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Environmental Impact of End-of-Life Tires: Life Cycle Assessment Comparison of Three Scenarios from a Case Study in Valle Del Cauca, Colombia

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Abstract: Life Cycle Assessment methodology has been applied to estimate diverse environmental impacts of different usage alternatives for worn-out tires at the end of their useful life in a case study at the Department of Valle del Cauca, Colombia. Different real scenarios were compared, which allowed for the assessment of the best environmental option for the management of worn-out tires. A method developed in the Institute of Environmental Sciences at University of Leiden, better known as CML-2001, was used to calculate the environmental impact indicators. The results show that the incineration of whole tires in cement plants, and the activities of grinding and floor manufacturing from granulated rubber, exhibited the best indicators, especially in terms of environmental load avoidance through the recovery of materials. Finally, the categories of depletion of the ozone layer, acidification, global warming potential, depletion of abiotic resources, and photochemical ozone formation revealed that the strongest environmental impacts are associated with retreading and the production of multipart asphalt. This is due to the use of synthetic rubber in the former alternative, and of liquid asphalt, gravel, and diesel consumption in the latter.

Keywords: life cycle assessment; global warming; environmental impact; worn-out tires

1. Introduction

The rapidly growing populations, as well as the rapidly growing economies, bring consequently an increase in waste generation, which becomes a challenge for health authorities and the environment of any city. Inappropriate management of municipal solid waste (MSW) can lead to contamination of water sources due to the percolation of leakage on public health [1].

As a developing country, Colombia has been adopting international legislative guidelines regarding the recovery and final disposal of products in their post consumption stage. According to the Colombian Ministry of Environment and Sustainable Development, the sustainable production and consumption policies of the government have made significant progress in the development of normative systems for the recovery of batteries, hospital debris, technological equipment (e.g., mobile phones, computers), car batteries, and worn-out tires. The last ones were regulated through a recent resolution [2].

Recovered worn-out tires have been used for several industrial and commercial purposes, among which their applications in civil engineering and as fuel are particularly significant. The former use has been mainly associated with the production of granulated rubber for oven heating in the cement and paper industries [3].

Firstly, it has been demonstrated that the use of these materials in combustion ovens constitutes a residue-free alternative, since the resulting ashes and slag are incorporated with the cement without seriously affecting its physicochemical properties [4,5]. In addition, the general replacement of conventional fuels with highly energetic residues stands out for its low emission of NO_x, SO_x, CO, PM10, persistent organic compounds, and heavy metals. Furthermore, the potential impact of this practice on human health due to the release of carcinogenic chemicals seems to be low [6–8].

The second important use for these materials is their application to civil engineering and consists of adding rubber from tires to asphalt mixtures in order not only to increase the collision-buffering capacity of the road, but also to reduce its maintenance cost and increase its useful life [9]. This might be a useful alternative when it comes to diminishing the elevated volumes of worn-out tires and the sanitization problems associated with them. But the process requires additional amounts of oil derivatives, which cause similar or slightly higher contamination levels when compared to those of the traditional process, which releases NO_x, SO_x, CO_2, and PM10 [3].

The third alternative, i.e., rubber obtained from worn-out tires, has been used as raw material for the manufacturing of diverse sub-products. This is the case of the production of floors, artificial lawn, and industrial molds [3]. These applications allow significant reductions in NO_x, SO_x, and CO_2 emissions, especially during the manufacturing of synthetic lawn. However, the latter involves an abundant production of solid debris associated with the separation of steel from rubber.

In Colombia, 71.9% of the final disposal processes applied to worn out tires in cities like Bogota D.C. consists in outdoors incinerations, which produce atmospheric contamination due to the emission of CO_2, NO_x, SO_x, and particulate material. This constitutes the main public concern with regard to the emissions resulting from worn out tires [2].

The manufacturing of synthetic lawn and floors are other alternatives, which have been adopted in Colombia, as is the case of "Hulex" in Bogota D.C. [10] and "Mundo Limpio" in the city of Medellin [11]. Another important industrial experience corresponds to "Renova" Group [12], from Bogota D.C., who have employed the steel extracted from tires to produce wire and nails. Finally, a Colombian company known as Incoasfaltos [13] (Bogotá, Colombia) has used ground rubber to produce modified asphalt.

