TRANSPORT & *LOGISTICS:*
the International Journal

Article history:
Received 31st March 2021
Accepted 10th August 2021
Available 16th August 2021

ISSN 2406-1069

Article citation info: Yakovlieva, A., Boichenko, S., Kale, U., Nagy, A. Recent advances in technologies for aircraft scrap tyres recycling and utilization. Transport & Logistics: the International Journal, 2021; Volume 21, Issue 50, August 2021, ISSN 2406-1069.

RECENT ADVANCES IN TECHNOLOGIES FOR AIRCRAFT SCRAP TYRES RECYCLING AND UTILIZATION

Anna Yakovlieva [1], Sergii Boichenko [1], Utku Kale [2], András Nagy [3]

[1]Ukrainian scientific-research and education center of chemmotology and certification of fuels, lubricants and technical liquids, National aviation university, Liubomyr Huzar (Kosmonavt Komarov) ave. 1, Kyiv, Ukraine; +380636308959; e-mail: anna.yakovlieva@nau.edu.ua, chemmotology@ukr.net

[2] Budapest University of Technology and Economics, Muegyetem rkp. 3, Budapest H-1111, Hungary; +36 1 463 1916; e-mail: ukale@vrht.bme.hu

[3]University of DunaújvárosTáncsics Mihály u. 1/a, 2400, Dunaújváros, Hungary; +36 (25) 551-224; e-mail: nagy.andras@uniduna.hu

Abstract:
The paper presents a complex review of the state of aviation tyres production and tecnologies for scrap aviation tyres utilization. The statistical analysis of aircraft tyres use and waste aircraft tyres accumulation is done. The negative impact of tyres accumulation and storage in the environment is considered. The perspective methods of aircraft tyres utilization are presented and considered. Among the most widespread and efficient treatment and utilization methods are: retreading, shredding, grinding, devulcanization, fuel production via pyrolisis and gasification and use as a raw material in other industries. Advantages and disadvantages of the considered method are discussed. Technological, economical, and environmental issues of technologies of tyres recycling are analyzed and considered. The most feasible ways for tyres disposal are proposed.

Key words:
aircraft tyres, scrap tyres, environmental pollution, disposal, recycling, treatment

INTRODUCTION

Modern manufacturers produce virtually indestructible tyres, which cause a significant environmental problem with an estimated 1.5 billion scrap tyres (ST) around the world, many of which finish up being dumped in forests and streams, as well as landfill [1]. Today, most STs finish their life being crumbed and used in playgrounds and sporting fields or burnt as furnace fuel. However, there is a limit on how many STs can be recycled in this way. Many aircraft STs end up on farm equipment – some companies specialize in turning plane tyres into a tractor, wagon, and backhoe tyres. Even after being retreaded many times, they're excellent for field use [2].

ST is considered to be a special type of waste with environmental, economic, and social issues. The problem of ST disposal is that tyres do not decay if buried, they resurface as they are of lower density than surrounding soil. If they are landfilled, they give an unstable surface to any landfill and the ground can't be used for building. If tyres are accumulated on the surface, they pose a fire danger. As well as creating an environmental problem, ST creates a health hazards in tropical regions as they keep water inside that provides the perfect habitat for breeding mosquitoes, which spread, malaria, dengue fever, Zika virus and other diseases [2, 3]. There is the potential for a future environmental disaster caused by the residues from burning STs, even in modern furnaces. It is also a kind of waste that could be refined as jet fuel and other oil-based products [4].

In addition, the tyres are a high-energy material that justifies the efforts in the advancement of technology, innovation, and research and development. Taking into account global situation with accumulation of STs there is a need to consider measures for its proper and efficient utilization and minimization of its impact on environment. Despite the available literature about technologies of motor vehicle tyres production and approaches to its recycling, there is a lack of systematized data on the considered problem in respect to aviation. Thus, the main aim of this paper is to review, analyse, and systematize the current state in production, use, and recycling of aircraft STs, focusing on existing and promising technologies for treatment [3, 4].

