Life cycle assessment of Chinese radial passenger vehicle tire

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Abstract

Purpose We evaluated and quantified the environmental impact of a radial tire product for passenger vehicles throughout the product's life cycle to identify key stages that contribute to the overall environmental burden and to find ways to reduce these burdens effectively. The study covers all relevant life cycle stages, from the acquisition of raw materials to the production, use, and end of life.

Methods Data collected onsite in 2014 by one of the largest Chinese tire companies were used in the assessment. The evaluation is presented in terms of individual impact category according to the CML model. Five impact categories (i.e., global warming potential (GWP), acidification potential (AP), photochemical oxidant creation potential (POCP), eutrophication potential (EP), and human toxicity potential (HTP)) were considered. The research was conducted in accordance with the ISO 14040/14044 standards.

Results and discussion Fuel (gasoline) consumption represents an important contribution to most impact categories, including the GWP, AP, POCP, and EP, during the use stage. The largest contributor to the HTP category is raw material

acquisition, mainly because of the impact of the production of organic chemicals. In the end-of-life stage, assuming that 100 % of used tires are collected and recycled to produce reclaimed rubber, the GWP, EP, and HTP contributions are negative, whereas those to the AP and POCP are positive. During the raw material acquisition stage, natural rubber, synthetic rubber, carbon black, and organic chemicals represent the largest contribution to the environmental impact categories. During the production stage, the compound blending process is the largest contributor to the AP and POCP, whereas vulcanizing and testing contribute most to the GWP, EP, and HTP.

Conclusions Vehicle fuel consumption and its proportion consumed by the tires during the use stage are key factors that contribute to environmental impact during tire life. Further investigations should be conducted to decrease the impact of these factors and improve the environmental performance of tire products.

Keywords Life cycle assessment · Life cycle perspective · Passenger vehicle · Radial tire product · Use-stage fuel consumption

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1 Introduction

China is the largest producer and seller of motor vehicles worldwide, and this fact has driven tire production and sales in the country. According to data from the China Rubber Industry Association, 562 million tires were produced in China in 2014. Radial tires accounted for 90.92 % of the total (Deng 2015). Among radial tires, the market for radial tires for passenger vehicles has grown rapidly, with 399 million produced in 2014, an increase of 8.1 % from the previous year. In addition, in 2014, the export volume of car tires from China

was 1.88 Mt, which accounted for 33.27 % of the total volume of exported tires (Deng 2015).

Simultaneously, the volume of discarded tires in China has been increasing rapidly; 315 million tires (~12.35 million tons) were introduced to the waste stream in 2014. By 2020, it is estimated that the volume of waste tires in China will be ~20 million tons per year (Cao 2015). It is becoming an urgent environmental and social need to dispose of these waste tires in a timely and safe manner (Li and Xu 2010).

In recent years, the government and the automotive industry have become increasingly interested in the environmental impact of tire products throughout the tire life cycle because of the significant amounts of resources consumed and pollutants emitted throughout this life cycle.

Life cycle assessment (LCA) has been proposed as a means of compiling and evaluating the inputs, outputs, and potential environmental impact of a product system throughout its life cycle (ISO 2006). Several LCA studies have been conducted on tire products. For example, Kořínek et al. (2012) evaluated the life cycle environmental impact of tire products and compared different waste treatment methods. Feraldi et al. (2013) conducted a comparative LCA of the following two kinds of waste tire treatments: material recycling and tire-derived fuel combustion. Li (2013) researched the full life cycle processes of tire production and resource recycling. Li et al. (2014) assessed the environmental impact of ground rubber produced from scrap tires to provide technical advice for cleaner production. Li and Xu (2010) assessed the environmental impact of four kinds of waste tire use methods in China. Xu (2010) identified six types of environmental impacts throughout the life cycle of a radial tire product, considering the raw material acquisition, production, and end-of-life stages but neglecting the use stage.

