A Discussion of Waste Tyre Utilization Options

Edison Muzenda

***Abstract*—**This paper communicates waste tyre management and utilization routes. Waste tyres can be utilized in various rubber applications such as in engineering and construction, environmental protection and agriculture. Energy and material recovery may also be achieved through thermal and thermochemical processes such as incineration and pyrolysis, gasification and liquefaction (PGL) process respectively. The social - economic and environmental benefit analysis of each treatment option is highlighted.

***Keywords*—** Energy, material, recovery, thermal, thermochemical and waste tyre.

I. Rubber Applications

TYRES are designed to be tough and hard-wearing, once they reach their end of life they are difficult to dispose. The main component of tyres, rubber, is a chemically cross-linked polymer; which is neither fusible nor soluble, consequently cannot be remoulded without degradation [1]. In rubber manufacturing, vulcanisation thermally disintegrates rubber creating a hard plastic rubber that retains its form for tyre application. Antioxidants are added to tyres to counter zone effects and material fatigue. The addition of steel, rayon and nylon plus the process of vulcanisation contribute to the non-recycling character of tyres. The processes and facilities required to extract rubber, steel and fibre from tyres are costly, and the resultant products are generally of low value [2]. Two major approaches to address this problem are recycling and the reclaiming of raw rubber materials.

A. Used and Waste Rubber

Polymers can be classified as thermoplastics or thermosetting materials. Thermoplastics soften when heated, may be moulded and then cooled to obtain the desired geometry. This process may be repeated either by direct reheating or preferably after grinding into granules. Thermosetting (thermosets) materials, like rubbers, upon processing and moulding are cross-linked and therefore cannot be softened or remoulded by heating again. Chemical additives are generally incorporated into both thermoplastics and thermosets as stabilizers, flame-retardants, colorants and plasticizers to optimize product properties and performance. As a result, thermoplastics are more readily recyclable than thermoset polymers and rubbers. Recycling of thermoplastics simply involves a reversible physical change by heating the resin above its processing temperature for reshaping and then cooling to room temperature to obtain the desired recycled product. Hence, recycling of thermoplastics is less troublesome and the technology for its re-fabrication is well established and economical. However recycling for thermosetting materials like rubbers is difficult. The three dimensional network of the thermoset polymer must be broken down either through the cleavage of crosslinks or the carbon–carbon linkage of the chain backbone. This is a much more resilient process and the fragmented products obtained by such cleavage are entirely different from the starting thermoset or even its precursor thermoplastics material. Thus, a recycled thermoplastic material competes directly with the virgin polymer. Its commercial viability depends upon the performance or cost benefit of the finished product, in contrast to thermoplastics. The technology for the recycling of thermoset polymers including rubbers is complex, costly and less viable commercially [2]. Reclaimed thermoplastics are used along with virgin resins and fresh additives to obtain desired properties in the formation of final products. Recycled plastics undergo significant changes in physical properties in its recycle phase, but still it retains an acceptable fraction of virgin resin properties [3]. This behaviour is also observed in reclaimed rubber.

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B. Reclaiming Rubber Raw Materials

The 2003 waste tyre situation in South African was as follows, 10% of waste tyres were landfilled, 4% recycled and the remaining 86% illegally re-grooved or dumped in the veld and burnt to recover steel or stockpiled**Error! Bookmark not defined.**. The 2003 waste tyre statistics for developed and developing countries is also shown in Table I.

TABLE I
2003 GLOBAL WASTE TYRE TREATMENT SITUATION

Method of treatment (%)	France 2003	Germany 2003	Italy 2003	UK 2003	Spain 2003	Japan 2003	South Africa
Retreading	26	15	22	23	15		
Recycled	33	19	20	39	9	16	4
Energy	19	53	37	17	12		
Landfill	22	7	8	18	60		10
Export	NA	6	13	3	4	31	0

Towards the end of the1950s, nearly one fifth of the rubber used in the United States and Europe was reclaimed. By the middle of the 1980s less than 1% of the world polymer consumption was in the form of reclaim [5]. In the beginning of the 20th century half of the rubber consumed was in the form of reclaim. It is expected that during the 21st century most of the scrap rubber will be recycled in the form of reclaim due to increasing environmental awareness.