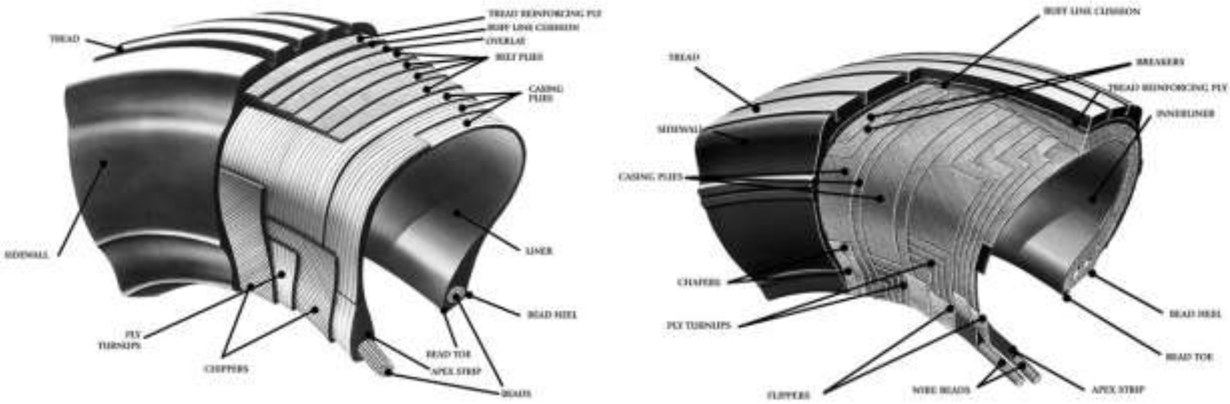
1 AIRCRAFT TYRES MARKET OVERVIEW

Aircraft tyres are among the most complex and sophisticated engineered products onboard aircraft. With properties that withstand heavy loads at high velocities and extreme temperatures, the demand for aircraft tyres is primarily driven by the consistently growing aviation sector worldwide. The global aircraft tyres market was valued at US$ 1,260.4 mln in 2017 and is set to demonstrate a 4.5% CAGR during the forecast period from 2018 to 2026 [5]. The aircraft tyres market includes the tyres used in military, commercial, and general aviation aircraft. The commercial segment of the market has the highest market share, and it is expected to register the highest CAGR during the next decades [5, 6]. There is a steep rise in air travel in the past five years. Airlines are expanding and introducing new routes to increase their market dominance, which has generated the demand for new aircraft. Additionally, the increasing success of LCC in emerging economies has also increased the sales of single-aisle aircraft over the years. In addition to these, the demand for wide-body aircraft has been increasing for longer routes. The procurement of new aircraft will simultaneously generate the demand for new tyres. The overall aircraft tyres market is highly consolidated in nature, with very limited companies operating in the market [7]. A few number of tyre manufacturers possess the technology to produce high-performance aircraft tyres. This is primarily due to the higher complexities involved in manufacturing these high-performance tyres [5, 6].

Aircraft tyres on a commercial jet aircraft are an amazing example of advanced design and manufacture. After all, they have to hit the runway and after an initial skid accelerate to 170 miles per hour and safely support the weight of a typical aircraft. The average number of landings for civil aircraft tyres is 250 to 300. Most commercial Boeing 737s reach this number in one to three weeks. For military fighter planes, tyres generally last 20 to 50 landings. According to report [3] Southwest Airlines (USA), for example, usually changes tyres every five to six weeks, and in the past year, it has used nearly 40,000 of them. Usually tyres at the aircraft's nose wear out first. At Frontier, front tyres tend to last an average of 219 landings, while main landing gear tyres can go for about 394 landings. Tyres usually wear out quicker at higher altitudes and in warmer temperatures, and airlines say tyres on some types of aircraft wear out faster than others. Having such a short period of use, it is clear that today plenty of commercial aircraft STs is available and require proper handling and utilization. For example, a Boeing 777 has 14, an A380, 22, and the AN225 cargo aircraft, 32 tyres [2-4]. Not to mention the thousands of STs discarded by general aviation and recreational flyers. Airlines and suppliers are constantly thinking about how they can be more sustainable and less wasteful [8]. This usually means retreading the tyres as many times as possible; airlines can retool and reuse a tyre seven times before it is no longer viable.

2 COMPOSITION OF TYRES

Tyres vary in size and design according to their purpose and manufacturer. Engineers are challenged with designing tyres with cool running, heat-resistant materials while simultaneously exceeding tyre service requirements [9]. Tyre prototypes are put through rigorous tests that simulate cycles of landings, take-offs, and taxi operations. Generally, there are 8 types of tyres, however, only two of them are used in aircraft applications — bias-ply tyres, and radial tyres (Fig. 1a, 1b). Although both types of tyres share some similarities in design, some differences need to be noted. Bias-ply tyres are popular choices for aircraft tyres because of their durability and retreadability. The tread is made of rubber mixed with other additives to obtain the desired level of toughness, durability, and resistance to wear. The tread pattern is designed to aircraft operational requirements, with the ribbed tread design used widely due to its good traction under varying runway conditions. A typical radial tyre with rigid belt provides increased landings and reduced rolling resistance. They have fewer components in their construction and are lighter than similarly sized bias-ply tyres [9].



a *b*

Fig. 1. *Construction of aviation tyres: a – radial tyres construction, b – bias-ply tyres construction*

Source: https://www.aviationpros.com/

The general composition of all tyres is very similar (Table 1) [10]. The rubber is the tyre main component; five types of rubber are used: natural rubber (NR), Styrene-Butadiene Rubber (SBR), Polybutadiene Rubber (BR), Isobutylene-isoprene Rubber (IR), and

Isobutylene-isoprene Halogenated Rubber [4, 8]. Textiles and metals are also part of the tyre. Currently, steel cords are used to reinforce the rubber compound and provide strength. Among the materials suitable for use are cotton, rayon, polyester, and steel [10]. The type and the percentages of other minor components depend on each manufacturer. These components are additives, sulphur compounds, and other hazardous compounds such as heavy metals (Table 2) [10]. Furthermore, the tyres are produced using oils that may contain significant levels of Polycyclic Aromatic Hydrocarbons (PAHs), added unintentionally [10].

