2016)
Natural rubber	1.456–1.859	145.6–195.7	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019; Sun et al., 2016)
Carbon black	1.496–2.515	149.6–340.0	kg	(Bras and Cobert, 2011; Korínek et al., 2012; Krömer et al., 1999; Piotrowska et al., 2019; Sun et al., 2016)
Silica	0.768–0.965	8.1–96.5	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019; Sun et al., 2016)
Sulfur	0.096–0.128	9.6–12.8	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019)
Zinc Oxide	0.128–0.210	12.8–15.8	kg	(Bras and Cobert, 2011; Krömer et al., 1999; Piotrowska et al., 2019)
Oil	0.472–0.612	47.2–61.2	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019)
Stearic acid	0.080–0.096	8.0–9.6	kg	(Bras and Cobert, 2011; Piotrowska et al., 2019)
Steel fiber	0.600–1.140	88.8–114.0	kg	(Bras and Cobert, 2011; Korínek et al., 2012; Piotrowska et al., 2019; Sun et al., 2016)
Textile	0.360–0.470	36.8–60.0	kg	(Bras and Cobert, 2011; Korínek et al., 2012; Piotrowska et al., 2019; Sun et al., 2016)
Electricity	34.85–37.34	1018.9–1019.2	kWh	(Sun et al., 2016; Sun et al., 2017)
Water	23.52–36.11	2476.3–3611.2	kg	(Piotrowska et al., 2019; Sun et al., 2016, 2017)
Steam	17.24–18.47	1815.1–1815.3	kg	(Sun et al., 2016, 2017)

[a] Amount of per tonne of tires is calculated from the amount per tire based on the weight of a car tire in the literature.

By comparing Tables 2 and 3, it is found that the electricity to produce one tonne of virgin tires is 1019 kWh, while the electricity consumption to for waste tire treatment is only 770.5–800 kWh, indicating the energy consumption can be significantly reduced by using recycled tires. In addition, by recycling waste tires, the by-products such as steel wine, fiber and iron scrap can be generated. If the environmental impacts are allocated to the by-products (according to their weights or economic values), the energy consumption of recycled tires can be considerably reduced.

3.3. *Life cycle impact assessment (LCIA)*

3.3.1. *LCIA methods*

LCIA is the third stage of LCA which evaluates the LCI results in environmental impact categories that can be easily interpreted (Dong and Ng, 2014; Mirabella et al., 2019). There are two approaches in LCIA, namely the midpoint (problem-oriented) and the endpoint (damage-oriented) approach (Abd Rashid and Yusoff, 2015; Chen et al., 2019). The midpoint approach assesses the environmental impacts at the emission level (e.g., emissions of carbon dioxide and sulfur dioxide), while the endpoint provides damage evaluations on the areas of protection (e.g.,

Table 3
Input and output of different treatment methods for 1 tonne (t) of waste tires.

Treatment methods	Input	Amount	Unit	Output	Amount	Unit	Data sources
Recycling of reclaimed rubber	ELT	1	t	Reclaimed rubber	670	kg	(Li et al., 2010; Sun et al., 2016, 2017)
	Electricity	770.5–800	kWh	Waste steel wine	700	kg	
	Water	7100	kg	Waste fiber	100	kg	
	Diesel	0.01	t				
Ambient pulverization process	ELT	1	t	Rubber granules	680–690	kg	(Corti and Lombardi, 2004; Feraldi et al., 2013; Li et al., 2010; Uson et al., 2012)
	Electricity	308–390	kWh	Steel scrap	160–275.5	kg	
	Steel knives	0.44–0.60	kg	Fiber/rubber residual	140	kg	
	Water	150	kg	Textile fibers	43.47–43.5	kg	
Cryogenic pulverization process	ELT	1	t	Pulverized tires	675	kg	Corti and Lombardi (2004)
	Electricity	50	kWh	Iron scrap	265	kg	
	Nitrogen	703	kg	Textile fibers	60	kg	
	Natural gas	1.55	m^3				
Pyrolysis	ELT	1	t	Carbon black	315	kg	(Banar, 2015; Li et al., 2010; Neri et al., 2018)
	Electricity	71–200	kWh	Oil	257	kg	
				Steel	130	kg	
Waste-to-energy	ELT	1	t	Electricity	132.2	kWh	
	Electricity	0.114	kWh	Iron scrap	220	kg	
	Sodium bicarbonate	120	kg				

Note: one data in “Amount” indicates that only one of the reviewed articles involves the input/output or two or more articles provide the data; while the data range in “Amount” indicates that two or more articles provide the data.

human health and ecosystem) (Dong and Ng, 2014). In the reviewed articles, 33 studies adopted the midpoint approaches, whereas only 6 chose the endpoint approaches. 10 studies used both the midpoint and endpoint approaches and 1 study did not indicate the adopted LCIA method.

Fig. 6 presents an analysis of LCIA methods employed in the selected studies. CML, ReCiPe and EI-99 (Eco-indicator 99) are the top three LCIA methods in the LCA study of tires. Six studies used more than one LCIA method, in particular when midpoint and endpoint impacts are both assessed. For example, Georgiopoulou and Lyberatos (2018) investigated waste tires and other wastes as alternative fuels in clinker kiln and evaluated 10 midpoint impact categories by CML and 11 endpoint damage categories by EI-99. Piotrowska et al. (2019) studied the whole life cycle of a car tire, by applying EI-99 (endpoint) to evaluate 11 impact categories and 3 damage categories, as well as CED for energy consumption and IPCC for carbon emissions. Several studies did not adopt an established LCIA method but calculated LCIA results based on self-developed models (Curry et al., 2011). There are some special cases as in Qu et al. (2013) which did not convert LCI results to LCIA results. This is not only due to the adoption of IO-LCA but also because of the main interests being carbon emissions and energy consumption (as the two categories are not difficult to be interpreted based on LCI results). In addition, there are a few studies that did not clearly specify a LCIA method used. This may downgrade the repeatability and reliability of these studies (Buratti et al., 2018).