Engineering and construction application: The rubber reclaimed from waste tyres has several applications. In civil engineering and the construction industry, they are used for play-ground surfaces, parking lots, bank stabilization, under road surface filling and asphalt modifiers. Tyres have essential building properties such as; light weight, low earth pressure, good thermal insulation and good drainage properties. Another important property is its improved damping property which is good for running vehicles. However, recent fires have set back the use of ground scrap rubber for many of these applications [2]. In most of these applications, scrap tyres replaces construction materials. Rubber modified asphalt has increased durability, reduced reflective cracking, thinner lift and increase skid resistance [6]. Asphalt modified rubber is also used for water-proofing membranes, crack and joint sealers, hot mix binders and roofing materials. The rubber improves asphalt ductility, thus increasing the temperature at which asphalt softens. The aggregate adhesive bond becomes stronger and increases asphalt shelf life.

Building environment application: Rubber is used for retaining walls, erosion control, barricading of shoring embankments, road embankment fill and thermal insulation in housing foundations.

Agricultural application: Farmers may use waste tyres as erosion control barriers.

Application of shredded, crumbed and granulated tyres: Shredded tyres can be used as fillers in roads, railway and construction developments. Finely shredded old tyres can also be used as mulch (protective cover) which is long lasting, and is presumed to be non-leachable [5]. Rubber mulches (in a variety of colours) have been awarded innovation awards, and are becoming widely used in gardens, parks, playgrounds and equestrian arenas. Rubber mulches are said to be permanent and aesthetically pleasing landscape materials. Waste tyre recycling is a promising environmentally-friendly solution to the waste tyre challenge in South Africa.

II. Material Recovery

Waste tyre can be milled to obtain powder or granules with a specific configuration using various techniques such as mechanical milling, cryogenic milling and de-vulcanization processes. However, de-vulcanization processes are rarely used because of their high operating costs [6].

A. Tyre remoulding and Mechanical Milling

Fatigued rubber is replaced with a new tread. The new tread rubber is fused to the old carcass by vulcanisation thus, re-treading the old tyre. Rubber is broken down by mechanical shredding at high temperatures with the purpose of recovering steel wire. Milling plants are normally of low cost and produce minimum emissions. However, the high power consumption and limited market for the products are the main drawbacks and thus require further research [6].

B. Cryo-mechanical Milling Process

In the mid-1960s, the technique of grinding scrap rubber, particularly tyres, in cryo-mechanical process was developed [7]. Cryogenically ground rubber is used in tyres; hoses; belts and mechanical goods; wire and cables and various other applications. This is particularly useful in tyre inner liners. In this process, the rubber is cooled using liquid nitrogen at a temperature range of $-60^{o}C$ to $-100^{0}C$. The rubber becomes fragile and mills easily into very fine particles using ball or hammer milling. The high consumption of both energy and liquid nitrogen make the process very expensive.

C. Microwave Method

This is used to cleave carbon–carbon bonds. Waste tyres and rubber material can be reclaimed without de-polymerization to a material capable of being re-compounded and re-vulcanized with physical properties equivalent to the original vulcanizate. This route provides an economical and ecologically sound recycling method for waste tyres. Furthermore, this process can produce products similar to virgin rubber. It has been found that the tensile property of devulcanized rubber and virgin rubber blend is almost comparable [8]. The cost of devulcanized hose and inner tube material by microwave method is only a fraction of the cost of the original compound. The transformation from waste to refined stock ready for remixing takes place in only about five minutes with usually 90–95% rubber recovery [7]. Therefore, the microwave technique is a unique reclaiming process with regards to product properties and process swiftness.

