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Review

A Review on Management of End of Life Tires (ELTs) and Alternative Uses of Textile Fibers

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Abstract: Annually, approximately 3 billion tires are commercially transacted worldwide each year and an equivalent amount is disposed of by the end of their life. Despite the increase in the life of tires and the global economic and pandemic crisis, the number of discarded tires is going to rise further due to the increasing demand for vehicles worldwide (approximately 5 billion tires by the end of 2030). The obsolete methods of tire disposal, including landfill, burning, etc., are a responsible for environmental issues (harmful substances production, air and soil pollution) and for the transmission of various diseases. Nowadays, approximately 70% of the total tires at the end of their life (ELTs) is recovered. The largest percentage of the recovered ELTs is intended for energy production or recovery as a fuel in cement industries or can be used for the production of various materials. A significant amount (approximately 95%) of the discarded ELTs can be reused. The products from the processing of ELTs can be fragments of different sizes and types, including: Trimmed rubber (70% by weight), steel wire (5–30% by weight), and fluff or textile fibers (up to 15% by weight). From the aforementioned materials, rubber and steel wires are mainly recovered and used for numerous applications. However, current ways of utilizing these materials will have to adapt or change in the near future, in order to comply with stricter regulations. The purpose of the current study is to sufficiently review recent progress on the management of ELTs, focusing on alternative uses of textile fibers such as additive for sound absorbing materials, bituminous conglomerates, concrete production, plastic materials, soil reinforcement, etc.

Keywords: end of life tires; energy recovery; material recycling; rubber; textile fibers

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Citation: Grammelis, P.; Margaritis, N.; Dallas, P.; Rakopoulos, D.; Mavrias, G. A review on Management of End of Life Tires (ELTs) and Alternative Uses of Textile Fibers. *Energies* **2021**, *14*, 571. https://doi.org/10.3390/en14030571

Received: 22 December 2020
Accepted: 20 January 2021
Published: 22 January 2021

1. Introduction

The constant increase of waste around the world is one of the most important issues that modern society is called to face, as they are connected to global pollution. In the United States, for more than 20 years, the rate of rubber waste production approximately 290 million/year [1]. Disposal of these high numbers of waste was an issue as they are non-biodegradable and non-condensing products, which remain on the landfills. Thus, nearly 2 billion tires were stored in the United States. The long-term storage of tires, without proper management, can lead to fire, toxic, and health hazards [2,3].

Initially, many countries have chosen landfill disposal as an option for managing old tires. However, this option was soon abandoned as tires occupy a huge volume in landfills and increase the risk of ignition. The impermeability of landfills is not always ensured, which means that hazardous substances generated during the decomposition of tires can penetrate the ground and affect the surrounding area. In this manner, they may pollute the water and the soil and can have harmful effects on the living organisms. Apart from the aforementioned, the burial of the tires was abandoned as these materials can be reused.

Another important point is that the production of ELTs (end of life tires) constantly increase worldwide. This is also the case at the European level, according to the European Tire and Rubber Manufacturers Association (ETRMA) [4]. Thus, the implementation of new technologies in order to manage ELTs, in an environmentally efficient and sustainable way, is imminent. In recent years, several plans have been prepared by the European Union (EU) concerning the management of waste. These plans aim at incorporating the reuse of wastes as raw materials following the norms of the circular economy [5,6]. A significant amount of the existing solid waste is the end-of-life vehicles (ELVs) and consequently the end-of-life tires (ELTs). Therefore, these types of waste are very high in EU waste legislation agenda. Thus, EU has included specific directives in this area [7]. Both European and national legislations are mainly based on the extended producer responsibility, concerning those involved in the waste management of their products [8]. In Italy, for example, the disposal of ELTs is carried out by various consortia formed by tire producers operating at the national level and by various authorized recycling companies, which are governed by a specific legal framework.

Part of the problem can be tackled by using tires as alternative fuels, after proper treatment. In Europe, the relatively recent Directive 2008/98/EC [9] on the waste management along with Directive 2009/28/EC [10] that subsidizes the biomass fraction of waste led to the reduction of landfills, increase of recycling of special waste streams (tires) and municipal solid waste (MSW), and the production of secondary fuels (RDF-refuse derived fuel, SRF—solid recovered fuel, etc.), which are already used as energy recovery materials in various applications (cement industry, central cogeneration units, large thermal power plants, etc.). “Alternative fuels” is a broad designation that includes any type of non-fossil solid fuel. Therefore, biomass fuels or fuels recovered from waste fall within this definition. The list of alternative fuels also includes tire-derived fuels (TDF), fuels deriving from tires that have reached the end of their life cycle. A list of European directives and regulations concerning the management of tires is presented in Table 1.

Table 1. European legislation concerning treatment of End of Life Tires (ELTs).

Year	Title—Reference	Content
1975	Council Directive 75/442/EEC (modified by Directive 2008/98/EC) [11]	ELTs characterized as non-hazardous wastes
1993	Council Regulation (EEC) No 259/93 [12]	Shipments of wastes—Supervision & Control (code: 4012 20 Used pneumatic tires)
1999	Council Directive 1999/31/EC [13]	Prohibition of tires disposed in landfills (whole tires 2003-shredded tires 2006)
2000	Commission Decision 2000/532/EC [14]	End-of-life vehicles are coded as “16 01 03”
2000	Directive 2000/76/EC [15]	Specific emission standards for the cement industry with effect from 2002.
2000	Directive 2000/53/EC [7]	Recovery of 85% of vehicles to be disposed off, with effect from 2006, with compulsory removal of tires from the vehicle
2001	Commission Decision 2001/118/EC [16]	ELTS classification code 16.01.03, (from 1 January 2002)
2005	COM (2005) 666 [17]	Features the need for additional actions in order to determine the optimal environmental options and targets for wastes. Includes the principle of producer responsibility
2008	Directive 2008/98/EC [9]	Basic principles of waste management (“the polluter pays” & “waste management hierarchy”). Introduces the waste end principle.
2009	Directive 2009/28/EC [10]	Mandating the levels of renewable energy use within the European Union from 2009 to 2021
2010	CEN TS 14,243 “Materials produced from end of life tires—Specification of categories based on their dimension(s) and impurities, and methods for determining their dimension(s) and impurities” [18]	Characterization of the materials resulting from ELTs in terms of dimensions and impurities including sampling and testing methods.
2018	Directive EU 2018/851 [19]	Amendments to Directive 2008/98/EC on waste (incl. legislation for treatment of waste)

