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Reuse of tires textile fibers in plastic compounds: is this scenario environmentally sustainable?

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Abstract

Even if specific directives have been issued to regulate the management of End of Life Tires (ELT), several materials are still not properly recovered. This is the case of textile fibers obtained from the treatment of ELTs. This study aims to investigate and quantify the environmental impacts related to the reuse of tires textile fibers as second-life material for the preparation of plastic compounds. The Life Cycle Assessment methodology has been used to compare the baseline scenarios (landfilling and incineration) with the reuse scenarios. Results obtained confirms that reuse scenarios are generally more environmental sustainable than the currently implemented strategies.

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1. Introduction

The number of worldwide car owners has reached 1 billion, and the number of end-of-life vehicles (ELVs) is estimated to be approximately 60 million. Such a large number elicits people's attention because natural resources are rapidly decreasing [1]. End-of-Life Tires (ELTs), which constitute a relevant portion of ELVs, are non-degradable wastes, generated in large amounts all over the world [2]. ELTs management systems differ in each country, depending on the specific country's waste management framework, implementation of innovative technologies and other aspects. In Europe, every year, about 3,4 million tonnes of old tires are treated to recover materials or energy [3][4]. Unlike rubber and steel that are currently reused in various application fields, the recovered textiles represent a special waste (European Waste Catalogue – EWC code 19.12.08) to be disposed. Textile fibers represent about 10% by weight of the ELTs, thus in Europe, about 320.000 tonnes per year of dirty fibrous material must be disposed as special waste. This leads to the generation of negative impacts on the environment, economic losses and public costs [5].

Beside the issue of ELTs disposal, there is the post-consumer plastic disposal issue that deserves equal attention. Typically, post-consumer plastic wastes are composed by mixed plastics of unknown composition and are potentially contaminated by organic fractions (such as food remains) or non-polymer inorganic fractions (such as paper) [6]. According to Elseoud [7], plastic wastes account for about 12% to 16% of global wastes. Recycling is not always feasible, due to problems to separate the mix composed by numerous types of polymers with different mechanical and technological characteristics.

Concerning polypropylene (PP), its recycling and reuse have been investigated in several literature studies. Guerrica-Echevarria et al. [8] have studied the changes of rheological and mechanical properties for recycled PP. Xiang et al. [9] have shown an important change in chemical structure and

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rheological values after different injection molding cycle. Meran et al. [10] have proved the good recyclability of PP by showing a slight decrease of the tensile strength (-15%) with a 100% recycled PP compared to a pure PP.

A possible solution to the above-mentioned weaknesses is the insertion of reinforcing fibers in the polymer matrices. Different studies showed how the use of fibers increases the properties of waste PP. The fibers can be natural [12] (e.g., cellulose, jute, hemp, straw, switch grass, kenaf, coir and bamboo), glass fibers, carbon, etc. [13]. However, it is hard to find information about the possible reuse of ELT fibers. Studies show that the fibers, mainly consisting of a blend of polyester, rayon and nylon fibers, have yielded positive results in different applications. Czvikovszky and Hargitai [14] investigated the use of waste textile fibers as reinforcing material for PP used in the production of car bumpers. Even in this case a positive result has been observed. Fibers give to the modified PP a greater resistance to bending and an acceptable impact strength, and contribute to increase the elasticity modulus.

The present paper wants to integrate the abovementioned studies by assessing the environmental impacts of the proposed EoL scenarios. The comparative evaluation is performed by using the standard Life Cycle Assessment (LCA) methodology [15], to verify if the fibers reuse positively influences the ELTs environmental impacts.

After this introduction, the paper is structured as follows. Section 2 illustrates the End of Life scenarios for ELTs textile fibers, Section 3 presents the conducted LCA study and the discussion of the obtained results, and, finally, Section 4 reports conclusions.