However, most of these studies focused on the end-of-life disposal of tire products, and few included the entire life cycle from the acquisition of raw materials to the end-of-life stage. Moreover, most LCA studies use foreign life cycle inventory (LCI) databases or secondary LCI databases and literature publications as data sources and therefore cannot represent the life cycle impact of a tire product from a current Chinese passenger vehicle. To address the abovementioned issues, we chose a single radial tire product for passenger vehicles to conduct a cradle-to-grave LCA, and primary on-site investigation data and the Chinese LCI background database were used in the analysis.

2 Goal and scope definition

2.1 Goal and scope

The objective of this study was to assess environmental impacts, analyze major environmental issues, identify key

contributory elements, and seek improvement opportunities throughout the life cycle of a Chinese radial tire product for passenger vehicles.

The functional unit selected for this research was “60,000 km driven using a radial passenger vehicle tire.” The reference flow is “a radial passenger vehicle tire product for use over distances greater than 60,000 km, which weighs 9.497 kg.” The technical information regarding the investigated tire product is shown in Table 1.

2.2 System boundaries

The entire life cycle of the tire product was considered in this LCA to estimate environmental emissions. The system boundaries are shown in Fig. 1. The four stages investigated were the acquisition of raw materials, production, use, and end of life.

The life cycle processes of the transportation from raw materials to the tire production site and the transportation from tire production site to the recycling and waste treatment plant were investigated. For each life cycle process, the raw materials, energy consumption, road transport requirements, and direct emissions were considered.

However, the impacts of the internal transport of products and semi-finished products during the production stage were not calculated because the relevant data are difficult to collect and the relative contribution is small. The tire product distribution stage was also not considered because a suitable model of the transport and delivery to final users is difficult to confirm, and this stage also has little impact on the results. The manufacturing of capital equipment such as on-site structures, machinery, equipment, and other infrastructure were not considered.

2.3 Methods and database

This study was conducted in accordance with the principles of the ISO 14040 series of standards for LCA (ISO 2006). The SimaPro 8 software suite was used as a support tool to establish the LCA model and perform the assessment.

The RCEES 2012 and Ecoinvent 3 databases were used. The former is a local Chinese life cycle inventory database developed by the Research Center for Eco-Environmental Sciences of the Chinese Academy of Sciences based on SimaPro software. It includes more than 1000 units and

Table 1 Technical information of the investigated tire product

Size	205/55R16
Load index	91
Speed rating	V
Weight (kg)	9.497
Applicable model	Passenger vehicle

Fig. 1 Tire product life cycle system boundaries

processes, such as transportation and waste treatment as well as metals, minerals, plastics, water, chemicals, fuels, and energy production (Liu et al. 2016; Sun et al. 2014; Yang et al. 2015).

3 Life cycle inventory analysis

3.1 Raw material acquisition stage

The data on the raw materials used in the investigated tire product were sourced from on-site investigations of one of the largest Chinese tire companies. The data were collected in 2014 during the manufacture of the target tire product. Natural rubber, synthetic rubber, carbon black, silicon dioxide, steel wire, polyester fiber, and nylon 6–6 are the main materials used in the raw material acquisition stage. Background data on all main materials were acquired from RCEES 2012. Other materials, such as active clay, zinc oxide, stearic acid, processing agent, and lubricating oil, were also considered. Life cycle background data on these other materials were obtained from the global average LCI data of Ecoinvent 3.0.

Data on the input of raw materials and the output of solid wastes for the target tire product were measured using the mass allocation method (by allocating the total tire products input/output of the passenger vehicle line to the target tire product). According to an on-site survey, all wastes are

recycled 100 % to avoid primary raw material production. The finished tire product has a mass of 9.497 kg. Table 2 shows the specific masses.

3.2 Production stage

As shown in Fig. 1, the production stage is quite complex and includes the processes of compound blending, rolling, extrusion, packet ring production, cutting and forming, vulcanizing, and testing. We combined closely related processes to avoid allocation. The following four main production processes were identified: compound blending, rolling and extrusion, cutting and forming, and vulcanizing and testing. Data on the energy consumption and pollutant emissions associated with the tire product were sourced from an on-site investigation of one of the largest Chinese tire companies.