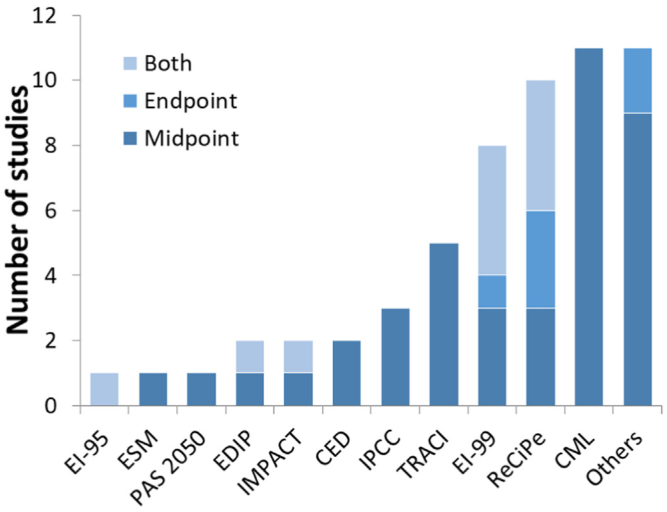


Fig. 6. LCIA methods of the selected studies.
(ESM - Ecological Scarcity Method; the studies with “Both” are repeatedly assigned “Midpoint” or “Endpoint”).

3.3.2. *Impact categories*

Fig. 7 shows the frequency of impact categories that were assessed in the selected studies. It is found that the most evaluated impact category in the LCA study of tires is climate change (or global warming), and there are 41 studies that evaluated impacts on this category. Some studies (Curry et al., 2011; Lin et al., 2017) were carried out only on the category of climate change. The popularity of this category is not only for the LCA of tires but also for the entire LCA community. Ozone depletion, acidification and eutrophication are the impact categories that were studied in more than 20 research articles, respectively. On the other hand, the impact categories of water pollutants, noise impact and radioactive substances are of less attention. This is mainly due to these categories overlapping with other categories which are more often studied (i.e., water pollutants vs freshwater eutrophication).

Since different LCA modeling tools were applied, some impact categories are found to be inconsistent among the studies, e.g., energy consumption versus fossil resource depletion. The studies that evaluate energy consumption may not evaluate fossil resource depletion (Feraldi et al., 2013) or vice versa (Marconi et al., 2018). The selection of impact categories is usually artificial or even subjective in the LCAs of tires, without giving a scientific basis. Furthermore, the occupation of land due to the stacking of waste tires has not been investigated, whereas this issue is severe in some regions and requires further attention.

3.3.3. *LCIA results*

3.3.3.1. Impacts of life cycle stages. Among the four life cycle stages, the impacts from the use stage are the largest (Eranki and Landis, 2019; Piotrowska et al., 2019), as the use stage consumes considerable amounts of fuel, mainly attributed to the rolling resistance (Pré Consultants, 2001). Table 4 presents the carbon emissions of a car tire, as well as the specifications on life distance, rolling resistance and fuel consumption. It is found that the carbon emissions generally increase with the distance and the rolling resistance. Large carbon emissions in Piotrowska et al. (2019) are due to the calculation method in which all the fuel

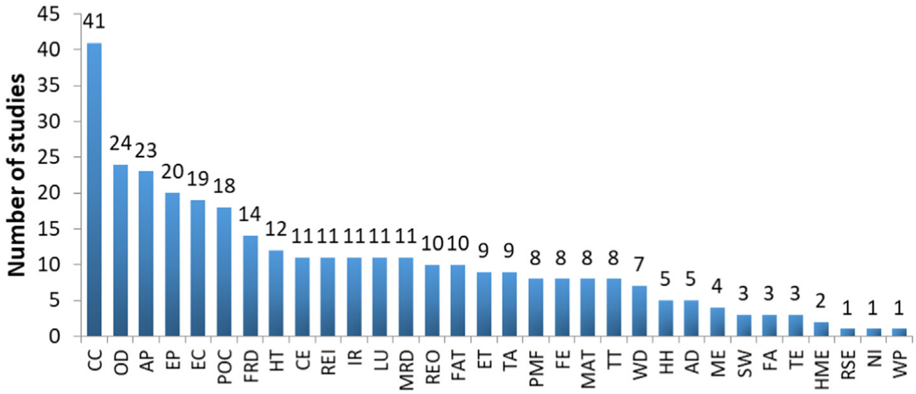


Fig. 7. Frequency of impact categories in the selected studies.
(see Appendix A for the full names of impact categories)

Table 4
Carbon emissions of a car tire in the life cycle stages.

Authors (year)	Tire type	Life distance (km)	Results (kg CO_2 eq)	Rolling resistance coefficient (kg/ton)	Tire fuel consumption (L/100 km)
Krömer et al. (1999)	P175/ 70R 13	50,000	6.2E+02	–	–
Bras and Cobert (2011)	P205/ 45R 17	67,620	5.5E+02	6	0.60
Sun et al. (2016)	P205/ 55R 16	60,000	6.9E+02	–	0.39
Sun et al. (2017)	P205/ 55R 16	60,000	8.4E+02	9.6	0.49
Sun et al. (2017)	P205/ 55R 16	60,000	7.2E+02	8.1	0.41
Piotrowska et al. (2019)	P205/ 55R 16	50,000	2.6E+06	–	1.5
Eranki and Landis (2019)	Guayule rubber tire	136,000	5.6E+02	10.2–10.9	–

Note: '-': not available.

consumption is assigned to the four tires without considering the fuel consumption for other vehicle parts. On the other hand, the low emissions are due to the allocating fuel consumption to the vehicle. For example, Sun et al. (2016) allocated 78% of fuel consumption to the vehicle and only 22% fuel consumption was attributed to tires. Consequently, the fuel consumption in Piotrowska et al. (2019) (1.5L/100 km) is nearly four times larger than in Sun et al. (2016) (0.39L/100 km). Therefore, the LCA results can be significantly affected by the allocation methods. The inconsistencies in LCA calculation and data processing, such as allocation methods, may result in considerable discrepancies in the LCA results.