There is still crucially necessary to apply End-of-Life (EOL) strategies for post-consumption products in order to reduce the environmental impact caused by emissions from outdoor incineration resulting from worn out tires, thus attaining the sustainable functioning of this supply chain [14–16]. Furthermore, the environmental impact of product recovery networks and EOL treatments can be estimated to assess the environmental sustainability of the system [17,18]. This can be done through the well-known and internationally standardized methodology Life Cycle Assessment (LCA).

LCA is a convenient methodology for evaluating environmental impacts of processes, products, goods, and services, during their entire life cycle, meaning from cradle to grave. LCA is an important tool for assessing the environmental impact of EOL strategies [19–22].

In this context, the present paper aimed at evaluating the environmental impact of worn-out tires at the end of their useful life. Three different scenarios, modeling worn out tire management strategies for the department of Valle del Cauca, were evaluated. Those scenarios were reuse and retreading, incineration, and grinding for new products, representing the most possible options for waste management in Colombia.

Retreading and Reuse consider the plant equipment, reprocessing, products, byproducts, and released wastes. This scenario includes appropriate sorting and recycling processes adding up their transport, and recovered materials because of recycling.

Incineration covers the whole equipment, the process itself, the electricity output, and the ash disposal. There are some other processes to be considered: the electrical energy recovery, estimated from calorific capacities, and the amount of total residual ashes, disposed in a landfill.

Grinding involves the transport from the cellars of the crushing plant selection. These initially passed through a primary milling process, in which the tire is disintegrated, and then to one side (crushing), where it is removed by many steel wheels. In the third fine grinding process, the textile fiber is extracted along with the remaining amount of steel, obtaining ground rubber.

Some scenarios provide positive and negative outputs. The positive ones stand for net emissions to the environment whereas the negative ones imply a good benefit, since these recovered materials would actually avoid using virgin materials.

Therefore, in the present Colombian case study, we focus on the environmental impacts from a life cycle point of view. It was done using the LCA methodology, in order to provide consistent sustainability information and criteria that facilitate adequate decision making to reduce, reuse, and recycle towards sustainable development.

State of the Art

During the last decade, some studies in developed and developing countries have resorted to LCA in order to estimate the environmental impact of tires along their lifecycle, and of different final disposal technologies (EOL treatments).

For EOL treatments, Molino et al. [23] evaluated the energetic potential of an alternative to the recycling of tires in the field of environmental protection. Such a study concluded that the steam gasification of scrap tires was found as sustainable and cost effective alternative compared to disposal in landfill.

Regarding the LCA methodology, a study done by Van Beukering et al. [24] analyzed the complete truck tire lifecycle, and determined the impact associated with each of its stages. They concluded that tires inevitably produce a negative environmental impact, which is further increased by inadequate final disposal strategies. Additionally, they found a clear need for harmonizing worn-out tire management environmental policies in Eastern and Western Europe. Ferrão et al. [14] affirm that the adoption of environmental policies as an extended responsibility of manufacturers forces the development of an end-of-life product management system in charge of promoting the collection, reuse, and recycling of worn-out tires. Such a system requires the participation of governmental, private, and educational institutions, together with manufacturers, traders, recyclers, and retreading companies. Making use of Eco-indicator 99, Ferrão et al. [14] compared the environmental impact of EOL technologies, and found that the incineration of rubber material in cement factories produces remarkably lower impacts. Likewise, recycling and reuse also have positive impacts, since the benefits correspond to the fact that the recovered materials would actually replace raw materials, which is extensively promoted in Portugal.

Still on the line of analyzing EOL treatments through LCA, Corti and Lombardi [18] compared the environmental impact produced by conventional combustion in cement ovens to that resulting from substitution with worn-out tires. This process was also compared to other alternatives of material recovery, namely mechanical and cryogenic powdering. From an environmental standpoint, the best result corresponded to substitution in cement ovens. In turn, Li et al. [16] resorted to Eco-Indicator 99 to compare several alternatives such as grinding, de-vulcanization, pyrolysis, and oil extraction from inner tubes. Pyrolysis was found to be the most eco-efficient option in the long term. Oil production is the most harmful alternative due to its elevated energetic consumption and air pollution levels.