2. End of Life scenarios for tire textile fibers

This study considers and compares different EoL scenarios for tires textile fibers. Possible scenarios have been selected by evaluating the standard practices in the European context, the scientific literature about fibers reuse in plastic compounds, and the existing research and pilot projects. At the end three EoL scenarios have been considered: (i) landfill, (ii) energy recovery, and (iii) reuse in plastic compounds. The first two options are the baseline scenarios, currently implemented in the real waste management chain. The last option, instead, is an innovative application for tires textile fibers to be studied to evaluate its environmental performance.

As it is well known, landfill (scenario ①) is the worst EoL scenario considering the environmental hierarchy [16]. It is always connected with losses of resources (both natural and economical), and damages to the environment (e.g. emissions on soil and water, land occupation) [17].

Incineration (scenario ②) is another open-loop EoL scenario that only permits to recover energy from materials. Concerning materials derived from ELTs, their incineration is generally easy, due to the high heating value. However, specific equipment is required to reduce toxic emissions, and only limited quantities of the embedded energy (about 40%) are converted in electricity or heat [18].

The reuse of tires textile fibers (scenario ③) foresees the preparation of polypropylene (PP)-based compounds. Plastic compounds with the same or improved mechanical performances of virgin PP compounds, can be obtained by opportunely mixing textile fibers with non-virgin PP, coming from wastes or scraps (both domestic and industrial). This potentially leads to relevant savings, due to the avoided use of virgin PP usually produced from fossil resources. However, after the shredding of ELTs, the output fibers (i.e. dirty fibers) contain a relevant percentage of rubber impurities (about 30% in weight), and cannot be directly used in plastic compounds. An additional process (i.e. centrifugal separation) is needed to finally obtain clean fibers, mainly composed by the nylon 66 polymer. Through this cleaning process also the residual rubber powder is obtained.

In order to verify the technical feasibility of the reuse scenario, two sets of compounding have been preliminarily carried out. The first series aimed to:

- check the extrudability of the clean fiber;
- verify the extrudability and injectability of a compound prepared with non-virgin PP.

The first series of compounding (Fig. 1) allows to demonstrate the possibility to produce compound by extruding low melting polymers as PP with ELT clean fibers. In particular, a low process temperature has been used in order to limit the polymer degradation and to avoid fibers carbonization.

Fig. 1. First series of compounding

The second series of compounding focused on the verification of mechanical tests: tensile, Vicat and impact. Two different types of material were tested: (i) virgin PP with 0% fibers content, and non-virgin PP from waste loaded with 50% of fibers (in weight).

The tensile tests were performed at a speed of 10 mm/min. Results are reported in Table 1.

Table 1. Tensile tests results of the compounds reinforced with fibers.

Fiber quantity [%]	Max Stress [MPa]	Deformation % to max stress [%]	Max deformation [%]	Young module [MPa]
0%	28.72	9.2	712	1465
50%	23.92	7.96	12.22	1305

The Vicat test, performed according to the ISO 306:2004 standard, allows to evaluate the penetration resistance of the material. The following Table 2 shows the Vicat test results.

Table 2. Vicat test results of the compounds reinforced with fibers.

Fiber quantity [%]	1st test value	2nd test value	3rd test value	Average value
0%	84	86	85	85
50%	78	80	81	79.7

The impact test was performed according to the parameters shown in the Table 3.

Table 3. Parameters used for the impact test.

Parameter	Value
Method	IZOD
bat [J]	11
Velocity [m/sec]	3.46
Thickness [mm]	4.00
Width [mm]	8.00

Table 4 shows the average values obtained for each type of tested material.

Table 4. Impact test results of the compounds reinforced with fibers.

Fiber quantity [%]	Resilience [KJ/m^2]
0%	5.6
50%	12.03

Results prove the technical feasibility of the developed reuse scenario. Some negative characteristics can be observed for the PP compound loaded with 50% of fibers: a lower elastic module value (i.e. Young module) and a lower maximum deformation value. However, an interesting increase of more than 50% of resiliency has been obtained.