Tab. 1. *Principal composition and properties of transport tyres*

		Function
Composition	Rubber 45 – 47% Carbon black 21.5 – 22% Steel 16.5 – 25% Textile 5.5% (Passenger car) Zinc oxide 1 – 2% Sulphur 1% Additives 5 – 7.5%	Structural-strain Physical properties improved Structural skeleton Structural skeleton Catalyst Vulcanizing agent
Heavy metals	Copper, cadmium, and lead trace content	
High calorific value	32 – 34 MJ/kg (1 ton is equivalent to 0,7 Ton of petroleum)	
Auto-ignition temperature	400 °C	
Weight	6.5 – 11 kg (automobile) 50 – 80 kg (trucks) ~ 4000 kg (mining dump truck)	

Source: G. Ramos, F. J. Alguacil, F. A. López, 2011

Tab. 2. *Hazardous components in tyres and regular contents*

Component	**Content (% weight)**	**Content (g)**
Copper compounds	Approx. 0.02	Approx. 1.4
Cadmium compounds	Max. 0.001	Max. 0.07
Zinc compounds	Approx. 1	Approx. 70
lead compounds	Max. 0.005	Max. 0.35
Acidic solutions or acids in solid form	Approx. 0.3 Content of halogens	Approx. 21 Content of halogens
Organohalogen compounds	Max. 0.10	Max. 7
Polycyclic Aromatic Hydrocarbons (PAH)	0 (After 1 January 2010)	0

Source: G. Ramos, F. J. Alguacil, F. A. López, 2011

3 TECHNOLOGIES OF SCRAP TYRES TREATMENT AND RECYCLING

During the last years, increasing of the amount of generated STs has been reduced, and the managed quantities have increased. For example, in Europe, 65% of the generated STs were going to landfills in 1992. The amount of STs was reduced to 3 %, 13% and 6%, in 2002, 2005 and 2008 respectively. The recovery of materials is the most popular way of STs treatment [12]. In most European countries, the storage on landfills has also reduced during the last decade [12], increasing significantly other treatment routes mainly in the recovery of materials.

The STs recycling procedure starts with selection and inspection, which are carried out to decide what can be reused, completely recovered, and what can go to recovery to be transformed into a new product or energy [7]. The general scheme of possible routes for STs disposal is presented in Fig. 2 [13]. After the selection, the tyres are transported to recovery facilities, where they are processed by the shredder and/or grinder. For example, for use in civil works, the whole recovery of STs will be necessary, only shred for use as fuel, or shred and granulate for material recovery, depending on the application.

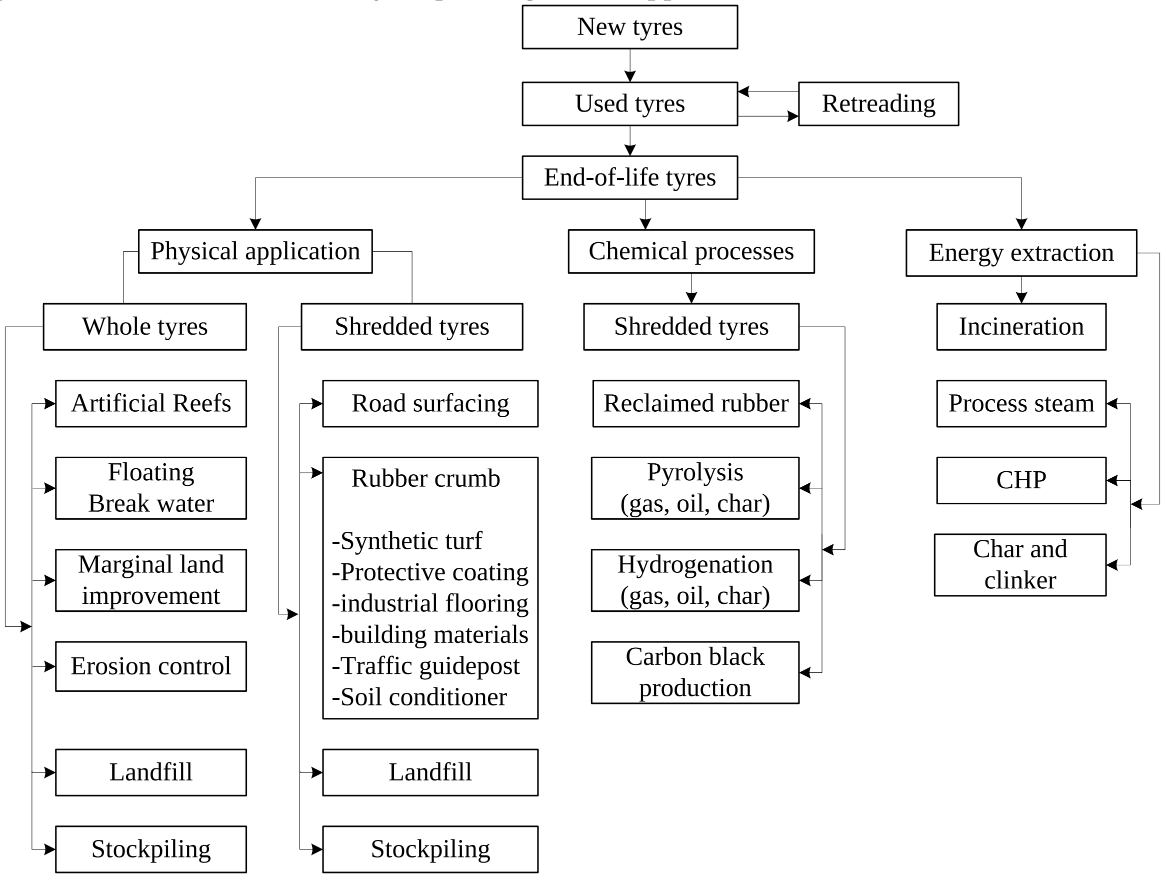


Fig. 2. *Re-use, recycle, and disposal route for ST*
Source: Phale, A.R., 2005

3.1 Scrap tyres treatment technologies

Retreading. Retreading is one of the most popular technologies for tyres reuse, especially for aircraft tyres. Retreading is a safe, economical, and environmentally-friendly way to give old tyres a new life: the worn tread surface is replaced by a new one. The end result is a tyre that can be reused [7, 11, 14].