Fiksel et al. [3] developed a comparative LCA as a tool for the design of products with worn-out tires. Thus, they identified environmentally friendly EOL alternatives to be compared with the traditional manufacturing of a series of evaluated products. According to these authors, the main uses of worn-out tires as raw materials correspond to asphalt and artificial lawn production in civil engineering and to the manufacturing of molds for diverse products. Comparative studies of the reduction of CO_2, NO_X, SO_X, and heavy-metal emissions have revealed that the most environmentally friendly alternative is synthetic lawn production, followed by manufacture of molds. The mentioned study found that asphalt production has a negative impact due to the many additives and special raw materials that need to be incorporated for the products to reach specified technical requirements.

Pieragostini et al. [17] have found that the use of LCA is currently growing on the part of public and private entities, who are obtaining several benefits from it. Among the latter, we can count environmental development strategies for the selection of industrial practices economic and cultural comparisons of processes, products, and activities across regions; identification of environmental improvement opportunities, and process and product optimization (design and innovation). The latter issue is capable of linking environmental impacts to operational and economic aspects of processes, to the point that in certain European countries, the environmental aspects have been integrated to corporate strategies that were traditionally centered on cost reduction. LCA has been used in many multi-purpose optimization models for the design of green supply networks. In designing worn-out tire recovery networks [15], which are applicable to hospital debris [20], all these authors have resorted to eco-indicators for the purpose of quantifying the environmental impacts generated by supply chain networks [20]. In both studies, this measurement was part of the objective function, which involved minimizing environmental impacts and optimizing economic objectives.

Uncertainty is present in any LCA study. This is the result of combined effects such as variability, error in measurement, poor estimation, non-representative, data, missing information, and assumptions of the model. Uncertainty in models can be classified according to three categories: (1) parameter uncertainty due to lack of precision in measurements data scarcity, (2) uncertainty of the scenario due to its construction, and (3) actual model uncertainty due to the mathematical methods employed for LCA calculation [25].

Numerous methods have been employed to conduct LCA uncertainty analyses. These usually evaluate the soundness of the results through mathematical techniques, e.g., sensibility analysis, which assesses the way the results are affected by changes in the adjusted inputs of the model [26]. The most common example is the analysis of scenarios, which resorts to probability distributions and random sampling, usually applying Monte Carlo simulations for intervals of analysis [27]. Another commonly used technique is the theory of Fuzzy Sets, in which the ranges of the determining variables are represented by probability distributions and/or fuzzy functions according to the degree of certainty of each variable or parameter [28].

2. Materials and Methods

LCA was applied according to the international guideline ISO 14040:2006 [19]. We divided the study into four parts: (1) definition of the goal and scope, (2) inventory analysis, (3) environmental impact evaluation, and (4) interpretation of results.

2.1. Goal and Scope Definition

In the context of LCA, scope and objective allow for the definition of the purpose of the study, the limits of the system to be evaluated, and its functional unit. The aim of this study was to estimate the environmental impact of worn out tires at the end of their useful life in the Department of Valle del Cauca. It is an area located in the western part of Colombia, facing the Pacific Ocean. It is considered one of the most important departments in the country economy due to the privileged location in the Pacific Ocean. Besides, the department has great social-economical influence mainly centered on agriculture, e.g., sugar cane, coffee, cotton, soy, and sorghum crops.

The relevance of this study is supported by national and local data, which shows that in 2014, the number of cars in the country increased by 10.5% with respect to the previous year. The National Industry Association reported that in 2015, Colombia had approximately 48 million inhabitants that made use of 4.2 million vehicles. That is, nine vehicles per 100 inhabitants. In 2012, the production at the national level was 0.74 times larger than in year 2010. In 2012, the country consumed 4.5 million tires, each of which lasted 18 months on average. Regional data from the same year shows that in the Department of Valle del Cauca, there were 32,900 tons of worn-out tires stored in uncontrolled spaces such as houses, public spaces, and open dumps [29].