The environmental impacts of a passenger car tire over the four life cycle stages are provided in Table 5. Both the midpoint and endpoint results are presented for the first five impact categories in Fig. 7, as well as the endpoint single score (in Point, Pt). Ferrão et al. (2008) reported that the use stage of tires accounts for 87% of the total impacts, while the production stage is responsible for 12%. The tire debris and other end-of-life processes (without considering the benefits of ELT recovery) contribute to 0.69%. The least contributing stage is the transportation, which only accounts for 0.22%. The relatively small and negligible impacts of the transportation is the reason why many studies ignored this stage (Piotrowska et al., 2019; Sun et al., 2016).

In terms of individual impact categories, the use stage contributes greatly to climate change, acidification, photochemical oxidation and eutrophication, while the raw material acquisition has considerable impact on human toxicity since more benzene and PAH are released (Pré Consultants, 2001; Sun et al., 2016). The production processes of tires are also reported to have significant impacts on respiratory inorganics, global warming and depletion of natural resources (Shanbag and Manjare, 2020). In the production stage, acidification and energy consumption have negative emissions, due to the use of bagasse as a co-product in energy generation, which can reduce 10% of energy consumption (Eranki and Landis, 2019). However, as the emissions of other categories are greater than the off-set of adoption of bagasse, the impacts of climate

Table 5
Environmental impacts of a passenger car tire.

Impact category	Production	Transportation	Use	End-of-life	Total	Unit	Data source
Climate change	0.28	0	2.4	−0.083	2.6	Pt	Bras and Cobert (2011)
	13.17–44.8	1.5–2.5	532–800	−4.2–0.5	564–843.5	kg CO_2 eq	(Eranki and Landis, 2019; Krömer et al., 1999; Sun et al., 2016, 2017)
Acidification	0.17	0	2.1	−0.063	2.2	Pt	Bras and Cobert (2011)
	−0.019–0.27	0.012–0.031	0.54–3.13	−0.0039–0.037	2.1–3.4	kg SO_2 eq	(Eranki and Landis, 2019; Krömer et al., 1999; Sun et al., 2016, 2017)
Eutrophication	0.17	0	2.1	−0.063	2.2	Pt	Bras and Cobert (2011)
	0.0047–0.031	0.0021	0.06–0.46	−0.0084–0.0080	0.39–0.48	kg PO_4^{3-} eq	(Krömer et al., 1999; Sun et al., 2016, 2017)
Ozone depletion	0.001	0	0	0	0.001	Pt	Bras and Cobert (2011)
	5.6E-06—6.9E-06	1.8E-07—1.9E-07	3.1E-04—3.3E-04	0	3.1E-04—3.3E-04	kg CFC-11 eq	Eranki and Landis (2019)
Energy consumption	2.5	0.001	19	−1.2	20.3	Pt	Bras and Cobert (2011)
	−0.5–1.2	0.016	7.5–15.5	−1.51–0.26	13.7–16.4	GJ	(Eranki and Landis, 2019; Krömer et al., 1999)
Single score	4.96–5.5	0.002–0.1	35.3–40	−0.95–0.32	39.6–46.0	Pt	(Bras and Cobert, 2011; Ferrão et al., 2008)

Note: Results of climate change, acidification, energy consumption, and ozone depletion of Eranki and Landis (2019) are estimated from graphs.

change, eutrophication and ozone depletion are positive.

3.3.3.2. Comparison of old and new tire models. Previous studies have attempted to investigate the improvement of environmental impacts of the new tire models by replacing some ingredients in tire formula (La Rosa et al., 2015). Table 6 lists the LCIA results of the old and new models of tires, for climate change and ecosystems. Significant improvements can be observed in most of studies. For example, Eranki and Landis (2019) replaced natural rubber and synthetic rubber with guayule, and observed 12% reduction in carbon emissions. One exception is in Krömer et al. (1999), which replaced rayon with polyester and the impact of the new model is slightly higher than the old model, since the use of polyester increases carbon emissions during raw material acquisition. Using 4% of recycled waste tires in the mixture with virgin rubber in manufacturing truck tires can reduce the impacts on ecosystem by 4.60%. If the recycled content increases to 10%, the reduction of impacts on ecosystem can be up to 4.65% (Lonca et al., 2018).

In most of the reviewed studies, new designs do not influence the life distance of tires. However, there are two exceptions. Eranki and Landis (2019) found that the life distance can be increased in the new design using guayule (from 70-80 thousand miles to 80–90 thousand miles). Lonca et al. (2018) reported that 4% of recycled waste rubber in tires has no impact on the life distance. However, when the recycled content increases to 10%, the life distance is reduced to 93% of the virgin tires. It should be noted that, when the LCA functional unit is distance, the changes of the life distance of new designs can also determine the environmental impacts. For example, if we compare the emissions caused by tire from a perspective of 1 km distance, then the results can be significantly changed. In general, it is strongly recommended to adopt recycled materials in the tire production, to have a significant improvement of the environmental performance of tire manufacturing.

3.3.3.3. Tire recovery methods. The excellent properties of tires, such as high heat value, resistance to mildew, heat, moisture, acids and other chemicals, make them a valuable resource (Torretta et al., 2015). Material recovery of tires can generate mainly four outputs, i.e., rubber, steel, textile fibers, and carbon black. Rubbers can be reused in a variety of applications, such as lightweight fillers (Djadouni et al., 2019), asphalt production (Ortiz-Rodriguez et al., 2017), road pavements (Farina et al., 2017), manufacturing of new tires (La Rosa et al., 2015), artificial turf and molded objects(Clauzade et al., 2010). Recycled steel can be used as a secondary material to replace anthracite and coke (Landi et al., 2016), as well as in concrete pavement and asphalt pavement (Achilleos et al., 2011; Landi et al., 2020). Tires textile fibers can be applied as additive of plastic compounds (Marconi et al., 2018) or bituminous conglomerates (Landi et al., 2018a). Carbon black is a substitute to the origin carbon black in the tire manufacturing (La Rosa et al., 2019). The energy recovery methods include the incineration in clinker kiln for cement production and the incineration at power plant to generate electricity (Krömer et al., 1999).