The ratio of retreads on the replacement car and truck tyre market in Europe still varies widely. For car tyres, retreads make up only 1-2% of the market in Switzerland and the Netherlands, but this amount rises to over 20% in Scandinavia. In Germany, retreads account for around 10% of car tyres, a ratio which rises to 20% for winter tyres. For truck tyres, the ratio of retreads is much higher, ranging from around 40% in Spain to over 70 % in Finland. In Germany and France, retreads make up around half of the replacement tyre market for trucks. Over 15 mln truck and bus tyres are used every year across the EU. Of these, around 8 mln are new tyres, and over 6 mln are retreads [12].

Retreading plays a particularly important role in aircraft tyres, which are subjected to extreme stresses. Retreading can take place up to twelve times. The testing procedures are naturally very stringent here, and safety takes top priority [8].

High-quality retreading is the alternative to new tyres for commercial vehicles since it offers safety, top running performance, and an excellent cost-benefit ratio. More and more consumers are recognizing and coming to appreciate the positive image of high-quality retreads [15].

Not every tyre is suitable for retreading, however. It depends if a casing can be reused also depends on the type of tyre. It is only possible in the following cases:

- The tyre has been looked after properly, handled with care, and driven with the correct air pressure in its "first life".
- The casing is in good condition and has not sustained any serious damage.

Generally, car tyres may be retreaded once, transport tyres – once as a general rule, truck tyres – one to three times, and aircraft tyres may be retreading up to 12 times [15].

There are three retreading systems according to the renewed surface [10]:

- Integral – renewing the tread and sidewall.
- Semi-integral – renewing the tread and part of the sidewall.
- Only the tread.

There are two retreading systems according to the adhesion system: a) hot retreaded, the vulcanization process is carried out in pressing machines at temperatures comprised between 150 – 160 °C; b) cold retreaded, the vulcanization process is carried out in autoclaves at temperatures between 98–125 °C [10].

Retreading can reduce raw material costs (30–50 %) and the STs generation, and results in the same benefits as a new tyre [5, 6]. As for drawbacks, the number of retreaded supporting a tyre is limited, and its features are reduced at times [17].

3.2 Scrap tyres recycling technologies

Shredding technologies. Mechanic shredder is one of the most typical transformations for STs recycling. The cut is performed with a shearing crusher of two or more parallel axes blades which spin at different speeds. The separation of the axes defines the final size, being able to find these fractions [14]:

- Small shred (50x50 mm) is mainly used as fuel in cement kilns;
- Medium shred (100x100 mm) is used as fuel or material recovery;
- Large shreds (150x150 mm) may be applied in civil engineerings, such as sealing of landfills, road construction, slope stabilization, road and railway embankments, drainage material (replacing sand and gravel), landfill construction, sound barriers, insulation, etc. The shred material may be also used for further finer granulation.

Cryogenic shredder technology uses liquid nitrogen to cool tyres to temperatures in a range of -50˚C – 100˚C, when the rubber turns into the glass state, becoming very fragile and easy to shred [18]. A shredded tyre allows its more convenient transportation, reducing of the volume of waste, and maybe further used in several applications [11, 14].

Grinding technologies. Presently, the common grinding methods include three processing stages: primary, secondary and tertiary, to achieve the fine grade of crumbed rubber, for example, the formation of rubber powders. The primary processing stage reduces down the whole tyre to a convenient processing size by utilizing any of the following three instruments: the cracker mill, the hammer mill (high impact), or the rotary shearer. The guillotine is another type of instrument that merely cuts the waste rubber. Generally, the rubbers are first shredded and then subjected to a grinding process. The secondary stage converts the coarse waste rubber chips to granular rubber material [18]. The two roll mill is similar to the cracker mill, but it is smaller and hence works at lower energy. Granulators are another type of rugged machine which produces finer particle sizes. Tertiary grinding is the ultimate breaking down of crumb rubbers to obtain a fine powder, for this 100% conversion in a single unit can be achieved with wet grinding techniques. Grinding can be performed either at room temperature or in the glass transition region through the use of liquid nitrogen in a cryogenic system.

Ambient grinding by crushing against metal rings is provided with holes [16]. Ambient grinding does not mean processing at room temperature, the milling temperature may rise up to 130 °C when using this grinding technology. The equipment can be powered by shovelling into the hopper or directly by conveyor belt from the grinding process. It is important to pre-shred for the feed with a material that has a uniform size. There is a trommel for classifying the rubber in three fractions after grinding [16]:

– Granulation 2.5 – 4 mm has the most applications.
– Pulverization 0.8 – 2.5 mm is used for artificial grass, as synthetic fibre filling with aggregate, or as a base layer.
– Micronization <0.8 mm may be used for mixing with bitumen during asphalt manufacturing.