Figure 1 illustrates the system and its scope, detailing the activities that have been included, classified as primary and secondary strategies. The primary strategy includes retreading, grinding, and incineration in cement factories, all featured by the use of whole tires. In turn, secondary strategies refer to the use of grinded components of the worn out product such as rubber, steel, and textile fiber. Particularly important are the production of wire, floors, and modified asphalt.

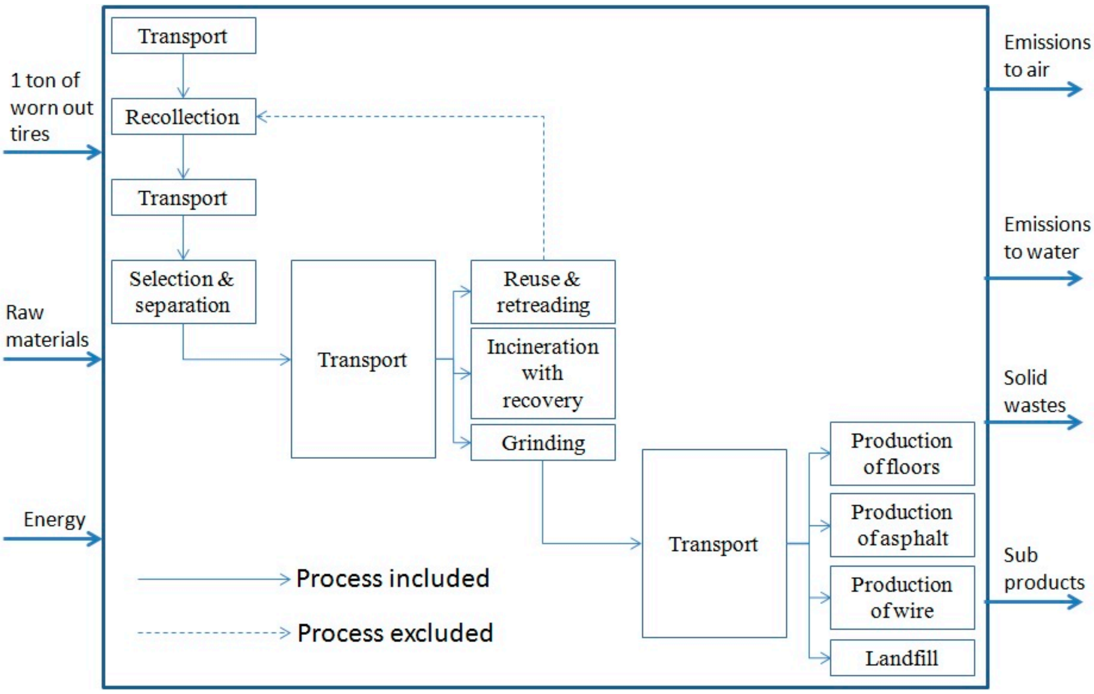

Figure 1. Worn out tire system and limits of the study.

An important activity that was also taken into consideration was transport. This analysis focused on the flow of the tires, from their collection in different municipalities, through their transport to collection centers, to their shipment to recycled product manufacturing plants in different areas of the department. The municipalities in question were classified as follows: 18 municipalities in the North—Eastern zone, 13 in the center of the department, 10 in the South, and one in the Pacific zone.

One (1) ton of worn out tires was defined as the functional unit (FU) for the processes of gathering, selection, separation, grinding, use in cement factories, and retreading (primary strategies). To the outputs from the secondary strategies as flows that are produced from 1 ton of worn out tire were assigned as follows.

The production of floors and modified asphalt (secondary strategies) were assigned one ton of ground rubber, while the production of textile fiber had 0.2 tons of the same material. Finally, 0.229 tons of recovered steel were assigned for wire production.

The following assumptions followed. The current worn out tire analysis considers the following product composition 18% natural rubber, 18% synthetic rubber, 22% lampblack, 22% steel, and 20% textile fiber [30].

Transportation at all stages of the chain is done in 35-ton load capacity vehicles. Electric power generation corresponds to an energetic mix of 78% hydro-electrical plants, 7% carbon, 12% gas, and 3% other sources, adapted from [31]. Transport includes the distance per kilometer (ton-km) and includes emissions produced by burning fossil fuels [32].