Fig. 8 gives the LCIA results of climate change and energy consumption for the two recovery methods of tires. The carbon emissions of material recovery range from −3217 kg CO_2 eq to 667 kg CO_2 eq per tonne of tires. The former is due to the reuse of rubber in synthetic turf, which avoids the production of raw materials (Clauzade et al., 2010). The latter is caused by the grinding process of asphalt production (Ortiz-Rodriguez et al., 2017). The carbon emissions of energy recovery range from −1466 kg CO_2 eq to −500 kg CO_2 eq. The average reduction of carbon emissions is 901 kg CO_2 eq for material recovery, and 748 kg CO_2 eq for energy recovery, indicating that material recovery performs better than energy recovery for the purpose of carbon reduction.

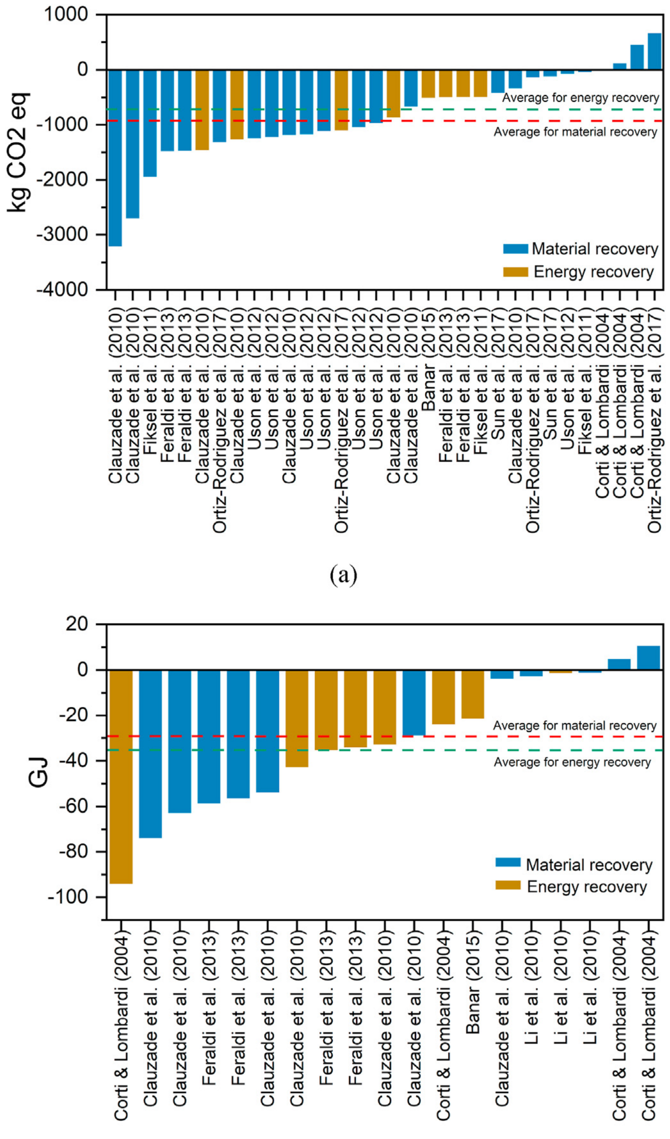
In terms of energy consumption, the best performance is found to be −94 GJ, which is from a waste-to-energy method. The worst case of energy consumption is 11 GJ, by a material recover method of cryogenic pulverization based treatment (Corti and Lombardi, 2004). It is understandable that energy recovery has better performance than material recovery for the purpose of energy reduction. The average energy reduced by material recovery methods is 29.8 GJ, which is less than 35.9 GJ for energy recovery methods.

Table 6

Comparison of the old and new models of tires in terms of LCIA results.

Authors (year)	Object	Description of improvement in new models	Life distance (km)	Impact category	Results (old/new)	Unit	System boundary
Saur et al. (1997)	A passenger tires	Silicon dioxide is added to replace carbon black as filler	40,000	GWP	2340/ 2,302#	kg CO_2 eq	Production and use stages
Krömer et al. (1999)	A passenger tire	Substituting silica for part of carbon black as filler	50,000	GWP	623.25/ 564.15	kg CO_2 eq	Whole life cycle except ELT stage
Krömer et al. (1999)	A passenger tire	Substituting polyester for rayon as textile fabric	50,000	GWP	623.25/ 625.17	kg CO_2 eq	Whole life cycle except ELT stage
Bras and Cobert (2011)	A passenger tire	The new model is an airless one-piece wheel-and-tire combination with a rubber tread bonded to a wheel hub with polyurethane spokes	67,620	GWP	533.1/ 520.4	Pt	Whole life cycle
La Rosa et al. (2015)	A tire	Using recycled waste tires in mixture with virgin rubber (75% rate)	–	GWP	3384.4/ 846	kg CO_2 eq	Production stage
Sun et al. (2017)	A passenger tire	Silicon dioxide is added to replace part of the carbon black as filler	60,000	GWP	843/713	kg CO_2 eq	Whole life cycle
Lin et al. (2017)	An electric bicycle tire	Replacing carbon black with graphene (100% rate)	–	GWP	4.56/3.49	kg CO_2 eq	Production stage
Eranki and Landis (2019)	A passenger tire	Replacing natural rubber and synthetic rubber with guayule (100% rate)	112,654–128,748/ 128,748–144,841	GWP	641/564	kg CO_2 eq	Whole life cycle
Lonca et al. (2018)	A truck tire	4% recycled content 10% recycled content	125,000–245,000 116,250–227,850	Ecosystems	−4.60* −4.65*	% %	Whole life cycle except transportation stage

Note: *estimated from a graph, the impact of alternative schemes is reduced by 4.6% (4% recycled content) and by 4.65% (10% recycled content) as compared with old model; # the fuel consumption in the use stage of the study is the fuel consumption of the whole vehicle.



(a)

(b)

Fig. 8. LCIA results of material and energy recoveries of one tonne of ELT for (a) climate change and (b) energy consumption. (Data from Fiksel et al. (2011) and Li et al. (2010) are estimated from graphs.).