2.1. Details of the EoL scenarios

Fig. 2 reports the details and the main processes involved in each considered scenario.

The scenario ① concerns the fiber disposal in landfill. In general, the landfilling scenario is not an environmental friendly solution, since fibers, like many other synthetic polymers, are not biodegradable. Landfills are facilities which, by nature, produce several impacts on the environment, such as land use or generation of liquid and gaseous contaminants. Data about landfill scenario has been taken from scientific literature (e.g. [20][21])

The incineration process (scenario ②) allows to recover energy contained in the material chemical structure and results in a waste volume reduction of 90–99%, with positive impacts in the quantity of materials to dispose in landfills. In this scenario, the destruction of foams and granules resulting from plastic solid waste also destroys CFCs and other harmful blowing agents. A number of environmental concerns is associated with co-incinerating plastic solid wastes, mainly emission of air pollutants such as CO2, NOx, Sox, VOCs and particulate matter. Data on the energy recovery processes have been taken from scientific literature (e.g. [22][23][24]).

Concerning the reuse scenarios ③, two different compound preparation technologies have been considered in this study: (i) the "traditional" extrusion process (scenario 3.1), and (ii) the Banbury process (scenario 3.2). The following items have been considered to analyze the environmental impact of the three identified scenarios:

- *Fiber cleaning*: after the shredding of ELTs, a specific centrifugal separator has to be used to finally obtain clean fibers and rubber powder. This process is performed in all the scenarios (it would not be necessary in the cases of landfill and energy recovery) essentially for economic reasons: (i) reduction of waste weight, that means cost reduction related to transport and disposal, and (ii) economic revenue from the commercialization of the recovered rubber powder;
- *Transportation* phases are needed in all the considered scenarios: from the ELTs recycler to landfill for scenario ①, from the ELTs recycler to incinerator for scenario ②, from the ELTs recycler to the compound producer for scenario ③;
- *Pellets production*: in order to be used in compound production, fibers have to be compacted to produce fiber pellets. This allows minimizing the volume and facilitates the transport and the use in extrusion processes. The compaction requires the use of paraffinic waxes as binders;
- *Pellets packaging*: fibers pellets are packed in big bags to be transported toward the compound producer;
- *Plastic waste shredding*: plastic wastes or scraps have to be shredded (or pulverized), in order to be used in the successive extrusion processes;
- *Compound production 3.1*: in this sub-scenario, the compound is produced through a co-rotating twin screw extruder, an equipment commonly used for plastic compound production;
- *Compound production 3.2 (1° step)*: in the first step of this sub-scenario, non-virgin PP and fibers are mixed through a specific Banbury mixer;
- *Compound production 3.2 (2° step)*: after the Banbury mixing, an extrusion process (single screw extruder) is needed to obtain a homogeneous compound, with acceptable quality and performance.

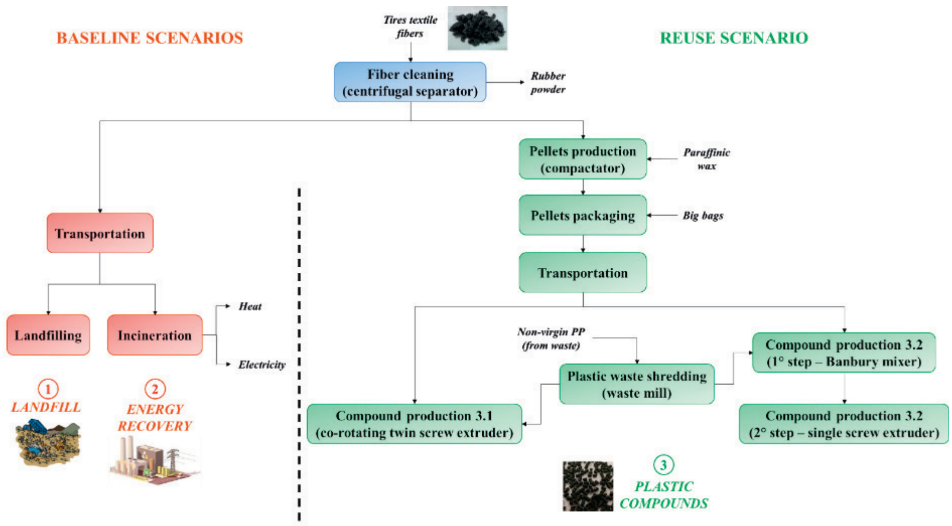

Fig. 2. EoL scenarios for tires textile fibers.