2.2. Inventory Analysis

This stage of the analysis focuses on the flows of the studied processes. Here, we describe the inputs of materials and energy, and the output emissions within the limits of the system. Each scenario was adapted to the Colombian case study. Therefore, data description (input and output) and collection of each process per FU is described as follows.

2.2.1. Recollection

This activity starts from the collection of used tires in the different stations in each municipality and their transportation to the collection centers. The process takes into account the transport per kilometer (ton-km) and includes emissions produced by burning fossil fuels. Adapted from [16,33], see Table 1.

Table 1. Inventory analysis for the recollection process.

Input	Quantity	Unit	Output	Quantity	Unit
Electricity Diesel Worn-out tires	8.05 1.76 1	kWh l Ton	Used tires recollected	1	Ton
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Electricity Diesel Used tires recollected Water	8.11 2.58 1 0.043	kWh L Ton m^3	Selected tires	1	Ton

2.2.2. Retreading

This includes the transport from the store selection until retreading. In the precured tread, which was to be assembled in the process of retreading, a tire casing have been previously prepared. Adapted from [3,30]. See Table 2.

Table 2. Inventory analysis for the retreading process.

Process	Input	Quantity	Unit	Output	Quantity	Unit
Precured tread	Energy Synthetic rubber Lampblack Natural rubber	12.34 841.5 468.84 96.7	kWh Kg Kg Kg	Engraving tread Retreaders cushion	1472.62 109.39	Kg Kg
Retreaders	Engraving tread Retreaders cushion Electricity	1472.62 109.39 1803.21	kg kg kWh	Retreaders tires Solid waste	1 721.29	Ton Kg
Primary process (Grinding)	Worn-out tires Electricity Water	1.00 2418.47 16.69	Ton kWh Kg	Ground tire	1.00	Ton
Secondary process (Triturate)	Electricity Ground Tire	1202.35 1.00	kWh Ton	Powdered Rubber Steel wire	798.48 201.52	Kg Kg
Secondary process (Triturate)	Electricity Powdered Rubber	1202.35 798.48	kWh kg	Granulated Rubber/Dust Steel wire Particulate material Textile fiber	571 27.48 0.054 200	Kg Kg Kg Kg

2.2.3. Incineration

This includes the transport of worn out tires from the cellars to the cement plant. These are downloaded and entered manually or via scroll ovens. Incineration thereof occurs and power is recovered for use for cement production process. Adapted from [18,30], see Table 3.

Table 3. Inventory analysis for the incineration process.

Input	Quantity	Unit	Output	Quantity	Unit
Diesel	6.05	Kg	Particulate material CO	1.00 100	Kg Kg
Electricity	1670	kWh	NO_x Energy SO_2	7.00 32,000.00 140	Kg MJ Kg

2.2.4. Production of Asphalt

The crumb rubber is transported to a plant of modified asphalt from the crushing plant. Unlike the traditional production process of asphalt that combines liquid asphalt to gravel, rubber granules are added to liquid asphalt in a mixer, in a separate process, before being mixed with the gravel in the tumble dryer, and the filtration chamber to obtain modified asphalt. Adapted from [3]. See Table 4.

Table 4. Inventory analysis for the asphalt production process.

Process	Input	Quantity	Unit	Output	Quantity	Unit
Cold feed hoppers	Rock Water Electricity	4100.00 200 0.43	Kg Kg kWh	Rock	4100.00	Kg
Sieving	Rock Electricity	4100 0.16	Kg kWh	Filtered Rock Waste	3650.00 450	Kg Kg
Liquid Asphalt Tank	Electricity Diesel Liquid asphalt	0.079 0, 4 310.00	kWh Kg Kg	Asphalt Cement	310	Kg
Rubber with Asphalt Mixture	Asphalt Cement Electricity Diesel Granulated Rubber	310 1.4 120 76	Kg kWh Kg Kg	Asphalt Modified with Rubber	380.00	Kg
Asphalt storage with rubber	Asphalt Modified with Rubber Electricity	380 0.14	Kg kWh	Asphalt Modified with Rubber	380.00	Kg
Drum Dryer	Filtered Rock Asphalt Modified with Rubber Electricity Diesel	3650 380 2.2 29	Kg Kg kWh Kg	Rubber Modified Asphalt Mixture	4500.00	Kg
Filtration Chamber	Rubber Modified Asphalt Mixture Electricity	4500 1.7	Kg kWh	Rubber Modified Asphalt Mixture Water Particulate Material	4500.00 190.00 2.30	Kg Kg Kg
Storage in Silos	Electricity Rubber Modified Asphalt Mixture	0.39 4500.00	kWh Kg	Rubber Modified Asphalt Mixture	4500.00	Kg