3.4. *Interpretation*

3.4.1. *Sensitivity analysis and uncertainty analysis*

The sensitivity analysis is to assess to what extent the final results might be changed by adjusting certain setups in LCA models, e.g., input data and LCIA methods (Jiang and Wu, 2019; Xu et al., 2019). Unfortunately, in the reviewed literature, only 19 studies conducted sensitivity analyses. Clauzade et al. (2010) examined the variations of the environmental impacts caused by using feedstock energy and replacing the energy mix in heating and granulation processes. For the application of ELT in pavement, Farina et al. (2014) studied the environmental impacts caused by changing the thickness of pavement wearing course and the maintenance frequency. Eranki and Landis (2019) conducted sensitivity analyses by changing the model parameters, such as rolling resistance coefficient, vehicle efficiency, and the relevant tire load. Corti and Lombardi (2004) employed sensitivity analyses in examining the effects of changing weighting factors.

Uncertainty analysis is recommended since the truncation errors can downgrade the reliability of LCA (Iqbal et al., 2020). However, only 5 of the reviewed articles carried out uncertainty analysis (Eranki and Landis, 2019; Feraldi et al., 2013; Fiksel et al., 2011; Meyer et al., 2017; Piotrowska et al., 2019), among which Eranki and Landis (2019) conducted uncertainty analyses of the input parameters based on the Monte Carlo method using @Risk, a statistical add-in in Excel. Triangular distributions were generated through 50,000 simulations. The uncertainty analyses indicated that the average uncertainty of the results of guayule rubber tire is 18–25% in positive error and 10–15% in negative error, while the uncertainty of the conventional tire is 14–19% in positive error and 13–18% in negative error. Piotrowska et al. (2019) carried out uncertainty analyses for all the inventory using SimaPro and the analyses generated 1000 LCIA results. The uncertainty analyses derived a probability of 95.5% that the eco-index of the car tire ranges from 111 to 209 Pt. Meyer et al. (2017) conducted uncertainty analyses with 100,000 iterations based on Monto Carlo methods in two approaches: Franco and Cucurachi. They found that the Franco approach is time-consuming as it needs numerous data for the considered situation, while the Cucurachi approach can lead to a quick and systematic integration of noise damage in LCA, which was difficult to understand and improve.

3.4.2. *Summarized findings of the reviewed articles*

In Table 7, the findings of the previous studies are summarized in accordance with the eight study aims in Table 1. In the whole life cycle of tire, the most influential stage is the use stage, due to the fuel consumption. ELT is a hot research area and both material and energy recovery methods can lead to environmental benefits. As compared to the traditional designs, the new designs of tires normally decrease the environmental burdens. One exception is the substitution of rayon by polyesters. The substitution can decrease impact in acidification but increase carbon emissions (Krömer et al., 1999).

Waste tires are widely adopted as secondary materials in various applications and this can significantly improve the environmental performance. However, the dry technology (replacing aggregates with rubber) for bituminous mixtures does not have significant improvement on environmental performance, whereas the wet technology (rubber as modifying agent) benefits environment (Farina et al., 2017). Cost evaluation is recommended in the sustainable assessment, in case that the feasibility of an environmental-friendly method is hampered by an unbearable burden of economic cost. Two treatment methods for ELT, i.e., reclaiming rubber production process and the gasification of tires, have greater environmental impacts. NG-WBT has positive impacts on both environmental and economic aspects.

4. Limitations and recommendations

The reviewed studies were mainly carried out in Europe, Asia and North America. In contrast, fewer studies can be found in South America, Africa and Oceania. Although the production of tires is mainly in Asia, Europe and North America, other regions also use tires in vehicles extensively. Thus, the lack of LCA studies in South America, Africa and Oceania may hinder the understanding of the life cycle impacts of tires in these places.

The reviewed studies cover eight research aims (referring to Table 1). It is found that ELT is the most studied topic, whereas relative fewer studies deal with the whole life cycle. This caused a problem of insufficient data to compare the inputs and outputs of LCA for tires, in particular for ELTs. More case studies are needed to provide the whole life cycle analysis to the different types of tires, which eventually leads to a benchmark system for evaluate the environmental impacts of tires.

Among the four life cycle stages of tires, the use stage accounts for most carbon emissions. In this regard, fuel efficiency improvement in the use stage, in particular, reducing the rolling resistance is of major concern in emission reduction. The transportation stage is relatively less important as compared to the other three stages. Consequently, a number of studies ignored the impacts from the transportation stage. However, a scientific basis is required for the decision on whether or not to include

Table 7
Summary of findings of reviewed articles.

Study aim	Findings
A1: Whole life cycle of tires	• Use stage is the most significant contributor to environmental impacts, since fuels are consumed to offset rolling resistance. • Fuel consumption in use stage has tremendous impacts to climate change, acidification and eutrophication. • Production stage contributes significantly to resource consumption. • Environmental impacts of the transportation stage are negligible.
A2: ELT	• Most recovery methods of ELT have positive environmental impacts. • Material recovery generally performs better than energy recovery for carbon reduction. • Energy recovery generally performs better than material recover for energy reduction. • Pyrolysis is an eco-effective ELT treatment technology.
A3: Comparison of designs	• New designs can in general decrease the environmental burdens in the life cycle of tires. • New designs mainly include: o replacing natural rubber or synthetic rubber with guayule; o shear bank design in Tweel by Michelin; o replacing carbon black with silica dioxide or graphene; o replacing rayon with polyester.
A4: Secondary materials	• Adoption of waste tires as secondary materials can improve environmental performance, and the applications include: o scrap tires used as fuel in clinker kiln; o waste tires used in the construction of retaining structures; o polypropylene and crumb rubber from ELT to replace aluminum in structural components; o crumb rubber, steel fiber and textile fiber used in asphalt and concrete pavement.
A5: New impacts	• Transport noise caused by a tire can be the most important among the different impacts on human health. • Tires used as drainage blanket to replace aggregates in landfill can bring environmental benefits but lead to higher economic cost. • Silica can cost more than carbon black as filler in the production stage, but less in the use stage. • It is economically feasible to use recycled waste tires as alternatives in pavements.
A6: Treatment processes	• Devulcanization stage consumed large amount of fuel has the most environmental impact during the production of reclaimed rubber. • The production process of reclaimed rubber has large impact on respiratory system and can lead to great damage to human health. • Gasification of shredded tires is not recommended as it can lead to severe environmental impacts and high costs.
A7: NG-WBT	• Compared with traditional dual tire assemblies, NG-WBT on pavement can benefit both environmental and economic aspects. • The environmental benefits of NG-WBT increase with the market penetration of NG-WBT at low traffic volume. • The thick asphalt pavement overlay at higher NG-WBT market penetration has more benefits of economy and environment.
A8: Others	• Rubber is the raw material that has significant environmental impact in production stage. • The centralized recycling of waste tires in urban agglomeration and the promotion of urban industrial symbiosis can promote sustainable development. • Road tires have environmental impacts to climate change at midpoint level and human health at endpoint level.

the transportation stage within the system boundary. In the same regards, the completeness of LCA study on tires should be evaluated. If a process or a material is neglected in the LCA modeling, it should be explicitly stated. The truncation errors caused by an incomplete system should be estimated and included in an LCA study of tires.