During the last decade, there has been an increasing number of tires being discarded as ELTs. The new methods for the treatment of ELTs tend to engage more environmentally friendly solutions, such as recycling and energy recovery. More specifically, in 2018, more than 3.1 million tons of ELTs was managed in the EU28, which led to 1,815,220 t of material recovery and 1,150,880 t ELTs were used for energy purposes [20]. This means that approximately 94% of ELTs were treated. Regarding the recovery of materials, 95,620 t of ELTs were used in civil engineering projects. On the other hand, 1,719,600 t of these materials were recycled. According to ETRMA (European Tire and Rubber Manufacturer's Association), material recovery is gaining ground as ELTs management option in EU [4]. Indicatively, in 1994, approximately 32% of European ELTs were recovered, while 68% were used for energy purposes. In 2007, the recovery of materials had risen to 54% while ELTs used for energy recovery reduced to 46%, and this proportion continues to change in 2013 to 48% and 52% and in 2018 to 58% and 36%, respectively. Typically, in Germany, over the last 20 years recycling has increased its share of ELTs management from 13% to 35%, while treatment for energy purposes reduced approximately by 15% (from 53% to 37%). In Greece, tires from all types of vehicles (agricultural machinery, heavy-duty vehicles, etc.) are converted into waste when they are no longer used. These tires are then collected and are used depending on demand. Management of tires mainly includes mechanical recycling (60% of the available ELTs) and thermal recovery (40% of the available ELTs). Finally, in a study conducted in EU concerning life cycle analysis of ELTs, the results showed that by recycling an amount of approximately 400,000 t of ELTs, which can be used as artificial turf, a reduction of approximately 280,000 t CO_2/year can be achieved [21].

Based on the aforementioned and due to the fact that legislation concerning ELTs is becoming more and more stringent, new alternative options of managing these wastes should be discovered. Thus, it is evident that the reuse of tires is necessary since, apart from the reduction of health and environmental risks, it will contribute to the promotion of circular economy. The present study focuses on recent aspects concerning the management of ELTs and new alternative ways of treating textile fibers, a byproduct of ELTs processing that so far has not attracted much of the attention of recent literature.

2. Composition of ELTs

The main material of tires is the rubber into which additives are introduced (textile, steel, wire, etc.) [22–24]. In tire manufacturing, the following criteria must be met: (a) Support of dynamic loads; (b) overcoming various obstacles; and (c) relatively long service life. In addition, the tires should: (a) Be resistant to mechanical stresses; (b) contribute to smooth driving; and (c) provide slippage resistance. Tire fabric provides structural integrity, resistance to wear, and traction control. Tire fibers consist of several layers e.g., rayon, nylon, and polyester. These layers provide resistance to mechanical wear and structural integrity. Structural integrity and the high level of resistance to wear is due to the adhesion between the fabrics and the rubber. This is achieved by inserting a steel or brass wire at the circumference of the side walls, which ties the layers of fabrics. The layers adhere firmly to the rubber, while the tire is subjected to repetitive and different types of stress. Therefore, the strength of tires and their ability to perform in extreme conditions is directly related to the adhesion of fabrics to the rubber surface. The types of tire configuration vary from manufacturer to manufacturer.

2.1. Rubber, Steel Wire and Textile Fibers

Tires of passenger cars contain higher amounts of synthetic rubber, while truck tires have a higher percentage of natural rubber. In the case of heavy-duty vehicles, the tires do not contain synthetic rubber. The composition of the material of the tires varies depending on the use. Thus, tires may contain approximately 70% rubber, 5% to 30% steel, and textiles (Figure 1) up to 15% [25]. The percentage of fabric in passenger car tires accounts approximately to 5% of the total mass of the tire, while in the case of heavy-duty vehicles the proportion of the fabric of the tires is smaller and in some cases there may be no fabric at all. On the other hand, the tires of these vehicles contain approximately 15% steel wire. Typical tire composition for passenger and heavy-duty vehicles (trucks, etc.) is given in Table 2. The belts of the tires of passenger cars consist mainly of steel (approximately 99% wt.) and aramid (approximately 1% wt.), which is also the case for the belts truck [23]. Although, when it comes to the composition of the tires' body, the composition of passenger cars and trucks differs. In the case of passenger cars, the body of the tires consists mainly of polyester and rayon, while the body of the tires of trucks most commonly consists of steel, polyester and nylon.

Figure 1. Textile fiber derived from ELTs.

Table 2. Typical composition of tires. Reproduced from [4], ETRMA.

Composition	Passenger Cars	Trucks
Rubber	47%	45%
Carbon Black	21.5%	22%
Steel	16.5%	25%
Fiber	5.5%	0%
Zinc Oxide	1%	2%
Additives	7.5%	5%

A typical tire can be produced by the utilization of materials such as synthetic rubber, mainly IIR (Isobutylene Isoprene Rubber), SBR (Styrene Butadiene Rubber), vulcanized natural rubber (NR), and various components that are added in order to give the desired properties to the tire (e.g., mechanical strength) [24]. A tire consists not only of rubber, but also of carbon, zinc oxide, sulfur, additives, steel wire, and fiber, which give the tire its final shape and properties. Significant differences in chemical composition and rubber structures are the reasons that tires are extremely resistant to biodegradation, photochemical decomposition, chemical reagents, and high temperature. This is the reason that managing of tires poses as a technological, economic, and environmental challenge.

Unlike rubber and steel of tires that are reused in various fields of application, tire fiber is characterized as a special waste (under CER—certified emission reduction code 19.12.08) that requires proper treatment [25]. A significant limitation of the tire recycling process is due to the difficulty in separating their components (rubber, fiber, and steel). As a result, fiber contains rubber quantities, which are a major obstacle to its recycling. This means that tire fiber is not a cheap and high-quality product, free of impurities. Based on CERTH's laboratory tests, according to ISO 3310-1:2000, typical proportion of textiles, after separation, is given in Table 3.

Table 3. Distribution of textile fiber and remaining rubber after separation.

Distribution	Total Quantity	Rubber	Textile Fiber
1000 µm	76.4–91%	0.5–11.8%	64.6–92.6%
1000–800 µm	0.3–6.3%	0.3–6.3%	>0.1%
800–500 µm	0.7–7.9%	0.7–7.9%	-
500–250 µm	0.6–5.8%	0.6–5.7%	>0.3%
<250 µm	1.9–5.6%	1.5–5.2%	>0.4%
Total		7–35.2%	64.7–93%

In Europe, approximately 320,000 t of tire fiber are disposed of annually as special waste [25]. This leads to environmental impacts, financial losses, and public spending. Fibers and wires are used, as mentioned, to reinforce the rubber of the tires. This reinforcement can be achieved in numerous ways, e.g., various alternating layers of rubber and wire or wires entirely placed inside the rubber. As mentioned previously, these materials must bind together and should not be separated from the rubber.