The energy consumption (including hybrid electricity, water, and steam) and pollutant emissions associated with the target tire product were measured using the mass allocation method. Separate from the compound blending process, the three other main processes (cutting and forming, rolling and extrusion, and vulcanizing and testing) result in some simultaneous energy consumption, which is measured by a single monitoring instrument for electricity, water, and steam; thus, this consumption should be calculated collectively to avoid allocation.

Table 2 LCI of the raw material acquisition and production stages for the target tire product

Category	Subcategory	Unit	Compound blending	Rolling and extrusion	Cutting and forming	Vulcanizing and testing	Other three processes	Total
Materials	Natural rubber	kg	1.859	0.000	0.000	0.000	0.000	1.859
	Synthetic rubber	kg	2.471	0.000	0.000	0.000	0.000	2.471
	Carbon black	kg	2.515	0.000	0.000	0.000	0.000	2.515
	Silicon dioxide	kg	0.077	0.000	0.000	0.000	0.000	0.077
	Other materials	kg	1.332	0.000	0.000	0.000	0.000	1.332
	Steel wire	kg	0.000	1.048	0.000	0.000	0.000	1.048
	Nylon 6-6	kg	0.000	0.083	0.000	0.000	0.000	0.083
	Polyester fiber	kg	0.000	0.309	0.000	0.000	0.000	0.309
Energy and resource	Electricity	MJ	14.440	4.570	1.700	3.010	11.130	34.850
	Water	kg	6.960	0.000	0.000	0.000	16.560	23.520
	Steam	kg	0.760	0.200	0.390	15.890	0.000	17.240
Emissions to air	Particle matter (PM)	g	—	—	—	—	—	243.510
	Volatile organic compounds (VOCs)	g	—	—	—	—	—	0.005
Emissions to water	Chemical oxygen demand (COD)	g	—	—	—	—	—	1.730
	NH ₄ ⁺ -N	g	—	—	—	—	—	0.190
	Suspended solid (SS)	g	—	—	—	—	—	0.690
Solid wastes	Waste wire cord fabric	kg	0.000	0.002	0.015	0.001	0.000	0.018
	Waste fiber fabric	kg	0.000	0.001	0.020	0.001	0.000	0.022
	Waste cord thread	kg	0.000	0.001	0.000	0.000	0.000	0.001
	Waste rubber	kg	0.001	0.001	0.000	0.000	0.000	0.002
	Waste steel wire	kg	0.000	0.001	0.003	0.000	0.000	0.004
	Waste tire	kg	0.000	0.000	0.000	0.073	0.000	0.073

The specific data on energy consumption and pollutant emission during the production stage are shown in Table 2. The life cycle background data for hybrid electricity and water were obtained from the RCEES 2012 database (Liu et al. 2016; Sun et al. 2014; Yang et al. 2015), and the life cycle background data for steam were obtained from the global average LCI data of Ecoinvent 3. In total, 34.850 MJ of electricity, 23.520 kg of water, and 17.240 kg of steam are consumed during the production stage for one unit of tire product.

The main pollutants include particulate matter and volatile organic compounds emitted into the air and the generation of suspended solids, NH₄⁺-N, and chemical oxygen demand in water. All data were measured, monitored, and reported in accordance with the national environmental laws.