Granulate have an irregular shape with considerable surface roughness, and the rubber is partially oxidized at the surface due to heat generated during the process [14].

During *cryogenic grinding*, the shredded rubber is cooled below the freezing point of -200 °C so that it loses its elasticity and thus can be easily disintegrated. This process uses liquid nitrogen first, and then the rubber passes through an impact mill where it becomes grounded. This technology enables rapid separation of the three components of tyres (rubber, steel, and fibres) [18].

The shape, fineness, and surface characteristics of grinded rubber obtained by cryogenic grinding are different from those obtained by ambient grinding. The granulate has a relatively smooth surface, a wide range of particle size, and minimal surface oxidation [14, 18]. Due to this cryogenically ground rubber powders possess a very poor physical binding ability.

Wet grinding is a rarely used process that consists of a series of grinding wheels that inject into the surface of the tyre a high-pressure water jet for cooling of dust rubber. The impact energy exerted by the water jet disintegrates the particles into smaller sizes. The water jets provide the added advantage of cooling down the system during the operation [19]. The major disadvantage of this process is the addition of a processing stage, for example, subsequent drying of the particles before finishing. Hence, this process adds to the total energy consumption, making it a costlier process. Moreover, proper separation of the reinforcement material cannot be achieved using this process [17].

During the *grinding by ozone cracking* the waste, tyre particles are first exposed to a higher concentration of ozone. The material degrades during exposure to ozone, and subsequently mechanical grinding is required for further processing and to obtain a fine powder. However, the obtained fine powder shows a low surface activity due to the oxidation of ozone. Similarly, the converse process is also applicable, in which cryogenic grinding is coupled with a subsequent ozone cracking process. Monomers can be recovered in this environmentally friendly process for hydrocarbon feedstocks. The initial break down of the vulcanized or cross-linked network through ozone cracking promotes subsequent thermal depolymerization techniques [20].

Many products can be obtained from the different sizes of grinded rubber, and for each use it is required a particular size (Table 3) [10].

Tab. 3. *Examples of granulated STs involved in different products*

No	Product	Size (mm)
1	Carpet backings	0.8 – 1.6
2	Moulded products	0.5 – 5
3	Playgrounds	1.6 – 2.5
4	Road paving materials	0 – 0.8
5	Running tracks/Sport field	1.6
6	Shoe soles	0.4 – 1.
7	Train and tram rails	0.4 – 1.
8	Tyre-Derived Fuels (TDF)	<25 – <50

Source: G. Ramos, F. J. Alguacil, F. A. López, 2011

The advantages of grinding technologies are to get fine and regular particles with a variable size distribution, as the granulate has greater scope in many applications [20]. The cryogenic grinding technology offers other advantages such as temperature monitoring, the existence of an inert atmosphere by avoiding the deterioration of rubber, it improves the surface morphology of the particles and smaller particles are obtained. Against, the grinding technologies have higher investment than shredding technologies. The wet and cryogenic grinding requires drying and can cause the leaching of ZnO, under certain environmental conditions (due to zinc compounds which are part of tyre additives) [18].

3.3 Scrap tyres recycling for energy recovery

Today, the *cement industry* is the main user of tyres as an alternative fuel source (TDF) (Table 4) [10]. 60% of generated STs are used as fuel in cement kilns in Austria; while 38%, 8%, and 6%, respectively are used in Germany, France, and Britain. Despite ST is an alternative fuel today, but it cannot exceed 20% of the total fossil fuel required in the manufacture of cement [12, 21 and 22].

Tab. 4*. Worldwide usage of STs as TDF*

Region	STs production (Mton)	Percentage used as TDF (%)	Facilities using eLts as TDF
Europe	2.50	41 (2006)	Cement kilns
Japan	0.80	70 (2006)	Cement kilns, paper mills, tyre factories
U.S.	2.92	53 (2005)	Cement kilns, paper/pulp mills, boilers

Source: G. Ramos, F. J. Alguacil, F. A. López, 2011

The clinker obtained from TDF by 20% substitution of conventional fuel is similar to that obtained using only pet coke [23]. Typically, the final product using TDF is characterized with the same quality parameters.

Shredded tyres can be also used at *steel plants* in electric arc furnaces as a substitute for anthracite (1.7 kg ST is equivalent to 1 kg of anthracite) [22] and part of the scrap. In addition to the use of the ELTs energy content, all the steel contained in tyres may be also recycled [10]. All without any appreciable changes in the levels of emissions of certain pollutants such as steel maker dust and gases, and it may be even smaller, as in the case of heavy metals and CO_2 (Table 5) [10].

Tab. 5. *Energy potential and CO2 emission from fuels*

Fuel	Energy (GJ/ton)	Emissions (kg CO_2/ton)	Emissions to energy ratio (kg CO_2/GJ)
Tyres	32.0	2.270	85
Carbon	27.0	2.430	90
Pet Coke	32.4	3.240	100
Diesel oil	46.0	3.220	70
Natural gas	39.0	1.989	51
Wood	10.2	1.122	110

Source: G. Ramos, F. J. Alguacil, F. A. López, 2011

The idea of the process is to introduce a mixture of scrap and STs into the electric arc furnace. The content of carbon in tyres contributes to the reduction of iron, saving consumption of reducing agent, the iron in the tyre joined the molten phase, improving metallurgical performance; and zinc in the tyre, joins the steel powder [8]. About 1,3 million STs per year are used in this way in the U.S. In Japan, about 4% of total STs were processed in this way, by 2008 [24]. Recently, Belgium, France, and Luxembourg have applied their industrial use, and it has potential for growth in the rest of Europe [12].