Chemical Characterization of Textile Fibers

CERTH's laboratory investigated the utilization of textile fiber as a secondary material produced during the processing of used tires. The textile fibers were collected from a representative industrial plant in Greece, which recycles vehicles tires. The industrial processes include mechanical granulation of the tires in order to remove the metal and synthetic fibers. Textile fibers were separated gravitationally with the implementation of air floatation. Sampling of textile fibers by CERTH was performed according to CEN/TS 14,243 [18]. CERTH conducted various analyses for the characterization of textile fiber as fuel in accordance with the latest European standards resulting from the technical instructions of the CEN 343 Committee. These included: (a) Proximate analysis; (b) determination of calorific value; (c) ultimate analysis; (d) determination of major and trace elements; (e) determination of ash fusion temperatures; (f) determination of ignition point; and (g) SEM (scanning electron microscope) analysis. Typical results of textile fibers are presented in Table 4. In Table 5, results including the concentrations of major and trace elements of textile are illustrated. Table 6 depicts a typical ash melting behavior of the textile fibers, which justifies the notion of deposits formation on furnace walls. The ignition-point determination, as can be seen in Figure 2, was conducted in a thermogravimetric analysis system [26]. The onset of ignition occurs at 366.3 °C, which is higher when compared to typical fuels such as biomass and lignite (Figure 2). Finally, SEM analysis (×150, ×300) was conducted in order to determine the geometrical characteristics and the composition of typical textile fiber (Figure 3).

Table 4. Typical analysis results for textile fiber.

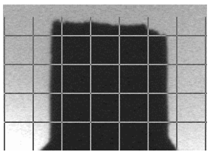
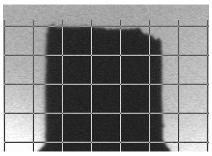
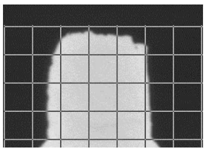
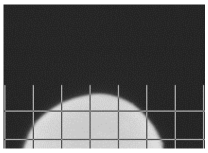
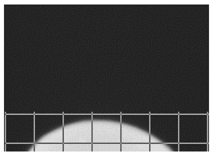
Moisture (wt.%, a.r) (CEN/TS 15414-1)	Proximate Analysis (w.t%, db) (EN 15414-3, 15402 & 15403)		Ultimate Analysis (wt.% db) (EN 15407, 15408 & ASTM D 516)						NCV, d.b. (MJ/kg) (EN 15400)	GCV, d.b. (MJ/kg) (EN 15400)
	Volatiles	Ash	C	H	N	S	Cl	O *		
1.3	72.3	7.1	79.34	7.75	0.64	1.12	0.11	11.04	31.75	33.39

* calculated by subtracting the other elements, d.b: dry basis, a.r.: as received.

Table 5. Typical concentrations of major and trace elements of textile fiber.

Concentrations (ppm, d.b. ash) (EN 15410 & 15411)							
Cd	Cr	Cu	Mn	Ni	Pb	Zn	Co
3.62	37.44	4251.06	315.2	7.08	267.34	192,732.72	1851.24
Al	Ca	Fe	K	Mg	Na	Si	
6821.1	51,245.91	45,707.05	8747.28	9450.78	6365.88	79,624.45	

Table 6. Ash melting behavior of typical textile fiber.

Ash Melting Behavior (CEN/TR 15404)				
Initial Temperature	**Shrinkage (ST)**	**Deformation (DT)**	**Hemisphere (HT)**	**Flow (FT)**
400 °C	732 °C	1060 °C	1151 °C	1164 °C
				

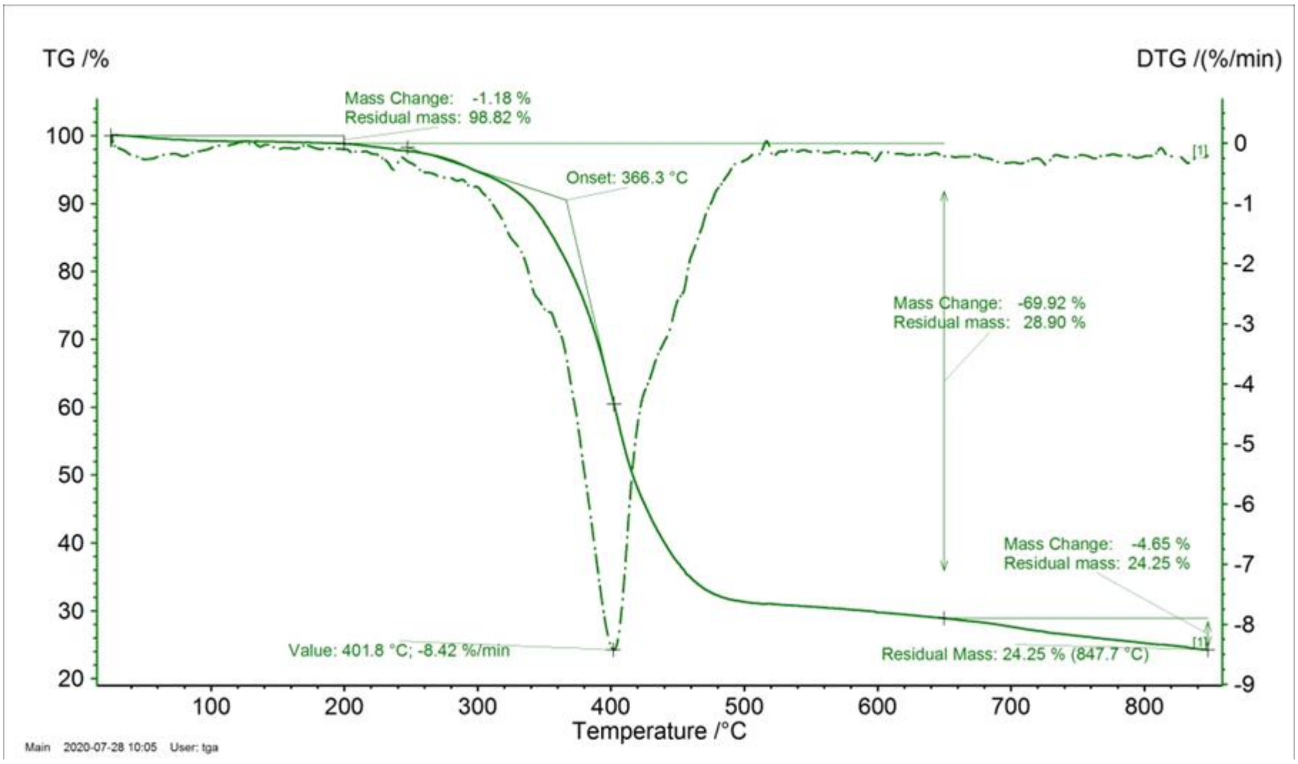


Figure 2. Ignition point determination of typical textile fiber.