3.3 Use stage

During the use stage, fuel is expended to counteract the rolling resistance of the tires. Fuel consumption during driving was allocated to each of the tires. We used the fuel consumption value provided by the Ministry of Industry and Information Technology of the People's Republic of China (MIIT 2015), which states that the average fuel consumption of Chinese

passenger vehicles in 2014 was 7.22 L/100 km. According to a survey of the Chinese car industry, the empirical proportion of a vehicle's fuel consumption that is attributable to the four tires is 20–25 % of the total fuel consumed by the vehicle (Liu et al. 2011; Qian 2010; Yang 2009); for this study, we chose to use a value of 22 %. We assumed that the target tire products were used by a gasoline passenger car. The fuel consumption of each tire product throughout its use life of 60,000 km can be calculated based on the fuel consumption of a passenger vehicle (7.22 L/100 km), the proportion of fuel consumed by the four tires (22 %), the use life (60,000 km), and the density of gasoline (0.73 kg/L). In this manner, the mass of fuel consumed by each tire product is found to be 173.93 kg.

From the on-site test measurement, the target tire product creates 1.50-kg crumb rubbers because of tire wear abrasion during the lifetime of 60,000 km, which is about 16 % of the tire weight. In other words, each target tire product produces about 25-mg crumb rubber for each kilometer driven. One-kilogram crumb rubber would produce 800-g particulate matters during the driving (Li 2011). Therefore, 1.2-kg particulate matters will generate through the tire wear abrasion during the lifetime of 60,000 km.

In our assumption, the gasoline passenger car, which was supposed to use the target tire product, was non-cylinder direct injection engine passenger car. Due to GB 18352.5—2013 “Limits and measurement methods for emissions from light-duty vehicles (China 5),” the measured value of particulate matter could be calculated at zero for non-cylinder direct injection gasoline engine car. Therefore, we conclude no particulate matter emission through the gasoline consumption.

3.4 End-of-life stage

Statistics show that in China, 70 % of waste tires can be recycled to produce reclaimed rubber (Jiang 2011). From an on-site survey of a Chinese waste tire recycling company, the inputs and outputs associated with the recycling of reclaimed rubber from 1 t of waste tires are shown in Table 3.

In this study, we assumed that 100 % of used tires are collected and recycled to produce reclaimed rubber and that waste steel wire and waste fiber are recycled to avoid primary raw material production. The reclaimed rubber is reused in place of 50 % of the synthetic rubber used in the production of rubber products. The recycling rates of waste steel wire and waste fiber are 95 and 50 %. The remaining components that could not be recycled and reused were treated as municipal solid wastes in accordance with a waste treatment scenario specified in the RCEES 2012 database (Liu et al. 2016; Sun et al. 2014; Yang et al. 2015).

4 Life cycle impact analysis

The CML (2001) method developed by the Institute of Environmental Sciences of Leiden University was selected as the base method to be used in this LCA to analyze environmental impacts. We chose five impact categories from this approach that are easily communicated, of general interest, and important with respect to the tire product system. These impact categories are the global warming potential (GWP 100a) in kilograms of CO₂ equivalent, the acidification potential (AP) in kilograms of SO₂ equivalent, the photochemical oxidant creation potential (POCP) in kilograms of C₂H₄ equivalent, the eutrophication potential (EP) in kilograms of PO₄³⁻ equivalent, and the human toxicity potential (HTP 100a) in kilograms of 1,4-DCB equivalent.

5 Results and discussion

5.1 Life cycle assessment results

The results of the LCA for one tire in all selected categories are presented in Table 4.

Table 3 List of inputs and outputs associated with the recycling of reclaimed rubber from 1 t of waste tires

Category	Material	Amount	Unit
Inputs	Waste tire	1.00	t
	Electricity	770.50	kWh
	Water	7.10	t
	Diesel	0.01	t
Outputs	Reclaimed rubber	0.67	t
	Waste steel wire	0.07	t
	Waste fiber	0.01	t
	SO ₂	0.72	kg
	NO _x	0.38	kg
	H ₂ S	0.18	kg
	Smoke dust	0.16	kg
	Powder dust	0.19	kg
	Non-methane hydrocarbon	0.76	kg

5.1.1 Global warming potential

The largest proportion of the GWP burden throughout the life cycle of one tire is related to the use stage (94.57 %), with the main contributor being fuel consumption. The raw material acquisition (4.31 %) and tire production (1.72 %) stages contribute only a small portion of the total. During the end-of-life stage, the recycling of used materials reduces the total GWP by 0.60 %.