Today, the use of STs as an *alternative fuel* in thermal power stations and pulp and paper mills is widespread in the U.S., and especially in Japan, but not in Europe [12]. The U.S. consumed 39 million tons of STs in 24 paper mills in 2005, and Japan 32% of STs generated in 2008, a percentage which is much higher than that used in the cement industry, which was 13% [12].

The great advantage of tyres as TDF is its high energy value (table 5) and it is an equal or better source of energy than other fuels [8]. STs can generate energy in a form of heat, electricity, or cogeneration and can be co-incinerated or used as the only source of energy in many processes. Moreover, STs can be used whole, shredded or granulated. The use of STs reduces emissions, for example, SOx because tyre contains less sulphur than conventional fuel, and emissions of greenhouse gases such as CO_2 because the carbon content per unit of energy is lower than in coal and pet coke [25]. The ash produced after STs combustion generally contains less heavy metals than the ash from coal combustion because in the cement kiln the rubber provides energy and iron and sulphur are incorporated into the cement [21 and 22]. The biggest disadvantage of STs energy recovery is their limited use as a 10–20% alternative fuel.

3.4 Advanced technologies of scrap tyres reuse

The use of STs dust in the *construction of roads* is one of the most important applications. The production of bituminous mixtures with tyre dust is relatively old technology. Rubber asphalt is expanded in the U.S., and Europe is expected to grow in the future [4, 8].

There are three types of rubber-modified concrete [10]:

– Rubber Modified Bitumen has properties similar to polymer-modified bitumen and the amount of dust needed is 12–15% by weight. It can be used for the same applications as polymer-modified bitumen: a layer of rolling thin staple F and M, blends, and mixes draining S intermediate layer with improved properties of fatigue and plastic deformations.

– Rubber Modified Bitumen with High Viscosity is manufactured with a higher proportion of rubber dust, between 15–22% by weight, and is used in applications where very high viscosity is required.
– Rubber Improved Bitumen has better features than conventional bitumen, and the percentage of rubber dust is usually between 8–12% by weight. It has intermediate properties between conventional and modified bitumen. Its principal application is as basic and intermediate layers and as wearing courses with conventional mixtures of heavy traffic categories T1 to T4.

The application of recycled tyres rubber in road construction has great advantages mainly because it saves nonrenewable raw materials, large volumes are needed in each project. In addition, rubber dust improves the properties of conventional bitumen. However, it competes at a disadvantage with the low prices of petroleum products and aggregates, and the cost of treatment of rubber dust is high [4, 8, 10].

STs devulcanization is a process of decomposition that allows the recycling of rubber from STs based on chemical bond breaking. The incorporation of grounded rubber particles into polymer blends is often not suitable due to the presence of a sulfur cross-link network. Compatibility becomes affected by sulfur cross-links which leads to a weak interface and deterioration in the properties of the final product, therefore, the necessity of devulcanization arises. Devulcanization can be achieved by utilizing several means such as chemical, ultrasonic, microwave, biological, and other methods [26].

The chemical devulcanization method for the processing of waste rubber is based on the utilization of several chemicals. The properties of reclaimed rubber deteriorate with devulcanization. Organic diallyl disulfide, diphenyl disulfide, inorganic phenylhydrazine–ferrous chloride, and so forth can be used for the production of devulcanized rubber. Organic solvents such as toluene and benzene are generally used for swelling of the rubbers as the first step towards devulcanization. Devulcanization can be achieved by controlled oxidation of the carbon framework of rubbers, forming COOH and NO_2 groups [27].

Ultrasonic devulcanization is based on vibration that creates a localized energy density that is sufficient to break the cross-links of S–S and C–S bonds. Ultrasonic vibration induces cavitations around impurities or voids in the cured rubber. Degradation and mechanical property loss is minimal in the ultrasonic devulcanization method. No chemicals are used in this process, making it a clean and environmentally friendly process. Key variable parameters in the ultrasonic devulcanization method are the devulcanization temperature and amplitude of the ultrasonic waves. Particle size depends on the above-mentioned parameters, along with the die pressure in the twin-screw extruder [28].

In microwave devulcanization, electromagnetic energy is used to break the cross-links of the S–S and C–S in the rubber with the aim of restoring the conformation ability of the rubber. The power source and time of processing can be varied to achieve the desired amount of cracking. Molecular interaction with the electromagnetic field is necessary in order to break the cross-links with microwave energy. The physical properties of the final product remain almost equivalent to the original vulcanizate. In molecular interactions, electromagnetic energy is converted into heat energy. The temperature in the range of 260–350 °C can be achieved using microwave treatment, and a 300 MHz to 300 GHz frequency is generally used in the microwave method [29].

The microbial devulcanization process uses sulfur-oxidizing and sulfur-reducing bacteria. The sulfur bonds of the vulcanized elastomers are cleaved with the use of microorganisms. A temperature-controlled bioreactor is needed, in which finely ground rubber powders are mixed with media containing the appropriate bacterium. The cleaving mechanism through the bacterium varies with the species of bacterium used in the process. Starting with approximately ten days to a few hundred days, the contact time may vary by a wide range. After processing, the newly formed devulcanized rubber materials are rinsed off properly in order to remove the microorganisms [30].