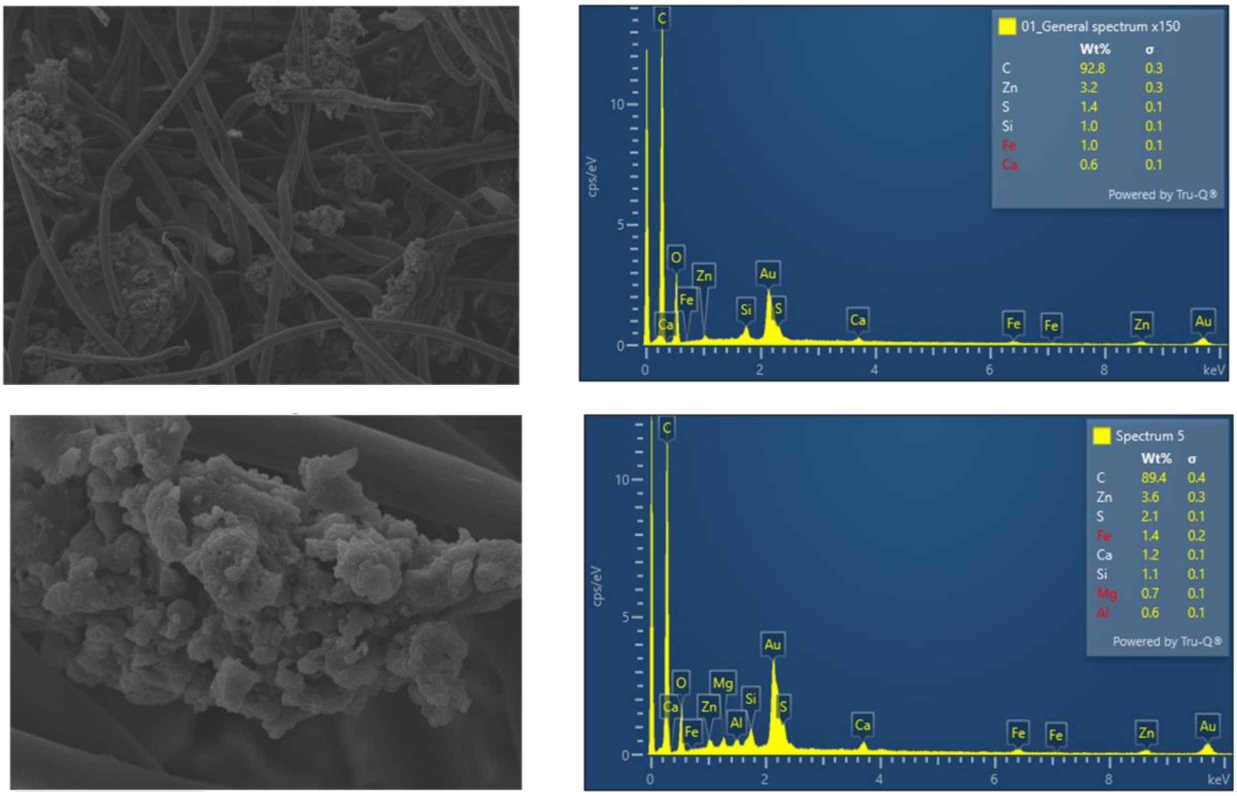


Figure 3. SEM of typical textile fiber (×150, ×300).

3. Management of ELTs

Within the EU directives, EU Courtiers are flexible to form national legislation to achieve EU targets complying simultaneously with the EU legislation. The EC Directive 1999/31 [13] set the basis for ELTs management so that within EU, nowadays, three (3) options for managing ELTs exist: (i) Extended Producer Responsibility (ERP) Scheme; (ii) Free Market System; and (iii) Tax System [27].

EPR means that the producer is fully or partially responsible for an end-of-life product, hence the original manufacturer has to guarantee that the waste deriving from its products is disposed of in an environmental manner, shifting the cost of managing the waste from the local solid waste agencies to the producers [28]. Many not-for-profit companies have been initiated and financed by tire producers in order to collect and recover the ELTs [29].

Under the Free Market System, all members involved in the recovery chain of a product are contracting under these systems conditions, acting though according to the legislation. Countries adopting this kind of tire management are Austria, Switzerland, Germany, and the UK. In particular, UK operates a so-called "managed free market", which requires reporting to the countries' authorities.

The third model is the Tax System, where within this type national authorities of each country are responsible for ELTs' management. In this model, tax is imposed upon tire producers, which is indirectly paid by the consumer. Croatia and Denmark apply such a management system.

In total, the most widely tire management system applied in Europe is the EPR scheme implemented at least in 21 countries [30], while some countries are moving from one system to another. EPR tire system should promote: (a) The reduction, reuse, and recycling of tire waste and (b) the energy recovery [31].

3.1. Energy Generation

"Energy Recovery" refers to specific methods for converting waste to energy, including heat, electricity, or fuel production. These non-recyclable materials can be transformed to the aforementioned options via numerous processes (combustion, pyrolysis, gasification, etc.) [32].

3.1.1. Combustion

The large-scale recovery of energy from waste in incineration plants is a high-cost technology, common mainly in developed countries. Open burning of course is not encouraged, due to harmful emissions and severe air pollution. Tire-derived fuel (TDF) made from ELTs seems a cost-efficient alternative to fossil fuels mainly for cement manufacturers, whose energy consumption is one of their largest expenditures. TDF's heating value is approximately equal to the heating value of oil, but almost slightly higher than the heating value of coal. Moreover, its use reduces NO_x emissions due to its more efficient incineration [33]. Incineration is the process of combustion for energy recovery and reduction of the waste volume [34]. In Greece, according to Ecoelastika [35], of the 34.65% of the materials used for energy recovery, 3.05% were supplied to the cement production furnaces as inorganic ash and incorporated into the produced product (clinker), while the remaining 31.6% was co-incinerated. Moreover, Global Recycling's statistics [33] state that "1.1 million tons of ELTs were energetically recovered by 81% in cement kilns and by 19% in urban heating and power plants in EU28, Switzerland, Norway, Serbia, and Turkey".