As shown in Fig. 2, of the various greenhouse gases, CO₂ emissions contribute the most to global warming (99.43 %). The other substances collectively contribute less than 1 % of the total and include predominantly CH₄ (0.38 %), CO (0.18 %), and N₂O (0.01 %).

5.1.2 Acidification potential

During the life cycle of the tire product, the use stage contributes the largest share of the AP (87.30 %). The contributions from the raw material acquisition (6.82 %) and production (5.30 %) stages are similar. The end-of-life stage contributes the least (0.58 %).

The largest of the life cycle AP burdens is NO_x (71.60 %). SO₂ is the second greatest contributor, accounting for 28.15 % of the total. The remaining pollutants contribute 0.25 % of the total and include HCl (0.18 %) and other pollutants (0.07 %).

5.1.3 Photochemical oxidant creation potential

The use stage accounts for more than half (63.93 %) of the total POCP of the tire product, followed by the production (17.61 %) and raw material acquisition (16.67 %) stages. The end-of-life stage contributes least to the POCP (1.79 %).

Table 4 LCA results for one tire throughout its life cycle

Impact category	Raw material acquisition	Production	Use	End of life	Total
GWP (kg CO ₂ e)	29.786	11.849	653.328	−4.119	690.844
AP (kg SO ₂ e)	0.143	0.111	1.826	0.012	2.091
POCP (kg C ₂ H ₄ e)	0.008	0.008	0.030	0.001	0.047
EP (kg PO ₄ ^{3−} e)	0.023	0.006	0.375	−0.008	0.395
HTP (kg 1,4-DCB e)	10.081	0.743	3.495	−3.391	10.927

The POCP is attributed primarily to SO₂ (49.85 %) and CO (45.17 %), whereas other pollutants contribute a small proportion (4.98 %) of the total.

5.1.4 Eutrophication potential

The use stage contributes the most (94.94 %) to the EP. The second greatest contribution to the EP is from the raw material acquisition stage (5.72 %). The production stage contributes 1.48 % of the total. During the end-of-life stage, the recycling of used materials reduces the total EP by 2.14 %.

The EP is attributed predominantly to NO_x emissions (98.48 %). The remaining pollutants collectively contribute less than 2 %, including phosphate (1.00 %), chemical oxygen demand (0.28 %), nitrate (0.14 %), and other pollutants (0.10 %).

5.1.5 Human toxicity

The largest proportion of the HTP burden throughout the life cycle of one tire is related to the raw material acquisition stage (92.25 %). The second largest contributor to the HTP is the use stage (31.98 %). The production stage accounts for the smallest contribution to the HTP (6.80 %). During the end-of-

life stage, the recycling of used materials reduces the total EP by 31.03 %.

The dominant contributing pollutants in the HTP category are NO_x (32.88 %) and benzene (25.65 %), followed by PAH (18.62 %) and arsenic (10.77 %). The remaining pollutants contribute similarly to the total, including nickel (3.83 %), chromium VI (3.67 %), and other pollutants (4.57 %).

5.2 Interpretation of life cycle results

5.2.1 Identification of major issues

The relative contributions of the different life cycle stages to each impact category for one item of the tire product are shown in Fig. 3. The use stage is the primary contributor to the GWP, AP, POCP, and EP and accounts for ~63–95 % of the total to each impact category, respectively. This is because of the fuel consumption that occurs during the use stage. The other three stages contribute less than 13 % of the total to the GWP, AP, and EP. The raw material acquisition and production stages contribute less than 7 and 6 % of the total, respectively, of each impact category. For the HTP, the largest contributor is the raw material acquisition stage. For the end-of-life stage, the GWP, EP, and HTP contributions are negative

Fig. 2 Contributions of various pollutants to the impacts of one tire

Fig. 3 Relative contributions of the life cycle stages to each impact category for the investigated tire product

(especially for the HTP) and the AP and POCP contributions are positive.