3. Environmental life cycle evaluation

The goal of this study is to calculate the environmental impacts related to the end of life of the textile fibers obtained from ELTs. The activity was carried out in collaboration with two Italian company: STECA S.p.a. an authorized recycler of ELTs, and TECNOFILM S.p.a., a producer of plastic compounds. The functional unit is defined as "dispose of the annual output of 787.5 tonnes of fibers derived from ELTs treatment carried out by STECA".

The study refers only to a specific step of the fiber life cycle. In particular, the study includes all the processes starting from the production of fibers in STECA until its disposal in landfill, incineration or reuse in plastic compounds. The system boundaries for the different scenarios considered, as well as the processes and activities included in the study, are summarized in Fig. 2.

Concerning the Life Cycle Inventory (LCI) phase, most of the data used is data of "background", which means they have been communicated by the involved companies, STECA and TECNOFILM. The exceptions are relative to:

- big bag unitary weight and composition that were obtained through a literature research;
- the production of wax paraffin that was obtained by consulting the "Professional" database of GaBi software;
- landfilling and energy recovery processes that were characterized through a literature analysis (see section 2.1).

Concerning allocation, the following hypothesis have been used for the analysis:

- mass allocation has been used to divide the environmental impact between the two outputs of the cleaning process: clean fibers and powder rubber. On the basis of experimental data, the 70% of the impacts have been allocated to clean fibers, while the 30% to rubber powder;
- system expansion has been used in case of non-virgin PP used to prepare fiber reinforced compounds. In particular, the avoided production of an equal quantity of virgin PP has been included in the analysis.

The inventory data are summarized in the Table 5.

The LCIA (Life Cycle Impact Assessment) method used for the calculation of the environmental impacts is the ReCiPe mid-point - Hierarchist (H) version – Europe [19].

Results shown in Table 6 and Fig. 3 demonstrates that reuse scenarios are promising solutions to reduce the environmental load related to tire textile fibers obtained from ELTs.

Table 5. Inventory data of the three EoL scenarios for tires textile fibers.

Scenario	Flow	Quantity
Common to all scenarios	Dirty fibers	1125 tonnes
	Electricity for fibers cleaning (quantity allocated to clean fibers)	640 MWh
	Clean fibers	787.5 tonnes
Landfill	Euro 5 trucks load	23 tonnes/travel
	Distance	900 km
Energy recovery	Euro 5 trucks load	23 tonnes/travel
	Distance	900 km
Reuse in plastic compounds	Paraffinic wax for pellets production	0.15 kg wax / kg fiber
	Electricity of pellets production	200 MWh
	PP for big bags production	340 kg
	Euro 5 trucks load	23 tonnes/travel
	Distance	50 km
	Non-virgin PP	603.75 tonnes
	Electricity for plastic waste shredding	169 MWh
	Electricity for compound production 3.1	422.63 MWh
	Electricity for compound production 3.2 (total)	528.28 MWh

Table 6. Details of the environmental impacts related to each flow in the three EoL scenarios for tires textile fibers.