3.1.2. Pyrolysis

Other thermochemical conversion options including pyrolysis/thermolysis and gasification provide higher energy efficiencies [36]. Moreover, less gaseous pollutants are formed, so lower volumes of combustion gases demand removal. Pyrolysis of ELTs, or thermolysis, is their thermal decomposition occurring under non-oxidative conditions (inert atmosphere or vacuum), which provides intermediate substances such as oil, char, and gas [37,38]. The efficiency of the process is much higher (20–30% higher) when shredded tires are used instead of whole ones [39]. The chemical products derived from this process may in some cases be used as feedstock for other processes. The proportion of the various products depends on the conditions and the reaction parameters. The maximum conversion of tires takes place at 600 °C, although temperature is not a decisive factor when it comes to the produced amounts of char and gas [40,41].

The char produced during pyrolysis may be very useful in the recovery of zinc [42]. Gas and oil, which approximately account to half of the amount of the products produced by pyrolysis, have an energy content comparable to conventional fuels or even higher (approximately 2 times higher than conventional woody biomass), while char is a fine particulate with low commercial interest because it consists of a complex mix of carbon black—as different types of carbon blacks used by tire manufactures—ash, and other inorganic material. The amount of chlorine content in carbon black may be three times higher when compared to chlorine content of tires [43]. This product may be also used as activated carbon, via chemical activation [44]. Moreover, the flash point of the oil produced during this process is approximately two times lower when compared to the flash point of diesel fuel [45]. This means that the risk of fire hazards is higher when storing this fuel. Similar results may can be obtained for the char and oil derived from tires, when they are treated in distillation unit at 550 °C and 1 atm, although the high content of sulfur may be problematic [46].

As for the gas products, these require significant cleaning due to the existence of hydrogen sulfides that can prove to be problematic. The gas products account to 10–30% of the ELTs products and reach a calorific value of 30–40 MJ/Nm^3 [44]. The economic feasibility of tire pyrolysis is strongly influenced by the value of the latter one [47,48], while the economic viability while economic viability is hindered by the fact that the prices obtained for the by-products frequently fail to justify the expense of the operation. As of

2015, approximately 1% of Italy ELTs are pyrolyzed for material recovery purposes aimed at products [42].

3.1.3. Gasification

Gasification is more complex when compared to pyrolysis, as chemical reactions occur on the material [49]. In gasification process, partial combustion of organic substances takes place. This process produces gases that can be used as feedstock or as a fuel. There are three distinctive gasification processes: (a) Common gasification; (b) plasma gasification; and (c) solar-assisted gasification. Similar to pyrolysis, the gasification process produces gases with high carbon and hydrogen contents, although the gaseous fraction in gasification is significantly higher when compared to the gases produced by pyrolysis [39]. On the other hand, the oil production in gasification is very low in high temperatures owing to thermal cracking, while the char production in low temperatures is comparable to the char produced in pyrolysis. The gasification of ELTs when using plasma may increase the hydrogen content to 99% [50]. Pressure is very important in the gasification process as its increase may result in higher yield, calorific value, CO, and H_2 contents [48], whereas when operating temperatures increase the syngas production is increased and the char yield is reduced [51]. The contribution of pressure is similar, even in the case that the char results from the distillation of scrap tires [52]. In higher temperatures (>1000 °C), the concentration of the produced gases changes and the predominant gas is H_2 instead of CH_4 [53]. Gasification and pyrolysis emit similar pollutants, but at lower concentrations compared to incineration and at smaller amounts, because of the processes' lower temperatures and of the low stoichiometric ratios used for these processes, respectively [36,39].

3.2. Material Recycling

ELTs recycling can provide whole tires or shredded materials of different sizes and types. Whole tires can directly find usage in various applications such as coastal protection, artificial reefs, slope stabilization, insulation, etc., while shredded materials can be used at cement and automotive industries or can be valuable secondary raw materials for building constructions, asphalt mix, and in civil engineering applications.

Products from ELTs that are mechanically sheared include rubber granules or chips (about 70%), steel (iron granules) (5–30%), and textile (fiber, tire fluff) (up to 10%) [54]. In Greece, the materials produced after complete mechanical processing of ELTs, via the implementation of shredding and grinding tires, in the recycling units during 2018 were 61% rubber crumb, 22% iron, and 17% textiles [35]. The latter, textile, is a waste with a significant environmental impact, the use of which has two main limitations: It contains a high amount of trapped rubber depending on the method and currently no applications exist for its re-use that makes recycling worthwhile. On the other hand, in some European countries, tire granulation and subsequent pyrolysis processes are carried out [55–57]. The granulation along with the use of magnets eliminates the steel, which simplifies the process [58]. Then, the chars deriving from these processes can be used for activated carbon production [55,59,60]. However, there are also other methods for tire recycling including: (a) Shredding and grinding, (b) ambient scrap tire, (c) pyrolysis, (d) Molectra, and (e) cryogenic crushing [61–64]. Shredding and grinding of tires leads to the production of crumb rubber. The second method includes granulation without cooling where crumbs of rubber are produced. The third method is based on the thermal decomposition under non-oxidative conditions that produces the following substances: (a) Oil, (b) char, and (c) gas. Molectra refers to a number of processes for tire handling including hydraulic removal, chemical treatment, grinding, air floatation, neutralization screening, whereas a major innovation is the recovery of gas and oil. The final method includes the freezing of the shredded materials (most commonly with liquid nitrogen), which are then crushed to crumb rubber of fine quality.

According to the Global Recycling statistics [33], in 2018, "material recovery of 1.9 million tons of ELTs took place mostly by granulation", indicating that 75% of Europe's ELTs were recycled for this scope annually. According to the U.S. Tire Manufacturers Association, approximately 300 million tires/year are scrapped. From the 4189 million tons of scrap tires, of 2017, approximately 81% were marketed; 43% were used as fuel for various industries, 25% were used in applications where ground rubber was required, 8% was used for civil engineering project, and 3% were exported [33].

Civil Engineering Uses

The various uses of used tires in civil engineering projects are described in ASTM D6270 [65], PAS 107 [66]. Table 7 summarizes the various applications of tires in civil engineering works, sport and safety projects, roads, and infrastructures [22].

Table 7. Construction applications with ELTs.