STs pyrolysis is the thermal degradation process of shred or granulated tyre in intermediate substances such as gas, oil, solid residue (char or carbonaceous solid residue), and steel. In the pyrolysis process, shred tyre (1–3 cm), or granulated tyre (0.5–4 mm) free from steel and textiles are heated at a moderate temperature (400–800°C) in the absence of oxygen or a limited amount [31]. The pyrolysis takes place in a reactor in the following steps [31]:

– Rubber is fed to the reactor and subjected to thermal cracking, breaking up into a volatile fraction and a solid residue.
– Volatile fraction is cooled and transforms into two fractions: a liquid fraction and a gas fraction.

The liquid fraction is about 35% of the initial weight. It is called tyre-derived oil and consists of organic compounds C5–C20. Tyre-derived oil consists of PAH`s comprising naphthalene and its derivatives, indene and its derivatives, and indan. The group includes derivatives of benzene and ethylbenzene, methyl, propyl, methyl ethyl, trimethyl, tetramethyl, and methyl propyl methylbenzene, toluene, and isopropyl toluene, and xylenes. Finally, the aromatic compounds group consists of alkanes and alkenes, mainly cyclical and straight-chain [32]. Gas fraction is about 20 % by weight and is composed mainly of hydrogen (H_2), hydrogen sulfide (H_2S), carbon oxides (COx), and light hydrocarbons (C1–C6), which can be used as fuel pyrolysis process or co-generation. It has a calorific value between 68–84 MJ/m^3 [10, 14].

– Solid residue is a mixture of steel and char or black carbon and accounts for 45 % of the initial weight.

Yields and composition depend on the temperature, pressure, residence time, particle size starting material, condensation temperature of the volatile fraction, and the type of kilns used [10].

The main advantage of pyrolysis technologies is a gas fraction that can be used as fuel in the process, as fuel in cement kilns or co-generation; tyre-derived oils have characteristics similar to a gas-oil trade being able to use as fuel in conventional furnaces and combustion engines, and the pyrolytic carbon black has great potential because it can enhance fuel substitution (when mixed with coal), absorbing light, the manufacture of polymeric materials, or as feedstock in the manufacture of charcoal and tyres. The most important drawback is the high cost of the process, and the price of the products that are not competitive to prices of the petroleum products.

STs gasification is another thermal treatment technology. The thermal degradation of organic matter is carried out in the reactor under a low-oxygen atmosphere and a temperature of about 600 ˚C [14]. The result is a synthesis gas or syngas with an approximate yield of 63 % by weight, and a solid phase representing about 37 % of total weight. The yield of the gasification process varies depending on the technology, fuel and gasifying agent used [32]. The syngas is composed mainly of hydrogen (H_2) and carbon monoxide (CO) which energy value can be used to produce electricity under a specially adapted internal combustion engine. The solid fraction is composed of carbon black and steel. These are easily separated for material recycling.

4 CONCLUSIONS

The current state of aviation tyres production and utilization industry is shown. Due to the rapid global growth of aviation sector, we may observe increasing demand in tyres production. Consequently, there is a tendency to increase in volumes of STs. This substantiates the necessity to develop environmentally friendly and energy efficient methods for STs disposal. Analysing the existing and promising disposal methods, it may be concluded that applying retreading may significantly prolong the lifespan of used aircraft tyres. Except that STs may be efficiently use as a raw material in such industries as cement production, road construction and fuel production and other application. Fuel production in a result of STs processing is relevant direction in technologies of STs. It may have significant potential as well as energy and financial benefit. Thus, development and implementation of system of STs disposal may provide its long-term use as well as efficient processing and secondary use with minimal negative impact on environment.

Author Contributions:
All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication. All authors have read and agreed to the published version of the manuscript.

Funding:
This research was funded by the EFOP-3.6.1-16-2016-00003 project which is co-financed by the European Union.
Acknowledgments:
This work is supported by the EFOP-3.6.1-16-2016-00003 project. The project is co-financed by the European Union.

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

References

[1] Rutzou, D. Public Relations. Available at: www.drpr.com.au

[2] Sumers, B. Old Airplane Tires Are Turned Into...What? Available at: https://www.cntraveler.com/stories/2016-05-27/old-airplane-tires-are-turned-into-what

[3] Media Release: Aussie recycler can turn old aircraft tires into bio fuel. Available at: https://www.gdtc6.com/aussie-recycler-can-turn-old-aircraft-tires-bio-fuel/

[4] Recycling & recovery of tires. Available at: https://www.roth-international.de/en/recycling-recovery/recycling-of-tires/

[5] Aircraft Tire Market - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2017 – 2025. Available at: https://www.transparencymarketresearch.com/aircraft-tire-market.html

[6] Global Aircraft Tire Market Research Report. Available at: https://www.marketresearchfuture.com/reports/aircraft-tire-market-2192

[7] Global Aircraft Tire Markets to 2026, Driven by the Growing Commercial Aviation Industry Worldwide. Available at: https://www.globenewswire.com/news-release/2018/11/30/1659920/0/en/Global-Aircraft-Tire-Markets-to-2026-Driven-by-the-Growing-Commercial-Aviation-Industry-Worldwide.html