Scenario	Process	Climate Change [kg CO2 eq.]	Fossil depletion [kg oil eq]	Freshwater eutrophication [kg P eq]	Ozone depletion [kg CFC eq]	Particulate matter formation [kg PM10 eq]	Terrestrial acidification [kg SO2 eq]
Landfill	Landfilling	6.02E+05	7.02E+03	8.44E+01	-1.18E-06	2.62E+02	1.06E+02
	Transportation	3.97E+04	1.31E+04	1.87E-01	3.23E-08	1.78E+01	4.98E+01
	Electricity consumption	2.87E+05	8.57E+04	1.38E+00	1.08E-05	1.33E+02	4.48E+02
	Total impact	9.29E+05	1.06E+05	8.60E+01	9.68E-06	4.13E+02	6.04E+02
Energy Recovery	Incineration	1.80E+06	1.93E+04	7.70E-02	3.31E-07	9.28E+02	2.43E+03
	Electricity generated	-1.36E+05	-3.05E+04	-6.22E-01	-3.39E-04	-6.73E+01	-2.11E+02
	Heat generated	-2.99E+04	-6.92E+03	-8.57E+00	-1.62E-06	-4.53E+02	-1.24E+03
	Transport	3.59E+04	1.18E+04	1.69E-01	2.92E-08	1.60E+01	4.48E+01
	Electricity consumption	2.87E+05	8.57E+04	1.38E+00	1.08E-05	1.33E+02	4.48E+02
	Total impact	1.95E+06	7.94E+04	-7.56E+00	-3.29E-04	5.58E+02	1.47E+03
Reuse in Plastic compound (Traditional)	Avoided PP production	-2.63E+06	-2.40E+06	-4.07E+00	-4.17E-06	-1.27E+03	-4.00E+03
	PP fiber	7.84E+02	6.22E+02	1.29E-03	7.89E-09	5.12E-01	1.52E+00
	Wax paraffins	1.26E+05	1.45E+05	3.42E-01	4.88E-07	1.05E+02	3.73E+02
	Transport	4.23E+03	1.39E+03	2.00E-02	3.44E-09	1.89E+00	5.31E+00
	Electricity consumption	6.41E+05	1.92E+05	3.08E+00	2.42E-05	2.99E+02	1.00E+03
	Total impact	-1.86E+06	-2.06E+06	-6.26E-01	2.06E-05	-8.62E+02	-2.62E+03
Reuse in Plastic compound (Banbury)	Avoided PP production	-2.63E+06	-2.40E+06	-4.07E+00	-4.17E-06	-1.27E+03	-4.00E+03
	PP fiber	7.84E+02	6.22E+02	1.29E-03	7.89E-09	5.12E-01	1.52E+00
	Wax paraffins	1.26E+05	1.45E+05	3.42E-01	4.88E-07	1.05E+02	3.73E+02
	Transport	4.23E+03	1.39E+03	2.00E-02	3.44E-09	1.89E+00	5.31E+00
	Electricity consumption	6.89E+05	2.06E+05	3.31E+00	2.60E-05	3.21E+02	1.08E+03
	Total impact	-1.81E+06	-2.05E+06	-3.99E-01	2.23E-05	-8.40E+02	-2.54E+03