Application	Source				
	Whole Car Tire	**Whole Truck Tire**	**Mixed Whole Tires**	**Truck Tire Tread**	**All Types**
Artificial Reefs	x				
Bridge Abutments	x	x			
Concrete Construction Additives					x
Construction Bales	x	x			
Culvert Drainage Beds	x	x			
Embankments	x	x	x		
Insulation	x	x			
Landfill Drainage Layer	x	x			
Slope Stabilization	x	x			
Temporary Roads	x	x			
Thermal Insulation	x	x	x		
Collision Barriers					x
Lightweight Fill	x	x	x		
Noise Barriers	x	x	x		
Equestrian Tracks	x	x	x		
Soccer/Hockey Pitches	x	x			
Indoor Safety Flooring	x	x			
Playground Surfaces	x	x			
Asphalt Additives					x
Asphalt Rubber	x	x			
Coatings	x			x	
Expansion Joints	x	x			
Road Furniture					x
Sealants	x				
Surfacing	x	x	x		
Train & Tram Rail Beds	x	x			
Wearing Course	x	x			

ELTs can be used in landfills in a number of applications e.g., as materials of drain-collection systems, as protective layer of the surrounding walls, as coverage of the waste, as materials of temporary and internal roads of landfills. In the aforementioned applications, the following sources of ELTs are used: Whole tires (>300 mm), shredded tires (50–300 mm), and tire chips (10–50 mm). The size depends on the cost of the application, the transportation, the availability, the landfill specifications, and the environmental conditions existing on the site of application. Significant parameters are the legal requirements [22,67,68].

Moreover, ELTs can be also used as a light additive in a wide range of civil engineering works, e.g., in retaining structures and embankments, bridge abutment, and as a slope stabilizer replacing aggregates and gravel. In the aforementioned applications, the ELTs that are mainly used derive from whole tires (pieces over 300 mm), shredded tires (50–300 mm), and tire chips (10–50 mm) [3,22,69]. ELTs, owing to their structural strength and stability, can be used as embankments in order to absorb the energy of the moving water.

Thus, ELTs can find application on seashores and rivers. ELTs have also been used to repair corroded kennels and small gorges [22,67,68]. Steel fibers derived from ELTs can be also used as a viable alternative to the common steel that is inserted in concrete mixtures, in terms of fresh and mechanical properties [70].

The implementation of ELTs as noise barriers can effectively reduce noise levels on major highways [71]. For this type of applications, whole or shredded tires are mainly used. Shredded or chipped ELTS can be also used for thermal insulation purposes. The thermal resistance of ELTs is much higher than that of gravel (7–8 times) [22]. In areas with medium or low temperatures, ELTs can be applied as road insulation material or for the insulation of other structures e.g., roofs, drainage [72–74]. These materials can be applied under asphalt to prevent cracking due to low temperatures or even as an additive of water pipes. Rubber in various forms, deriving from ELTs, has been used as an additive to inert materials in mortars and concrete.

ELTs can be used for the production of concrete for special applications, as long as the proper processes are implemented. The produced concrete with ELTs components has a reduced specific weight, increased resistance to cracking, resistance to deformation, and higher ability to absorb vibrations. However, depending on the percentage, size, and type of ELTs used, the concrete may present reduced mechanical properties [75–81].

Rubbers from ELTs can be inserted into asphalt mixtures via: (a) Wet process and (b) dry process [82]. During the wet process, the crumb acts as an asphalt modifier, while during the dry process, chips, crumbs, or powder are used as a fine-grained fraction of aggregates. The wet method is applicable to hot-rolled bituminous mixtures as well as to bituminous coatings. It consists of adding rubber powder (up to 4.75 mm) to the asphalt in a ratio of 18–25%, before adding it to the aggregates. The product produced from this mixture is the modified rubber asphalt. Wet process is the most common one, as improved performance compared to conventional hot mixture asphalts was observed, for most climatic types. Dense composition coatings with rubber-modified asphalt proved to achieve similar performance when compared to layers of conventional thicker mixtures. Asphalt layers modified with rubber have a greater lifespan than layers of conventional mixtures [83–86]. In general, the production cost of powder-modified rubber asphalt is from 20% to 100% higher than that of the common asphalt. In countries like Spain, more than 1000 km of asphalt road modified with tires exist, of which more than 360 km were modified with the dry process and more than 800 km were modified with the wet process.

4. Alternative Uses and Opportunities for the Use of Textile Fibers

Each year, more than 1.5 billion tires are discarded [87] and this may rise as the quantities of the produced vehicles increase. The discarded tires are expected to increase to 5 billion by 2030 [88], while the highest percentage of the end of life tires are sent to landfill or for incineration. Therefore, the proper management of ELTs, such as rubber and textile fibers, is of major importance and is expected to contribute to sustainable development. Proper management of ELTs may result in the production of various valuable products, which can be used in a number of applications. In the following, the opportunities for use of textile fibers are presented, a byproduct of ELTs processing that has not been examined thoroughly in the recent literature, despite the fact that its use seems promising.

4.1. Sound Absorbing Materials

In general, there are many different recycling processes for ELTs, where the steel wire is recovered, and the tire rubber can be reused. Until now, the components of the tires have not been reused. However, these parts, consisting mainly of fabrics, can be partially separated from the tire during the recycling process. The remaining material is commonly known as textile fiber. This component of ELTs can be used to produce a new absorbent soundproofing material, which can provide a simultaneous solution to the problem of both noise pollution and environmental pollution.

Tire fibers obtained from ELTs wastes can be used as components for insulation. From the aforementioned materials, aerogel, a new type of material, can be successfully developed. The work of Gesser and Goswam showed that these new materials have high porosity, low density, large specific surface area, high thermal insulation capacity, and significant acoustic insulation properties [89]. In general, aerogels have great potential since they can be used in the automotive industry as sound absorbing material for vehicles. Nowadays, vehicle noise is an important design parameter, as it is interrelated to the comfort levels of driver and passengers and can help prevent driver's stress levels and fatigue.

Thai et al. attempted to develop elastic aerogel from RCTF (recycled car tire fibers), by using polyvinyl alcohol and glutaraldehyde as cross-linkers via a new refrigeration drying method [90]. In this particular study, aerogels have been thoroughly investigated for applications such as building sound-insulation. The proposed drying method played a decisive role in avoiding shrinkage and collapsing of the new material, as well as in achieving properties such as low density and high porosity. The open porous of the aerogel means that RCTFs have contributed to the formation of the porous network. In addition, the density of aerogels is analogous to the fiber concentration. The acoustic properties of the aerogels were investigated in impedance tubes. The study showed that the increase of RCTF concentration leads to an increase in the contacts between the fibers. This results to higher surface frictions (greater energy losses) and internal reflections (greater frictional losses), which increase the level of sound absorption. When compared to commercial foams, this new material achieved better absorbency, especially at frequencies 2000–3000 Hz.