Figure 4 shows the relative contributions to each impact category of the raw material acquisition stage for the tire product. In the GWP, AP, and EP categories, rubber and carbon black are the predominant contributors. The predominant contributors overall are the rubbers, including both natural and synthetic rubber, which together account for nearly half of the total contribution to each of the three impact categories above. However, for both the HTP and POCP, the largest proportion of the burden in the raw material acquisition stage is related to other materials, with the main contributor being organic chemicals. By contrast, other materials collectively contribute less than 16 % to the other three impact categories. In all five impact categories, carbon black contributes ~11–25 % of the total to each impact category, respectively; steel wire accounts for less than 12 %; and fiber contributes less than 8 %.

The relative contributions to each impact category in the production stage for the tire product are shown in Fig. 5. The compound blending process is the largest contributor to the AP and POCP, primarily because of its electricity consumption. Vulcanizing and testing contribute the most to the GWP, the EP, and especially the HTP (86.30 %); this is ascribed to the significant amounts of steam consumed during vulcanization. In all five impact categories, rolling and extrusion represent contributions of about 10 % to the GWP, AP, POCP, and EP and less than 3 % of the total to the HTP. The “other three processes” contribution, which includes the collective contributions from cutting and forming, rolling and extrusion, and

vulcanizing and testing, represents less than 31 % of the total in each impact category; the majority of which can be attributed to the consumption of water and electricity.

In the end-of-life stage, used tires are recycled to produce reclaimed rubber, which is reused in place of synthetic rubber for the production of rubber products. Waste steel wire and waste fiber are recycled to avoid primary raw material production. The relative contributions to each impact category in the end-of-life stage for the tire product are shown in Fig. 6. The impact of the end-of-life stage is negative for the GWP, EP, and HTP. However, the production of reclaimed rubber and waste treatment also exert some environmental impact. As shown in Fig. 6, for the AP and POCP, the environmental benefit from the recycling of waste materials is insufficient to outweigh the environmental impact from reclaimed rubber production and waste treatment. Therefore, AP and POCP impacts exist during the end-of-life stage.

Throughout the life cycle of the tire product, gaseous pollutants, such as CO₂, NO_x, SO₂, CO, benzene, and PAH, are the main contributors to the environmental impact categories. Figure 7 shows the distribution of these major pollutants throughout the life cycle of the tire product. The use stage contributes the most to emissions of CO₂, NO_x (~95 %), total PM (80.51 %), and SO₂ and CO (>64 %) throughout the life cycle. The raw material acquisition stage is the primary contributor (>100 %) to benzene and PAH emissions throughout the life cycle. The production stage contributes more than 10 % of the PAH, total PM, SO₂, and CO emissions but less than 5 % of the other three pollutants. During the end-of-life stage, the recycling method used to produce reclaimed rubber

Fig. 4 Relative contributions to each impact category in the raw material acquisition stage for the investigated tire product

serves to reduce a large proportion of the PAH (50.52 %) and benzene (15.98 %) emissions but generates a small contribution (<3 %) to the SO₂, CO, and total PM.

5.2.2 Sensitivity analysis

The use stage is the primary contributor to most of the environmental impact categories throughout the life cycle of the tire product, primarily because of the fuel consumed to counteract frictional resistance while driving.

A single-element sensitivity analysis was conducted to examine how fuel consumption influences the environmental impact categories. Two parameters, namely, the vehicle's fuel consumption during the use stage and the proportion of fuel consumed by the tires with respect to the vehicle's total fuel consumption during the use stage, were varied to examine their effects on the contributions to different environmental impact categories.

When the vehicle's fuel consumption during the use stage was varied by ± 10 % from its base value (7.22 L/100 km), the

environmental impacts in terms of the GWP, AP, POCP, EP, and HTP changed by ± 9.46 , ± 8.73 , ± 6.39 , ± 9.49 , and ± 3.20 %, respectively.