III. Energy and Material Recovery

In light of the overall environmental impact along with the drive towards energy and material conservation, new waste tyre disposal options are being developed and implemented. Material and energy recovery through process, such as pyrolysis, can significantly address the waste tyre disposal problem. Fig. 1 shows possible waste tyre treatment routes.

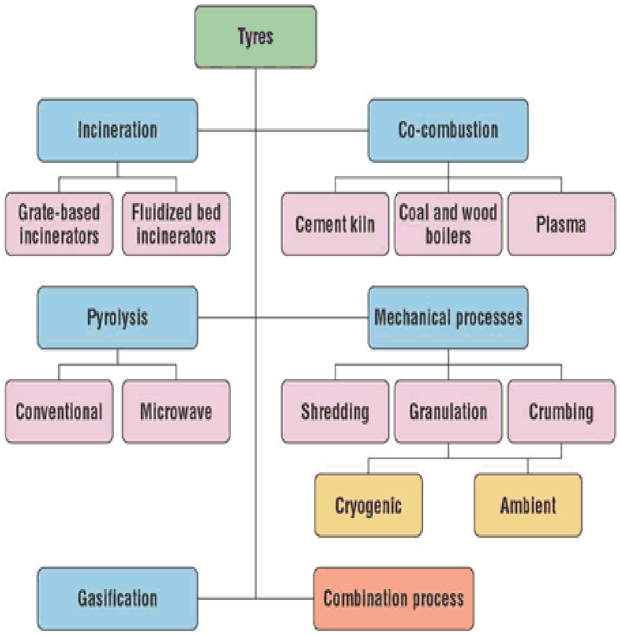

Fig. 1 Technologies for managing scrap tyres [9]

– *A. Thermal Treatment*

The thermal treatment processes encompass combustion (incineration), gasification and pyrolysis of waste tyres, with the following advantages [10]:

– The volume of waste can be reduced by more than 90%.
– Net energy production with possible material recovery.
– Destruction of organic substances which are harmful to human health.

The following difficulties are associated with the thermal treatment of waste tyres [10]:

– Disposal of ash: Lead and cadmium salts used as stabilisers during tyre production remain as ash causing disposal problems.
– Toxic gases: Burning of tyres produce toxic gases such as SO_2, H_2S, HCl, HCN and these require further treatment.
– Soot: Incomplete burning of waste tyres produces soot. This has a much higher heating value than municipal refuse, so requires further combustion and hence requires higher flame temperatures.
– Appropriate incinerators: To address the challenges such as higher temperatures, minimal oxygen conditions and corrosive action of the gases. Appropriate materials of construction are required.

Incineration: The incineration of waste tyres may be defined as the reduction of combustible wastes to inert residue by controlled high-temperature combustion. A typical waste tyre incineration process flow diagram is shown in Fig. 2. The combustion process is spontaneous above 400^{o}C. It is a highly exothermic process and once the process has stabilized it becomes self-supporting. The thermal efficiency of this process is approximately 40% [11]. Waste tyres having a calorific value of 7.5 - 8 MJ/kg, are used as fuel in incinerators. The gas produced may be used as heat for industrial processing or electricity production. Burning of refuse in steam-generating incinerators and using it as a supplementary fuel is advanced and proven waste to energy utilisation [10]. Furnace design and efficiency influences the general combustion performance. Incinerators have to be designed for excellent burning and reduced soot production. Walls and furnace beds must be able to withstand high temperatures of approximately 1150^{o}C. Combustion efficiency, the ratio of thermal energy output to global energy input, usually depends on interdependent factors such as the fuel's physical characteristics, plant design, manufacturing and operating conditions. The use of waste as a supplementary fuel in power plants offers many advantages and drawbacks as shown in Table II.