Maderuelo-Sanz et al. studied the sound properties of materials produced from ELTs tire fibers, with and without the addition of resin [91]. More specifically, the sound insulation behavior of composite materials, consisting of single- and double-layer structures, was analyzed as follows: (a) Recycled rubber particles (GTR—ground tire rubber); (b) fibers; and (c) their combination. The perforated panels were used as a reflective surface in order to measure sound absorption. The new materials were produced via thermal compression. Owing to the different microstructures of the samples, significant differences in their non-acoustic properties were observed. These differences, due to the variation of the porous microstructures, were also responsible for the variation of the acoustic properties of the tested materials. The best performance achieved at 2000 Hz was the absorption coefficient of 0.99. The study showed that the absorption coefficient is connected to the compression that is subjected to the samples. As the compression increases, the sound absorption coefficient is significantly reduced due to the porosity decrease and the increase of tortuosity and flow resistivity. The study also showed that use of resin results in the decrease of the porosity, and the increase of flow resistivity, which leads to the reduction of sound absorption properties of the sample. The single-layer materials were compared with commercial sound absorbing materials (e.g., glass-wool) with approximately the same thickness. The new materials presented equal or better sound absorbing properties. The new materials have higher absorption coefficients at the frequencies 0–2400 Hz, reaching a maximum value (0.99) of the absorption coefficient, whereas the commercial materials achieve maximum value (0.9) of absorption coefficient at higher frequencies (3500 Hz or higher). Finally, double-layer samples were prepared and were compared with the aforementioned single-layer samples. In general, the study showed that the maximum absorption shifts to lower frequencies, higher absorption coefficient achieved at approximately 1000 Hz instead of 2000 Hz, which is due to the thickness increase of the samples.

Jimenez-Espadafor et al. investigated the acoustic properties of new two-layer material using tire fibers containing rubber-residues and ceiling-tiles [92]. The acoustic properties of the new materials were studied by taking into account the density, triturating mesh size in terms of measuring the acoustic absorption coefficient and modeling. The acoustic properties of the new material were investigated with the use of a high (800–6300 Hz) and low-medium (100–2500 Hz) frequency impendence tube. The results showed that the sound absorption coefficient decreases as the density of the material increases. The acoustic behavior tests showed that the static air-flow resistivity increases while the density of the material increases (non-linearly), which leads to higher absorption coefficients. Moreover, the size of the mesh plays an important role on the absorption of lower frequencies, although a specific mesh size exists to achieving the optimal sound absorption. Finally, the study showed that the improvement of the acoustic properties of the proposed materials does not necessarily contribute to the optimization of their mechanical properties.

4.2. Bituminous Conglomerates

Significant progress has been made in recent years in the recycling of ELTs as this material can be used in civil engineering works [93]. Textile can be characterized as a tricky material though, as it cannot be easily separated from the other components that make-up the tire. The study of ELTs fiber for the production of mortars derived from tire components, were rejected due to their high cost of production [94].

In the work of Landi et al., the mechanical properties of ELT fibers as bituminous mixtures were studied [25]. Insertion of the prepared material into a matrix with temperatures lower than the melting point is important, in order to use fibers as reinforcing material. The results of the research showed that fibers can be a promising option in the field of modified asphalts, as higher tensile modulus and fatigue strength values were noticed. Another study investigated the characteristics of hot mix asphalts with ELTs fibers [95]. The results showed no significant improvement in the mechanical properties when compared with the common asphalt mixtures. On the other hand, the fatigue resistance was enhanced, especially when the horizontal stresses were low.

Landi et al. evaluated the economic and environmental sustainability of the use of ELTs fibers. The results showed that ELTs fibers can be reused for the preparation of reinforced bituminous mixtures with improved mechanical performance [96]. ELTs fibers can be a promising substitute for the cellulose that is used as reinforcement in bituminous mixtures, as long as the fibers are properly prepared (proper compression). Moreover, significant benefits were observed when reusing ELTs fiber in terms of reducing the environmental footprint and acidification, compared to the standard incineration process for energy recovery. Finally, tire fibers, in some cases, can be an economically viable option, while no issues can arise for the future use of fibers in real industrial applications based on sensitivity and hazard analyses. When it comes to porosity, the addition of ELTs waste decreased the open porosity and reduced the specific density of the concrete, whereas the open porosity of the material was increased.

4.3. Concrete Production

In previous years, ELTs were burned in cement industry furnaces. In recent years, many scientists have investigated the use of tire waste in the production of building materials. The trimmed rubbers of ELT were tested for the manufacturing of ceramics, bituminous mixtures, and concrete [97–100]. In the field of civil engineering works, a number of publications can be found concerning the use of rubber in the production of various materials [85–89,101–105].

The study of Malaiskinie et al. attempted to determine the effect of ELTs tire-cord (textile fibers) along together with trimmed rubber, on the properties of concrete of different types (CEM I & II) [106]. The results of the density analysis of concrete mixtures showed that the used ELTs reduced the density and the thermal conductivity coefficient (linearly) of both cements, and that the compressive strength was reduced when ELTs materials increased in the mixture. Moreover, a decrease in the density increased the water absorbance of the materials. Finally, post-crack toughness of the concrete increased with the addition of ELT materials.

Chen et al. studied the flexural fatigue behavior due to bending of reinforced concrete (FRC—Fiber Reinforced Concrete), with the addition of various proportions of recycled polymer fibers (RTPF—Recycled Tire Polymer Fiber) [107]. FRC is commonly used on civil engineering works and can be subjected to significant fatigue. Previous studies showed that concrete reinforced with an appropriate amount of RTPF performs very well in terms of dynamic compressive properties and resistance to shrinkage [108,109]. The results of the study revealed that the concrete mixture reinforced with RTPF showed greater ultimate flexural strength, while on the other hand workability and compressive strength of these materials decreased. When comparing materials reinforced with RTPF against those containing PPF (polypropylene fiber), both materials present the same fatigue failure mechanisms, hence RTPF in proper amounts can replace PPF.

Serdar et al. studied several concrete products, which contain raw materials obtained from ELT including textile fiber [108]. Until now, polypropylene fibers have been used in concrete products in order to prevent the onset of cracks due to inherent shrinkage and shrinkage caused by drying. Due to the similar dimensions of the ELT textile fibers and polypropylene fibers, the replacement of the latter material was investigated. The results showed that the addition of ELTs textile fibers is similar to those of propylene fibers in terms of shrinkage due to drying. On the other hand, the addition of propylene fibers to the aforementioned significantly increases their resistance to chloride penetration, whereas materials with textile fibers show higher resistivity to water penetration. This work concluded that the use of recycled fibers in concrete reduces the shrinkage and may as well prevent the risk of cracking due to improper curing.