In the reviewed studies, the inconsistencies in LCA methodology have been observed in many aspects, such as FUs, allocation, system boundary, data input, LCIA methods, etc. Notably, the FUs are not consistent in the LCA studies of tires, which is a main obstacle for comparing between the studies. As the mass- and number-based FUs are more common in tire LCA studies, future studies are recommended to provide results for both mass- and number-based FUs. The allocation is a problem in tire LCA studies, and only a few studies clearly indicated the allocation methods. If the allocation is involved, the specifications of allocation methods and the by-products should be clearly stated. The adoption of secondary data (e.g., database) is almost unavoidable in LCA. The studies acquired data from different databases (e.g., Ecoinvent, CLCD). When secondary data are used, it is necessary to provide more details of the data source and the quality. It is suggested to conduct a sensitivity analysis on the secondary data, so that the variations caused by the secondary data can be detected.

The inconsistencies of LCIA methods in the study of tires have caused difficulties in comparing the LCA results. The reviewed studies investigated impact categories based on diverse characterization and normalization models. For the impact categories related to carbon emissions, some studies selected energy consumption, while others studied fossil fuel depletion. These two categories are closely related but the results cannot be directly compared. The comparison should be made based on a conversion, and the selection of conversion factors is relatively artificial, making the comparison unreliable. Since the focus of the impact was on climate change, the other impact categories were less studied.

The ELT recovery is strongly recommended for its significant environmental benefits. Based on the analyses, it is recommended to conduct material recovery when the carbon emissions are the primary concern and energy recovery when the energy consumption is the major issue. In the sustainability assessments, the cost evaluation of the recovery options of ELT should be conducted. In the life cycle of tires, the adoption of secondary materials can greatly improve the environmental performance. Future research directions include new model designing of tires for low fuel consumption, secondary materials of better performance, and new recovery methods of ELT.

Although sensitivity analysis and uncertainty analysis are two methods that can greatly improve the understanding of LCIA results, only a few studies conducted these analyses. Sensitivity analysis can unveil the influential variables for an impact category, being an effective method to detect the “hot-spots” in the life cycle of tires. Uncertainty analysis can provide details to evaluate the quality of LCA models. The lack of studies with these analyses is one of the drawbacks of the LCA implementation in the tire industry. It is strongly recommended to conduct both sensitivity analysis and uncertainty analysis in the LCA study of tires in the future.

5. Conclusions

This study reviewed 50 tire LCA papers in the literature based on a systematic review approach. It is found that the interest in the LCA study of tires has increased significantly in the last decade. The whole life cycle of tires, ELTs, secondary materials, the comparison of designs, and new impacts are the hot topics of LCA studies on tires. Most studies investigated the end-of-life stage of tires, while overlooked the transport stage due to its seemingly low environmental impacts. The use stage of a tire is the main contributor to environmental impacts. The carbon emissions in the use stage ranged from 550 kg CO_2 eq to 840 kg CO_2 eq per car tire. To improve the environmental performance of tires, the recovery of ELT, adoption of secondary materials, and new tire designs are recommended.

Most studies (47 of the 50 reviewed articles) adopted process-based LCAs and 33 reviewed studies provided midpoint impact assessments. Climate change, ozone depletion, acidification and eutrophication are the most studied impact categories. The LCA modeling tools, CML, ReCiPe and EI-99, were applied with high frequencies. Inconsistencies exist in several aspects, i.e., FUs, LCIA methods, impact categories, etc. Specifications on the allocation methods and the selection criteria for secondary data as well as the data source should be reported. Sensitivity analysis and uncertainty analysis should be conducted to improve the reliability and robustness of LCA on tires.

Declaration of competing interest

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

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Appendix A. Summary of the selected LCA studies on tires