TABLE II
INCINERATION BENEFIT ANALYSIS

Advantages	Disadvantages
Maximum heat-recovery	Large capital-investment
Low air-pollution emissions	Need for flue-gas cleaning
Environmentally-acceptable process	Relatively high operating cost
Reduced power-production costs	Skilled labour is required to operate the system

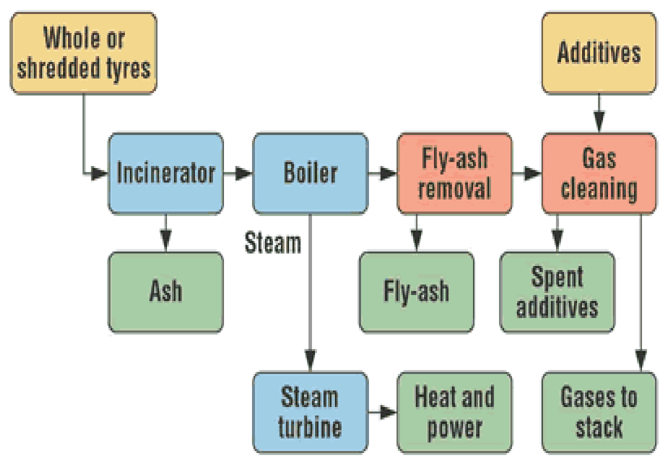

Fig. 2 The scrap tyre incineration process

IV. Pyrolysis, Gasification and Liquefaction (PGL) Processes

PGL processes present alternatives for the disposal of scrap tyres. These technologies are currently used for the conversion of carbonaceous materials to resource fuels and other products, and these may become more significant as the supplies of natural fuels become depleted.

A. Gasification

Gasification is a sub-stoichiometric oxidation of organic material. Typical gasification steps are shown in Fig. 3. The thermochemical process for gasification is more reactive than pyrolysis. It involves the use of air, oxygen (O_2), hydrogen (H_2), or steam/water as a reaction agent. While gasification processes vary considerably, typical gasifiers operate at temperatures between 700° and 800° C. The energy efficiency of the gasification process is reported to be around 76% [12]. The initial step, de-volatilization, is similar to the initial step in the pyrolysis reaction. Depending on the gasification process, the de-volatilization step can take place in a separate reactor upstream of the gasification reaction, in the same reactor, or simultaneously with the gasification reaction. The gasification process can include a number of different chemical reactions, depending on the process conditions and the gasification agent. Equations (1) to (8) show gasification reactions for carbonaceous char.

$$C + CO_2 = 2CO \quad \Delta H° = +172\ kJ \tag{1}$$

$$C + H_2O\ (g) = CO + H_2 \quad \Delta H° = +130\ kJ \tag{2}$$

$$C + 2H_2O\ (g) = CO_2 + 2H_2 \quad \Delta H° = +88\ kJ \tag{3}$$

$$C + 2H_2 = CH_4 \quad \Delta H° = -71\ kJ \tag{4}$$

$$CO + H_2O\ (g) = CO_2 + H_2 \quad \Delta H° = -42\ kJ \tag{5}$$

$$CO + 3H_2 = CH_4 + H_2O\ (g) \quad \Delta H° = -205\ kJ \tag{6}$$

$$C + 1/2\ O_2 = CO \quad \Delta H° = -109\ kJ \tag{7}$$

$$C + O_2 = CO_2 \quad \Delta H° = -390\ kJ \tag{8}$$

The oxygen requirement for the partial oxidation process can be supplied by air, oxygen enriched air, or pure oxygen at a range of pressures. The method of delivery of the oxygen is an important factor in determining the expense and efficiency of the process. Energy is required to compress the combustion air or to cause the cryogenic separation of oxygen from the air. This additional energy use lowers the overall energy efficiency of the process. However, due to the absence of nitrogen in the final gaseous product, its calorific value can be improved from relatively low values of 4 to 10MJ/ m^3 using low-cost, air-blown partial oxidation driven gasifiers, to values of 10 to 15 MJ/m^3 for oxygen-blown processes and 25 to 30 MJ/m^3 for hydrogen-blown processes, which compares well with natural gas, $39MJ/m^3$.

Indirect heating of the feedstock in the gasifier through circulation of inert solid particles such as sand from an externally fired heater may improve thermal energy management of the process [10].