The work of Oikonomou and Mavridou investigated the properties of cement mortars reinforced with textile fibers from ELTs of different proportions [110]. Textile fibers were divided into two categories: (a) Those washed with water, and (b) those not subjected to washing. The results showed that the addition of textile fibers reduces the consistency of the tested mixtures. Moreover, due to the low specific weight of textile fibers, when its proportion increases the bulk density of the composite material decreases. The mixtures with high amount of textile fiber presented significant reduction to the compressive strength when compared to the conventional material. Flexural strength and dynamic modulus of elasticity of the materials with textile fibers were also decreased. However, mixtures containing washed textile fiber showed better behavior, in terms of compressive strength, flexural strength, and modulus dynamic elasticity when compared to those not subjected to washing. In terms of water absorption, the addition of textile fibers resulted in the reduction of the amount of water entering the sample, while mixtures with washed textile fibers absorbed less water than those with unwashed fibers. Finally, the microstructure observation of the aforementioned mixtures showed that when a high amount of textile fibers is used, they are unequally distributed to the matrix hence explaining the deterioration of mechanical properties.

4.4. Plastic Materials

The lack of data concerning the characteristics of ELTs, during the previous years, was an obstacle for their reuse, so that they ended up in landfills or were intended for thermal use. However, as shown by Czvikovszky and Hargitai [111], ELTs textile fibers can be used for the production of plastic products and more specifically as reinforcement to polypropylene (PP) that is used in car bumpers. According to their research, the addition of textile fibers showed promising results including greater flexural strength, modulus of elasticity, and impact strength.

Landi et al. studied various scenarios for the use of ELTs textile fiber as PP reinforcement [25]. The results showed that textile fibers in plastic compounds increased the resistance of plastic materials to impact and deformation. However, after shredding the ELTs, the fibers are not free of rubber and thus cannot be used directly in plastic compounds. Processes such as centrifugal separation are required to receive pure textile fibers.

The study of Marconi et al. examined the scenario of using ELTs textile fiber for the preparation of PP [112]. Two types of PP were investigated: (a) PP with no additional fiber and (b) PP with textile fiber 50% (w/w). Low temperature was used in the process to limit the degradation of the polymer and to avoid carbonization of the fibers. The results showed that PPs with 50% textile fiber have lower elastic module and lower maximum deformation, while on the other hand their resilience is increased.

4.5. Soil Reinforcement

Apart from the production of different types of plastic components, concrete, asphalt, and sound absorbers, ELTs can also be used as soil reinforcement. Mucsi et al. investigated the use of steel fibers from ELTs that can be employed as geopolymer [113]. The addition of the aforementioned material showed promising results. In the work of Abbaspour et al., an effort was made to reuse ELTs textile fiber as soil reinforcement [114]. Two different soil types were collected, clayey and sandy, and the textile fibers were received from a factory that treats various types of tires. Microscopic observation showed that there were pieces of rubber, which increase the interaction between soil and fibers. The results showed that with the addition of textile fiber to the soil, the maximum dry density (MDD) is reduced and the optimum moisture content (OMC) is increased. OMC differences, when adding textile fibers to clayey soils, are much higher than those observed in sandy soils. For both types of soil an increase of textile fiber (up to 2%) does not affect ductility, but for higher proportions of textile fibers their ductility is increased. When it comes to UCS (Unconfined Compressive Strength), the addition of textile to the clay enhances the ductility of the soil, nonetheless the addition of higher amount of textile fibers to clay soils results in a significant reduction of its strength. The addition of textile fiber to sandy soils leads to a significant increase in UCS. In sandy soils, the addition of textile fiber increased the STS (Split Tensile Strength). Finally, the microscopic observation showed that there is lubrication between clay minerals and textile fibers, resulting in reduction of the strength parameters.

5. Conclusions

In recent years, the number of tires used worldwide has increased and is expected to increase even more in the years to come. Tires constitute a waste that requires treatment as it can cause serious environmental and health issues. During the previous years, obsolete methods were implemented for tire management, including disposal to landfills or incineration. However, in recent years, the management of ELTs has changed, as the legislation regarding their use is becoming more and more stringent. At the European level, 90% or more of ELTs are reused in various activities. Initially, ELTs were used for energy purposes, but in recent years, their use as secondary material has begun to gain ground. The energy exploitation of ELTs can be achieved through various methods including combustion, pyrolysis, gasification, etc. However, there are specific restrictions on the use of tires as fuel in the EU, as set out in technical instructions of the CEN 343 Committee. That is, the fuel should be characterized by specific analyses. Although energy recovery is low in the EU Waste Management hierarchy, it is an alternative option when the increased annual amounts of ELTs cannot be all directed to recycling. Depending on size, scrap tires can be up to 30% biomass as measured by ASTM D6866.

On the other hand, ELTs, as mentioned before, can either be recycled or used in a variety of applications. These applications belong mainly in the field of civil engineering works, including the use of ELTs materials as part of asphalt mixtures, cement, insulation, and sound absorbing materials. ELTs mainly consist of: (a) Rubber; (b) steel wire; and (c) textile fiber. In the international literature, there is extensive reference to the use of rubber and wires for various applications, however little research has been carried out concerning the use of the textile fiber. This is due to the difficulty in separating the textile fibers from the other materials. Full chemical characterization of textile fibers has been conducted in order to better understand the properties of this material.

Recent research on the alternative uses of textile fiber was also presented. These included the use of textile fiber as sound absorbing or soil reinforcing material, as well as for the production of plastics, asphalt mixtures, and cements. Based on these works, textile fiber seems to be very competitive as sound absorbing material when compared to usual commercial materials. In the field of bituminous conglomerates, textile fiber can be also a promising option. On the other hand, in the cement production area, textile fiber as an additive can enhance some properties, yet degrading important ones such as mechanical properties. When it comes to the replacement of polypropylene, textile fiber can be a good alternative in the production of plastics and cement. Finally, in the field of soil reinforcement, the addition of textile fiber may reduce maximum dry density and compressive strength, while increasing optimum moisture content and ductility.

Author Contributions: Conceptualization, P.G. and N.M.; methodology, N.M.; investigation, P.D. and G.M.; resources, G.M., P.D., and N.M.; writing—original draft preparation, N.M. and D.R.; writing—review and editing; supervision, P.G.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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