Authors (year)	Research object	Location	Functional unit (FU)	System boundary				Allocation method	LCI source	LCIA method	Modeling software	Impact categories	Citation*
				P	T	U	D						
Saur et al. (1997)	Passenger vehicle tire (P185/70 R13)	Europe	16 tires	Y		Y		N.A.	N.A.	N.A.	N.A.	1,2	2
Krömer et al. (1999)	Passenger vehicle tire (P175/70 R 13)	Europe	A tire	Y	Y	Y	Y	Mass based, energy based and cut-off	Plant, interviews and literature	N.A.	N.A.	1,2,6, 14,22	0
Beukering and Janssen (2000)	Truck tires	Europe	1 tonne of tires	Y	Y	Y	Y	Economy based	literature	N.A.	N.A.	34	30
Pré Consultants (2001)	Passenger vehicle tire (P195/65 R15)	Europe	A tire	Y	Y	Y	Y	N.A.	Plant	N.A.	N.A.	N.A.	9
Corti and Lombardi (2004)	ELT	Italy	1 ton of tires				Y	N.A.	Plant and I-LCA	Eco-indicator 95	N.A.	1,2,4, 6,8,12, 14,19, 20,30, 34	121
Ferrão et al. (2008)	ELT	Portugal	A tire	Y	Y	Y	Y	N.A.	Literature	Eco-indicator 99	N.A.	34	114
Khoo (2009)	Gasification of ELT	Singapore	1 ton of product gas				Y	N.A.	Literature and industry reports	EDIP	GaBi	1,4,6,29	174
Clauzade et al. (2010)	ELT	France	1 tonne of tires				Y	System expansion	Plant, literature and questionnaire	N.A.	NS	1,2,6,12, 14,19,20	38
Li et al. (2010)	ELT	China	1 tonne of waste tires				Y	System expansion		Eco-indicator 99	GaBi	1,6,8, 9,10,13, 14,18	68
Achilleos et al. (2011)	Steel-fibre-reinforced roller-compacted concrete pavement	Cyprus	Construction of 1 km 2-lane pavement with width 7m				Y	N.A.	Plant, literature, government document and database embedded in software	NS	GaBi	2	57
Bras and Cobert (2011)	P205/ 45R17and Tweel tire	America	A tire	Y	Y	Y	Y	N.A.	Literature, industry report, BUWAL250 and Ecoinvent	EDIP and Eco-indicator 99	N.A.	1,6,8, 9,10,11, 12,13,14, 15,16, 17,18,34	40
Curry et al. (2011)	ELT	England	One bale/ A tire/1 tonne of tires				Y	N.A.	Plant, interviews and literature	N.A.	N.A.	1	7
Fiksel et al. (2011)	ELT	North America	1 tonne of waste tires				Y	Mass based	Plant, literature, NREL and SimaPro	TRACI	SimaPro	1,4,6, 7,8,12, 13,14	69
Korínek et al. (2012)	Passenger tire	Czech	A tire	Y	Y	Y$^{\#}$	Y	N.A.	Laboratory , plant and literature	CML	GaBi	1,4,6,11, 12,14,22, 24,25	3
Uson et al. (2012)	ELT	Spain	1 tonne of tires				Y	System expansion	Plant	CML	SimaPro	1	22
Feraldi et al. (2013)	ELT	America	1 tonne of waste tires				Y	N.A.	Plant and literature	IPCC、TRACI	N.A.	1,2,4, 6,9, 10,14, 16,17	55

(continued on next column)

(*continued*)

Authors (year)	Research object	Location	Functional unit (FU)	System boundary				Allocation method	LCI source	LCIA method	Modeling software	Impact categories	Citation*
				P	T	U	D						
Qu et al. (2013)	Material metabolism in an urban agglomeration	China	1 ton of scrap tires				Y	N.A.	Literature, yearbook and industry reports	N.A.	N.A.	20, emissions of several pollutant types	15
Simões et al. (2013)	A frame to function as a support for solar panels	Portugal	A structural frame				Y	mass based	Plant, BUWAL 250, Ecoinvent, USLCI and ELCD	Eco-indicator 99	SimaPro	1,6,8, 9,10,11, 12,13,14, 15,16, 17,18,34	6
Farina et al. (2014)	ELT	Italy	1 m of built pavement				Y	N.A.	Plant, interviews, literature, report and Ecoinvent 2.2	ReCiPe	SimaPro	1,2,3, 4,5,11, 12,15, 17,18, 19,22, 23,24, 25,26, 28,34	16
Li et al. (2014)	Production technology of reclaimed rubber	China	Product 20 000 tons reclaimed rubber				Y	N.A.	Plant and database embedded in software	Eco-indicator 99	SimaPro	1,6,8, 9,10,11, 12,13,14, 15,16, 17,18,34	11
Banar (2015)	ELT	TurKey	1 ton of waste tires				Y	System expansion	Plant, Ecoinvent	CML、Eco-indicator 99	SimaPro	1,6,14, 21,22,23	4
La Rosa et al. (2015)	Tire with new formula	Italy	1 kg of ground tire rubber/a tire	Y				N.A.	Plant and laboratory	CML	SimaPro	1,2,4, 6,12,14, 21,22,23, 24,25	5
Elkafoury and Negm (2016)	All types of tires on the Egyptian road network	Egypt	All tires on the road in 2012		Y	Y		N.A.	Literature, reports and database embedded in software	IMPACT	N.A.	1,4,9, 10,26,27	6
Landi et al. (2016)	fiber acquisition process/waste fibers	Italy	29 140 kg waste tires /6 000 kg fibers				Y	N.A.	Plant and Ecoinvent v3.0	ReCiPe	SimaPro	34	32
Malijonyte et al. (2016)	ELT and other solid waste	Baltic States	1 GJ of fuel input for incineration				Y	N.A.	Plant	N.A.	SimaPro	34	7
Sun et al. (2016)	Passenger vehicle tire	China	A tire	Y		Y	Y	N.A.	Plant, RCEES 2012 and Ecoinvent v3	CML	SimaPro	1,4,6,7,14	10
Dong et al. (2017)	An urban industrial symbiosis system	China	The whole supply chain of scrap tire recycling within one year				Y	N.A.	Plant, questionnaires, yearbook and literature	N.A.	N.A.	1	61
Farina et al. (2017)	Pavement wearing courses	Italy	1 m of built pavement layer				Y	N.A.	Plant, literature, report, interviews and Ecoinvent 2.2	ReCiPe	SimaPro	1,2,3, 4,5,11, 12,15,18, 19,22,23, 24,25,26, 28,34	98
Lin et al. (2017)	Electric bicycle tires	China	A tire	Y				N.A.	Plant	PAS 2050	SimaPro	1	6
Ortiz-Rodriguez et al. (2017)	ELT	Colombia	1 ton of tires				Y	N.A.	Literature and Ecoinvent v2.01	CML	LCA-Date Manager	1,4,6, 12,14,22	9
Sun et al. (2017)	Passenger vehicle tire	China	A tire	Y		Y	Y	Mass based	Plant, CALCD and Ecoinvent v3	CML	SimaPro	1,4,6,7,14	4
Meyer et al. (2017)	Car tire	N.A.	A tire	Y		Y	Y	N.A.	Plant, literature and Ecoinvent v2.2	ReCiPe	N.A.	34	8
		Italy					Y	N.A.		N.A.	SimaPro	1,2	40

(*continued on next column*)

(*continued*)