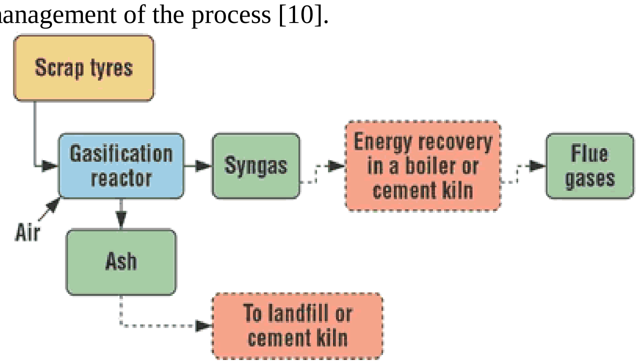

Fig. 2 Scrap tyre gasification process

B. Liquefaction

In the early 1980s, pilot studies focused on the liquefaction of wood wastes. For scrap tyres, this will involve melting the rubber and mixing the melt with another liquid such as waste engine oil for processing. Practical methods have been tried. Pilot studies used steam and catalysts producing oil with a heating value of 34.89 MJ/kg and a specific gravity of 1.03. The costs of commercial production were estimated to be higher than coal liquefaction [13].

The Bourns College of Engineering, Centre for Environmental Research and Technology (CECERT) at the University of California Riverside studied the hydrothermal treatment of waste tyres using high-pressure water heated to 250°C. Liquefaction was used as a pre-treatment step to separate the rubber for pyrolysis and gasification from steel belting.

C. Energy recovery

Waste tyres can be utilised as a fuel source. Tyres produce the same amount of energy per unit mass as oil and slightly more than coal [14]. Hence, tyres can be used as an efficient fuel for industrial processes such as power plants with minimum negative environmental impact compared to coal. In most cases tyres are shredded but the use of whole tyres is also possible with large machinery. The presence of steel belts hinders the use of whole tyres. The Shredding of whole tyres and removal of wires can be integrated as part of the process. Energy from the direct combustion of waste tyre can be utilized in metal works, paper mills, tyre factories and on a smaller scale, in farms, greenhouses and sewage treatment plants.

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Biography: Edison Muzenda is a Full Professor of Chemical Engineering, the Research and Postgraduate Coordinator as well as Head of the Environmental and Process Systems Engineering Research Group in the Department of Chemical Engineering at the University of Johannesburg. Professor Muzenda holds a BSc Hons (ZIM, **1994**) and a PhD in Chemical Engineering (Birmingham, **2000***)*. He has more than **15** years' experience in academia which he gained at different Institutions: National University of Science and Technology, University of Birmingham, Bulawayo Polytechnic, University of Witwatersrand, University of South Africa and the University of Johannesburg. Through his academic preparation and career, Edison has held several management and leadership positions such as member of the student representative council, research group leader, university committees' member, staff qualification coordinator as well as research and postgraduate coordinator. Edison's teaching interests and experience are in unit operations, multi-stage separation processes, environmental engineering, chemical engineering thermodynamics, entrepreneurship skills, professional engineering skills, research methodology as well as process economics, management and optimization. He is a recipient of several awards and scholarships for academic excellence. His research interests are in waste water treatment, gas scrubbing, environment, waste minimization and utilization, green energy engineering as well as phase equilibrium measurement and computation. He has published more than **180** international peer reviewed and refereed scientific articles in journals, conferences and books. Edison has supervised **28** postgraduate students, **4** postdoctoral fellows as well as more than **140** Honours and BTech research students. He serves as reviewer for a number of reputable international conferences and journals. Edison is a member of the Faculty of Engineering and Built Environment Research and Process, Energy and Environmental Technology Committees. He has also chaired several sessions at International Conferences. Edison is an associate member of the Institution of Chemical Engineers (AMIChemE), member of the International Association of Engineers (IAENG); associate member of Water Institute of Southern Africa (WISA), Associate Editor for the South African Journal of Chemical Engineering as well as a member of the Scientific Technical Committees and Editorial Boards of several scientific organizations.