2.2.5. Production of Floors

The crumb rubber is transported from crushing plant to a factory manufacturing synthetic floor. In the pressing process, it is mixed with clay and sand to achieve nonslip properties of the product. Excess water is removed in the process by drying. Tiles and/or recycled rubber mats are obtained to cover surfaces. Adapted from [30,34]. See Table 5.

Table 5. Inventory analysis for the production of floors.

Input	Quantity	Unit	Output	Quantity	Unit
Ethylene-propylene Ground Rubber	750 1	Kg Ton	Rubber Floors	4038.14	Kg
Clay Sand	1750.75 1250	Kg Kg	Water	712.62	Kg

2.2.6. Production of Wires

The recovered steel crushing plants are transported to the wire manufacturing plant. This is melted with other materials that help strengthen their metallic properties, making bullion square. After the hot rolling process, rolls of wire rod are cold drawn to reduce circulation, and the desired size of the wire section is obtained. Furthermore, this includes the selection and separation, which corresponds to the transportation from the collection centers to the store. This includes also processes such as cleaning and separation that are involved in the production of floors, asphalt, and wire. Adapted from [31,35]. See Table 6.

Table 6. Inventory analysis for the production of wires.

Input	Quantity	Unit	Output	Quantity	Unit
Extracted Steel	229	Kg	Wire	902.53	Kg
Iron Ore	1360	Kg	Particulate Material CO	1.23 20.71	Kg Kg
Lime	73.1	Kg	NO_x SO_2	2.18 5.641	Kg Kg
Limestone	60.81	Kg	CO_2 Waste	1626.62 177.29	Kg Kg

The Ecoinvent V2.01 database was used to have the inventory data of the processes involved in the study. The software LCA-Data Manager® has been used to validate, create, and modify the diverse scenarios under study. Material balances in the inventory have also been carried out [36]. The equation modelling used by LCA-Data Manager® was done according to guidelines for conducting an LCA study step-by-step on the ISO standard according to the following Equation, adapted from [37]:

$$\text{Environmental impact indicator} = (\text{quantities} \times \text{inventories} \times \text{characterization factors}) \quad (1)$$

2.3. Environmental Impact Evaluation

The next step in the LCA methodology is the Life Cycle Impact Assessment (LCIA). The LCIA evaluates potential environmental impacts, and estimates the resources used in the modelled system. It is determined which extractions and emissions contribute to the diverse impact categories. The current research based the impact assessment upon the CML 2 method (2001) developed by the Institute of Environmental Sciences at University of Leiden [38]. The following impacts were considered: Acidification (AP, kg SO_2 equivalent.), Eutrophication (EP, kg PO_4 equivalent.), Global warming (GWP, kg CO_2 equivalent.), Photochemical ozone formation (PO, kg ethylene equivalent.), Depletion of abiotic resources (DAR, kg Antimony equivalent.), Depletion of the ozone layer (OD, kg CFC-11 equivalent.), and Human toxicity (HT, kg 1.4-DCB equivalent.).

3. Results

The results of the current LCA study are presented in Table 7. It shows the indicators corresponding to each of the disposal strategies at the end of the lifecycle of the tires. As it can be observed, there are positive and negative values. The first ones mean net emissions to the environment. The second ones become a benefit corresponding to the fact that these recovered materials would actually avoid using virgin raw materials.

Table 7. Environmental impact results for each stage of the designed network.