Authors (year)	Research object	Location	Functional unit (FU)	System boundary				Allocation method	LCI source	LCIA method	Modeling software	Impact categories	Citation*
				P	T	U	D						
Buratti et al. (2018)	Insulating and acoustic panels		1 m^2 of manufactured panel						Plant, literature, estimate models and Ecoinvent				
Landi et al., 2018a	Textile fibers derived from ELT	Italy	787.5 tonnes of fibers				Y	System expansion and cut-off	Plant, interviews, report and Ecoinvent 3.1	CML	SimaPro	1,4,6, 12,14,21, 22,23, 24,25	35
Landi et al., 2018b	Textile fibers derived from ELT	Italy	787.5 tonnes of fibers				Y	System expansion	Plant , literature and database embedded in software	ReCiPe	GaBi	1,3,5, 12,18,26	21
Georgiopoulou and Lyberatos (2018)	ELT	Greece	Production of 1 ton of clinker				Y	N.A.	Literature and database embedded in software	CML and Eco-indicator 99	SimaPro	1,6,8, 9,10,11, 12,13,14, 15,16,17, 18,21,22, 23,24,25	49
Lonca et al. (2018)	Haulage truck tire	Brazilian and Europe	A tire	Y		Y	Y	System expansion and economy based	Plant and Ecoinvent v2.2	ReCiPe	SimaPro	34	53
Marconi et al. (2018)	Textile fibers derived from ELT	Italy	787.5 tonnes of fibers				Y	System expansion and mass based	Plant , literature and professional	ReCiPe	GaBi	1,3,6, 12,18,26	18
Neri et al. (2018)	ELT	Italy	1 ton of tires				Y	NS	Plant and literature	ReCiPe	SimaPro	1,3,16, 17,18, 22,34	8
Eranki and Landis (2019)	Car tire	America	A tire	Y	Y	Y	Y	System expansion	Laboratory , plant, literature and Ecoinvent v3.1	TRACI	NS	1,2,4, 6,7,9, 10,12,13, 14,18	4
Djadouni et al. (2019)	Powder derived from ELT	America	Constructi30. 4 × 3.3m retaining wall				Y	N.A.	Literature, database embedded in software	N.A.	Athena	1,2,4, 5,6, 12,13	7
Gigli et al. (2019)	Textile fibers derived from ELT	Italy	787.5 tonnes of fibers				Y	Cut-off	Plant, literature and Ecoinvent	ReCiPe	GaBi	1,3,5, 12,18,26	32
Kang et al. (2019)	New-generation wide-base tires and pavement	America	Two-mile -two-lane-year			Y*		N.A.	University, protection agency, literature and US-Ecoinvent	TRACI	N.A.	1,2	9
La Rosa et al. (2019)	Thermolysis process	Italy	Recycle 1 kg carbon black				Y	System expansion	Laboratory , plant, literature, industry report and Ecoinvent v3.0	CML	SimaPro	1,4,6, 12,14,21, 22,23, 24,25	1
Piotrowska et al. (2019)	Passenger tire (P205/55/ R16)	Europe	A tire	Y		Y	Y	N.A.	Plant and Ecoinvent v3.2	Eco-indicator 99, IPCC and CED	SimaPro	1,2,6, 8,9,10, 11,12,13, 14,15,16, 17,18,34	16
Puccini et al. (2019)	pavements	Italy	400 m and 464.5 m of pavement of an urban road				Y	Cut-off	Plant, interviews, report, literature and Ecoinvent v3.2	Ecological scarcity method	SimaPro	1,2,3, 8,12,15, 16,17,19, 30,31, 32,33	6
Said et al. (2020)	New-generation wide-base tires and pavement	Canada	Two-lane and one -mile-long flexible pavement			Y*		N.A.	Literature and commercial database	TRACI	N.A.	1,2	2
Heidari and Younesi (2020)	ELT	Iran	Production of 1 g of carbon nanospheres				Y	N.A.	Laboratory , plant and Ecoinvent v3.4	CML	SimaPro	1,2,4,5, 7,8,10, 11,12,15, 16,19,24, 26,27, 28,29	3
		Italy					Y	N.A.			GaBi		10

(*continued on next column*)

(*continued*)

Authors (year)	Research object	Location	Functional unit (FU)	System boundary				Allocation method	LCI source	LCIA method	Modeling software	Impact categories	Citation*
				P	T	U	D						
Landi et al. (2020)	Hot mix asphalt mixtures		1 m^2 of hot mix aspalt mixture for a motorway road						Plant, literature, interviews and database embedded in software	CED, IPCC, ReCiPe		1,2,3, 4,5,11, 12,15,16, 17,18,19, 22,23,24, 25,26, 28,34	
Shanbag and Manjare (2020)	Tire	India	A tire	Y				N.A.	Plant and Ecoinvent	IMPACT	SimaPro	1,2,5, 8,9,10, 11,12,15, 16,17,24, 26,27, 29,34	4

Note: abbreviations: P - production; T - Transportation; U - use; D - disposal; Y - yes; N - no; N.A. - not available; * - only the environmental impact caused by fuel consumption due to rolling resistance is considered; # - only the air pollution caused by tire wear is considered; 1-climate change (CC); 2-energy consumption (EC); 3-particulate matter formation (PMF); 4-photochemical oxidant creation (POC); 5-freshwater eutrophication (FE); 6-acidification potential (AP); 7-human health (HH); 8-carcinogenic effect (CE); 9-respiratory effects organics (REO); 10-respiratory effects inorganics (REI); 11-ironizing radiation (IR); 12-ozone depletion (OD); 13-ecotoxicity (ET); 14-eutrophication (EP); 15-land use (LU); 16-economy (EO); 17-mineral resource depletion (MRD); 18-fossil resource depletion (FRD); 19-water depletion (WD); 20-solid waste (SW); 21-abiotic depletion (AD); 22-human toxicity (HT); 23-marine aquatic toxicity (MAT); 24-freshwater aquatic toxicity (FAT); 25-terrestrial toxicity (TT); 26-terrestrial acidification (TA); 27-freshwater acidification (FA); 28-marine eutrophication (ME); 29-terrestrial eutrophication (TE); 30-heavy metal emissions (HME); 31-radioactive substance emissions (RSE); 32-noise impact (NI); 33-water pollutants (WP); 34-endpoint.

*Citations were searched in Google Scholar, the survey was conducted on March 12, 2021.

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