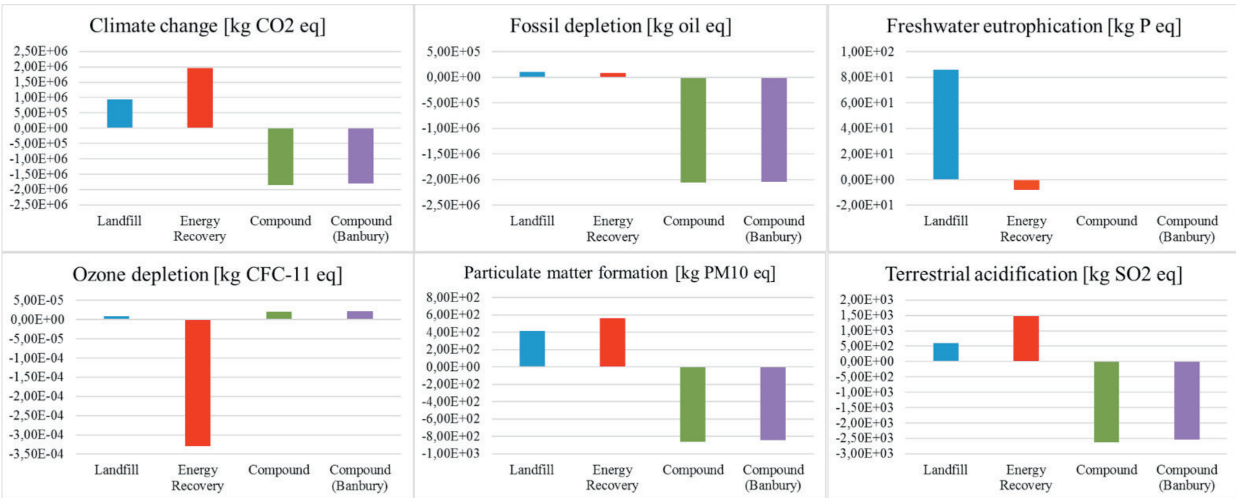

Fig. 3. Environmental impacts of the three EoL scenarios for tires textile fibers.

Going into more details, reuse is the best scenario in terms of “Climate change”, while energy recovery scenario leads to very high impacts. This is mainly due to the incineration process that certainly causes relevant emissions of toxic substances. In the "landfill" scenario, significant impacts are caused both by the release of biogas due to waste and by the consumption of electricity for the cleaning of the fibers.

Considering the "Fossil depletion" indicator the situation is even more pronounced. Reuse scenarios lead to a positive gain, as reuse allows to save fossil fuels (coal, oil, etc.) due to the avoided production of virgin PP that can be substituted by using non-virgin PP from waste and tire textile fibers.

Regarding impacts related to the excess enrichment of nutrients in water (“Freshwater eutrophication” indicator), the landfill scenario is the most impactful, due to the potential release of leachates in land and groundwaters.

Considering the "Ozone Depletion Potential" (i.e. relative measure of the ozone depletion capacity) the energy recovery is the most environmental friendly scenario, due to the gain in terms of electricity and heat produced. In this case the reuse scenarios are the worst options, due to the consumption of electricity to treat the fibers and to prepare compounds.

"Fine Particulate Matter" (PM10) represents a complex mixture of organic and inorganic substances that can potentially cause health problems by reaching the upper part of the airways and lungs when inhaled. Both the landfill and the energy recovery scenarios have significant impacts. Particularly in the energy recovery scenario, despite the gains in heat and electricity production, there is a significant overall impact due to the plastic combustion process. In the reuse scenarios, the avoided use of fuels for the production of virgin PP leads to relevant environmental savings.

"Terrestrial acidification" is characterized by changes in soil chemical properties following the deposition of nutrients (namely, nitrogen and sulphur) in acidifying forms. In the reuse scenarios, the avoided use of fossil resources for the production of virgin PP leads to relevant environmental savings. In the landfill scenario the greatest impact is due to electricity consumption for fiber cleaning. Finally, the worst option is the energy recovery scenario with the incineration process that strongly contributes to the total impact.

4. Conclusions

This paper presents a comparative environmental evaluation of three different end of life scenarios of textile fibers recovered from ELTs. The most common EoL scenarios for this material are landfill and incineration for energy recovery. In this study, also a reuse scenario (application as reinforcement in PP plastic compound) is considered. The LCA methodology has been used to perform the environmental evaluations. The analysis considers all the processes and activities from the production of the textile fiber (obtained through the shredding of the ELTs) to the disposal or incineration or reuse of this material.

From the analysis, it is not possible to univocally identify the best scenario, although reuse scenarios appear to be very promising. Depending on the considered indicator the lower impacts have been obtained for the reuse or the energy recovery scenarios. Landfill scenario, which is currently the most common and the less expensive for the STECA company, can be never considered as the most environmental friendly solution for the management of EoL tire textile fibers.

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