Environmental Indicator	Retreading	Incineration	Grinding for		
			Production of Floors	Production of Asphalt	Production of Wire
GWP (kg CO_2 equivalent.)	1.24×10^{3}	-1.11×10^{3}	-1.32×10^{3}	6.67×10^{2}	-1.42×10^{2}
AP (kg SO_2 equivalent.)	5.67	−4.78	−5.26	9.94×10^{3}	-4.66×10^{-2}
EP (kg PO_4 equivalent.)	1.01	−2.32	−1.81	6.56×10^{-1}	1.45
PO (kg ethylene equivalent.)	2.18×10^{-1}	-3.39×10^{-1}	-2.88×10^{-1}	-5.86×10^{-2}	-2.09×10^{-1}
OD (kg CFC-11 equivalent.)	4.24×10^{-4}	-1.43×10^{-4}	-2.89×10^{-4}	6.82×10^{-1}	9.43×10^{-7}
HT (kg 1.4DCB equivalent.)	-7.60×10^{2}	-1.72×10^{3}	-4.64×10^{2}	1.02×10^{2}	-2.25×10^{3}
DAR (kg antimony equivalent.)	2.46×10^{1}	-1.22×10^{1}	-1.91×10^{1}	4.08×10^{1}	7.52

In terms of environmental impact on the global warming process, the alternatives incineration, mechanical grinding, and the manufacture of floors and wire generate benefits in terms of kg CO_2 equivalent. This is due to the recovery of tire components such as synthetic rubber and steel, whose environmental load is thus prevented. In turn, the highest impacts in the script actually correspond to retreading and modified asphalt production. The impact produced by the retreading process is associated with the use of synthetic rubber in the manufacturing of the tread band, which makes this the alternative with the strongest impact in the network. When it comes to the production of modified asphalt, the consumption of liquid asphalt, gravel, and diesel has a negative impact on this indicator. Yet, this impact is counterbalanced by the recovery of synthetic rubber.

As in the case of the previous indicator, the alternatives grinding, incineration, and floor and wire manufacturing bring about environmental benefits in terms of acidification. Contrarily, the process of retreading and the production of modified asphalt are the ones that produce the strongest environmental impacts. The latter process, in fact, is the one that generates highest amount of kg SO_2 equivalents, mostly due to diesel consumption.

In terms of eutrophication and acidification, which are measured through the amount of phosphate (kg PO_4) generated by each process, incineration and floor manufacturing produce the lowest of all environmental loads. In contrast, retreading has a negative impact due to the use of synthetic rubber.

Measured through the production of ethylene-equivalents (kg), photochemical ozone formation reveals that the environmental impact of the processes of gathering and selection are almost insignificant (about 10^{-4}). Except for the process of retreading, all the studied alternatives generate low or even positive environmental impacts in this category, due to the recovery of synthetic rubber, textile fiber, and steel. Therefore, incineration, and floor manufacturing exhibit the most positive impacts.

With respect to the depletion of the ozone layer, the first stages of the chain, namely gathering and selection produce insignificantly negative environmental impacts (about 10^{-6} and 10^{-7} respectively). The alternatives incineration and grinding, as well as the manufacturing of floors and wire, prevent environmental impacts in this category, although certainly in small amounts (around 10^{-4} for the first three alternatives, and 10^{-7} for wire manufacturing). Retreading produces a low negative environmental impact (about 10^{-4}), which is associated with the use of synthetic rubber during the process. Finally, a negative impact is due to the production of modified asphalt, mainly resulting from the use of diesel as its source of energy.

As to human toxicity, those alternatives that imply the recovery of steel, as is the case of retreading, incineration, grinding, and wire production, determines positive impacts that result from avoiding the environmental loads associated with this material. Besides, floor manufacturing is beneficial through the recovery of synthetic rubber. For its part, asphalt production produces negative impacts due to the use of gravel, liquid asphalt, and diesel in the process.

Finally, abiotic resource depletion, as measured in kg antimony equivalents, reveals that incineration, grinding, and floor manufacturing are positive strategies due to the recovery of synthetic rubber. Contrarily, retreading consumes this component to manufacture the tread band, and for this reason, it produces a negative impact. The strongest negative impact results in the production of modified asphalt, due to the use of liquid asphalt and diesel as its energy source.