When the proportion of fuel consumed by the tires with respect to the total during the use stage was varied by ± 10 % from its base value (22 %), the environmental impacts in terms of the GWP, AP, POCP, EP, and HTP changed by ± 9.46 , ± 8.73 , ± 6.39 , ± 9.49 , and ± 3.20 %, respectively.

Therefore, it can be concluded that the vehicle's fuel consumption and the proportion of fuel consumed by the tires during the use stage are key factors that contribute to the environmental impacts of the tire product.

5.3 Recommendations for improvement

Based on the research results and their interpretation, the following measures would be useful for improving the environmental impacts observed throughout the tire product life cycle.

Fig. 5 Relative contributions to each impact category in the production stage for the investigated tire product

Fig. 6 Relative contributions to each impact category in the end-of-life stage for the investigated tire product

First, the use of reclaimed rubber would reduce the consumption of natural and synthetic rubber. Reducing the amounts of organic chemicals used and increasing the use of renewable materials or environmentally friendly materials would increase the environmental benefit during the raw material acquisition stage.

Second, by partially substituting silicon dioxide or silica gel for carbon black as filler, it is possible to reduce the rolling resistance of a tire while maintaining its skid and wear resistances (Krömer et al. 1999; Xiong et al. 2004; Zhang et al. 2014b). This also helps to reduce the fuel consumption of the tire during the use stage and reduces its environmental impact throughout its life cycle. Liu et al. (2011) have reported that the rolling resistance of a silica gel tire, compared with that of an ordinary carbon black tire, can be reduced by a maximum of 15 %, thereby leading to a reduction in fuel consumption and greenhouse gas emissions by ~2–3 %. In tests performed by Michelin using white carbon black and solution-polymerized butadiene styrene rubber, the rolling

resistance of a tire was reduced by 35 % and its fuel consumption was reduced by ~3–5 % (Qian 2010).

Third, to reduce the amounts of electricity, water, and steam consumed during the compound blending and vulcanizing and testing processes in the production stage, on-site management should be strengthened by implementing an intelligent digitalized energy management system. Furthermore, new energy-saving technology could be implemented to improve production efficiency, such as the use of high-pressure steam to shorten the vulcanizing time, the substitution of microcirculation for hot water circulation, and the recovery of waste steam during the vulcanizing process (Hao et al. 2012; Jiang 2013; Zhang et al. 2014a).

6 Conclusions

Confidence in measures to improve the environmental performance of products requires a system-wide perspective. LCA

Fig. 7 Distribution of the major pollutants produced throughout the life cycle of the investigated tire product

and life cycle engineering are valuable tools for achieving this goal.

We present a cradle-to-grave LCA of one Chinese passenger vehicle tire product based on first-hand survey data to assess the product's environmental impacts. Key factors and recommended improvements were identified based on the LCA results.

The use stage was found to contribute the most to the GWP, AP, POCP, and EP impact categories. The vehicle's fuel consumption and the proportion of fuel consumed by the tires during the use stage are key factors in determining the environmental impacts of the tire product. The largest contributor to the HTP category is the raw material acquisition stage, primarily related to the production of organic chemicals. The GWP, EP, and HTP contributions from the end-of-life stage are negative, whereas the AP and POCP contributions from this stage are positive.

During the raw material acquisition stage, natural rubber, synthetic rubber, carbon black, and organic chemicals present the largest contributions to the environmental impact categories. These impacts could be mitigated by replacing some natural and synthetic rubbers with reclaimed rubber and some carbon black with silicon dioxide or silica gel and by reducing the use of organic chemicals. The compound blending and vulcanizing processes exert the greatest environmental impacts during the production stage; therefore, new energy-saving technology and an energy management system could be implemented to save energy and reduce emissions during this stage.

Tires are complex products with complex interactions with the environment. Further investigations should be conducted to implement LCA as part of the product development process and improve the environmental performance of tires. Overall, this quantitative LCA study can serve as a benchmark for the environmental performance of Chinese passenger vehicle tire products.

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