[8] Boichenko, S., Ivanchenko, O., Lejda K. et al., 2019, Ecologistyka, recyckling I utylizatsiia transport, NAU, Kyiv, 266 p. (in Ukrainian)

[9] Escobar, J. Understanding the basics of aircraft tire construction and maintenance. Available at: https://www.aviationpros.com/aircraft/article/10388042/understanding-the-basics-of-aircraft-tire-construction-and-maintenance

[10] Ramos, G., Alguacil, F. J., López, F. A., 2011. "The recycling of end-of-life tyres. technological review", Revista de Metalurgia, 47 (3), pp. 273-284

[11] Kwon, E., Castaldi, M.J., 2009, "Fundamental Understanding of the Thermal Degradation Mechanisms of Waste Tires and Their Air Pollutant Generation in a N_2 Atmosphere", Environmental science & technology 43 (15), pp. 5996-6002

[12] European Tyre & Rubber Manufacturers Association, (ETRMA). Available at: www.etrma.org

[13] Phale, A.R., 2005. Environmental impact and waste management of used tyres in the SRA – a mini-dissertation submitted in part-fulfillment of the requirement for the degree of Magister atrium, 74 p.

[14] Adhikari, J., Das, A., Sinha, et al., 2018, chapter 1: "Grinding of Waste Rubber", Rubber Recycling: Challenges and Developments, pp. 1-23

[15] New life for tyres. KRAIBURG Austria GmbH & Co. KG, Available at: https://www.kraiburg-austria.com/en/tyres-retreading/retreading-techniques/

[16] Krömer, S. 2002, Life Cycle Assessment of a car tyre, Continental AG (Ed.), Hannover, Germany, pp. 1-44.

[17] Basel Convention, Revised technical guidelines on environmentally sound management of used tyres, 2010, UNEP (Ed.), Genova, Italy, pp. 1-56.

[18] Dierkes, W., De, S. K., Isayev, A. I., Khait, K. 2005, "Untreated and Treated Rubber Powder", Rubber Recycling, CRC Press, Taylor& Francis Group, p. 3

[19] Rouse, M. W. De, S. K., Isayev, A. I., Khait, K. 2005, "Manufacturing Practices for the Development of Crumb Rubber Materials from Whole Tires", Rubber Recycling, CRC Press, Taylor& Francis Group, p. 1.

[20] Bilgili, E., Arastoopour, H., Bernstein, B. 2001. "Pulverization of rubber granulates using the solid-state shear extrusion (SSSE) process": Part I. Process concepts and characteristics, Powder Technology, 115, pp. 265-276

[21] Singh, S., Nimmo, W., Gibbs, B.M., Williams, P.T. 2009, "Waste tyre rubber as a secondary fuel for power plants", Fuel, 88, p. 2473-2480.

[22] Chou, L.H., Lu, C.K., Chang, J.R., Lee, M.T. 2007, "Use of waste rubber as concrete additive", Waste Management. Res. 25, pp. 68-76.

[23] Zhou, L., Wang, Y., Huang, Q., Cai, J. 2006, “Thermogravimetric characteristics and kinetic of coal /plastic blends co-pyrolysis”, Fuel Processing Technology. 87, pp. 963-969.

[24] Mino, T. 2009, “Tyre Industry of Japan”, JATMA (Ed.), Tokyo, Japan, pp. 1-32.

[25] Reisan, J.I. 1997, Air Emissions from Scrap Tire Combustion, United States Environmental Protection Agency (EPA) (Ed.), Research Paper EPA-600/R-97-115, California, United States, pp. 1-120.

[26] Masaki, K., Ohkawara, S. I., Hirano, T., Seno, M., Sato, T. 2004, “Devulcanization of nitrile butadiene rubber in nitrobenzene”, Journal of applied polymer science., 91, pp. 3342-3353

[27] Rooj, S., Basak, G.C., Maji, P. K., Bhowmick, A. K. 2011, “New Route for Devulcanization of Natural Rubber and the Properties of Devulcanized Rubber”, Journal of polymers and environment, 19, pp. 382-390

[28] Isayev, I., Liang, T., Lewis, T. M. 2014, “Effect of particle size on ultrasonic devulcanization of tire rubber in twin-screw extruder”, Rubber Chemical Technology, 87, pp. 86-102.

[29] Zanchet, A., Carli, L. N., Giovanela, et. al. J. S. 2012,“Use of styrene butadiene rubber industrial waste devulcanized by microwave in rubber composites for automotive application”, Materials Design, 39, pp. 437-443 .

[30] Sato, S., Honda, Y., Kuwahara, M., et. al. T. 2004, “Microbial Scission of Sulfide Linkages in Vulcanized Natural Rubber by a White Rot Basidiomycete, Ceriporiopsis subvermispora”, Biomacromolecules, 5, pp. 511-515

[31] Ucar, S., Karagoz, S., Ozkan A. R., Yanik, J. 2005, “Evaluation of two different scrap tires as hydrocarbon source by pyrolysis”, Fuel, 84, pp. 1884-1892.

[32] López, F.A., Centeno, T.A., Alguacil, F.J., Lobato, B., 2011, “Distillation of granulated scrap tires in a pilot plant”, Journal of hazardous materials. 190, pp. 285-