4. Discussion

An adequate management of worn-out tires implies the development of processes of gathering, selection, and separation. Gathering was observed to generate the lowest impact within the network under study. Transportation from the different gathering centers in the municipalities to the major stockpiling centers determines the strongest impacts within the collection process. Both activities produce significant amounts of CO_2 kg equivalents (global warming). The impacts associated with the selection and separation processes are relatively low when compared to the alternatives of use. However, global warming and human toxicity indicate that they are, respectively, 20 and 14 times higher than those produced by the gathering process are. The total impact of this process is also incremented by transportation from the gathering centers to the warehouses where selection takes place.

Among the primary strategies, incineration in cement factories and grinding show negative values for all the studied impact categories. This means they are beneficial activities, as they avoid environmental loads and allow for the recovery of materials for recycling. In other words, the avoided impact (recovery of materials and energy saving) is higher than the one produced by the activity itself. The global warming values for incineration are significantly lower (almost half as much) than those exhibited by grinding.

Human toxicity shows similar values for both alternatives. In turn, the process of retreading has a negative environmental impact across all the evaluated impact categories, except for human toxicity, wherein this activity records negative values (positive impacts). This is caused by the use of both natural and synthetic rubber for the manufacturing of the tread band.

Regarding the usage alternatives for grinding sub products, floor manufacturing is the one that most prevents environmental impacts in all the categories. The global warming record of this activity is the most negative value of the entire network, which reveals this activity as the most environmentally friendly alternative in this category. For its part, wire production also records important environmental benefits in almost all indicators, except for eutrophication and abiotic resource depletion. The latter result is due to the consumption of carbon as energy source during the process. Contrarily, the production of modified asphalt produces negative environmental impacts in all indicators, resulting from the traditional use of diesel, liquid asphalt, and gravel. The environmental impact generated by this alternative is not significantly different from that generated by traditional methods of asphaltic mix production.

These results coincide with those of [3], who have ascertained that the use of worn-out tires for the production of artificial lawn (a very similar process to floor manufacturing) and for their incineration in Cement Factories hold the largest environmental impact reduction potentials. Similarly, reference [18] have observed that the replacement of traditional fuels with worn-out tires in the production of cement produces interesting environmental results. In accordance with these data, the most environmentally friendly alternatives are incineration in cement factories, grinding, and floor manufacturing from granulated rubber.

While the above-mentioned studies have applied LCA analyses in Europe and China, this mode of assessment is still an important need in developing countries, especially in Latin America. This is particularly true, not only in face of the need to evaluate the environmental adequacy of specific management systems for post consumption residues, but of the great potential observed in the recycling industry in this region as well. This industry, indeed, might become a powerful source of important opportunities in face of the challenges of the future, which are specifically related to the availability of renewable and nonrenewable raw materials [39,40].

5. Conclusions

The alternatives floor manufacturing, incineration in cement factories, and mechanical grinding have positive environmental impacts. In turn, gathering, selection, and separation activities present negative environmental impacts of low magnitude. Finally, the retreading and manufacturing of modified asphalt generates the strongest negative environmental impacts.

The environmental impact indicators for the gathering, selection, and separation activities show positive values; therefore, they represent a negative environmental impact, mostly associated with elevated fossil fuel consumption levels. Still, these values are considered low when compared to the other usage alternatives under consideration. The global warming and human toxicity indicators are approximately 20 and 14 times smaller than those of the other activities analyzed in the studied logistic network.

The longer the traveled distance between facilities intended for gathering, separation, and usage alternatives, the stronger is the environmental impact of the transport activities. This is particularly true with regard to global warming, due to the fossil fuel consumption involved in transportation.

Wire manufacturing generates positive and negative environmental impacts. Using worn-out tires for the recovery of steel and, later, wire manufacture generates positive environmental impacts associated with global warming, acidification, photochemical oxidation, and human toxicity. Yet, negative environmental impacts result from eutrophication, the destruction of the ozone layer, and the depletion of abiotic resources, mainly due to the use of fossil fuels such as gas or carbon for the melting of steel at elevated temperatures.

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